

Some Physical Factors Affecting Contaminant Hydrology in Cold Environments

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Some of the physical effects of cold temperatures that should be considered when developing a contaminant-transport model are surveyed in this paper. The discussion begins with the following working definition of the term *cold region* for the purpose of contaminant hydrology modeling: an area with appreciable frozen ground and a substantial fraction of the annual precipitation as snow. Models that estimate the liquid water content and hydraulic conductivity of frozen ground are discussed.

Lexically, the adjective "cold" refers to an environment in which the ambient temperature is noticeably below body temperature. A cold region is one in which lower temperatures have significant effects on natural environments or human activities. Although moderate temperatures may be perceived as cold, cold regions have been typically defined by the intervals in which ambient temperatures are below the freezing point of water, because it is at these temperatures that the effects of cold temperatures are most pronounced. Among the criteria that have been used to delineate cold regions are (1)

1. Air temperatures below 0°C (32°F) or -18°C (0°F) that have a 50 percent likelihood of being observed annually,
2. Mean annual snow depth,
3. Ice cover on navigable rivers, and
4. Isolines based on permanence, depth, and continuity of frozen ground.

Traditionally, the maps made from plotting isograms based on these criteria delineate the changes in human activities due to cold. For example, isograms based on frozen ground delineate changes in the construction requirements for building footings. Isograms based on ice cover indicate the navigability of the waters during some portion of the year.

The purpose of this paper is to discuss how cold temperatures affect contaminant-transport modeling. Accordingly, cold regions should be delineated by the phenomena necessary to make the model a valid representation of the pertinent chemical, physical, and microbiological processes that determine the fate of contaminants in the cold environment. Low temperatures affect the physics of contaminant transport by freezing the water in the ground (sometimes to great depths) and by blanketing the ground (seasonally or permanently) with snow. Since no maps have been drawn delineating cold regions' effects on contaminant hydrology, the natural delineations would be those for snow covers and the extent of ground freezing.

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EXTENT OF COLD REGIONS

In comparing the hydrologic systems of cold regions with those of warmer areas, two factors distinguish the former systems:

1. Some of the annual precipitation occurs as snow, which completes its role in the hydrologic cycle for a comparatively brief period during snowmelt.
2. The ground freezes to some depth. Ground freezing reduces the soil's permeability and its water-storage capacity. Accordingly, freezing of the ground dramatically decreases the soil's infiltration rate and just as dramatically increases soil runoff due to rain and snowmelt.

To be hydrologically important, a cold region must receive an appreciable proportion of its precipitation as snow, and its ground must be frozen so that the infiltration of the melting snow is limited. In the Northern Hemisphere, these two criteria can be applied to delineate the extent of cold regions for the purposes of contaminant-transport modeling.

Snow Cover

Maps with isograms of various annual snow depths have been developed (1) (Figure 1). Much of the United States has average maximum snow depths of 0.3 m (12 in.) or more. This includes all or part of the following states: Alaska, California, Connecticut, Idaho, Illinois, Indiana, Maine, Massachusetts, Michigan, Minnesota, Missouri, Montana, Nebraska, Nevada, New Hampshire, New Jersey, New York, North Dakota, Ohio, Pennsylvania, South Dakota, Utah, Vermont, Washington, Wisconsin, and Wyoming. The isogram in Figure 1 indicates the annual quantity, but not annual fraction, of precipitation that typically arrives as snow and therefore does not indicate the relative importance of snow to a region's hydrology. Accordingly the isogram in Figure 1 may not adequately delineate snow-affected areas in drier regions.

Frozen Ground

Three major classes of frozen ground are recognized: seasonally frozen ground, discontinuous permafrost, and permafrost.

Seasonally Frozen Ground

The potential inadequacy of snow-depth isograms to delineate cold, dry areas is borne out by the map of permafrost and frost-

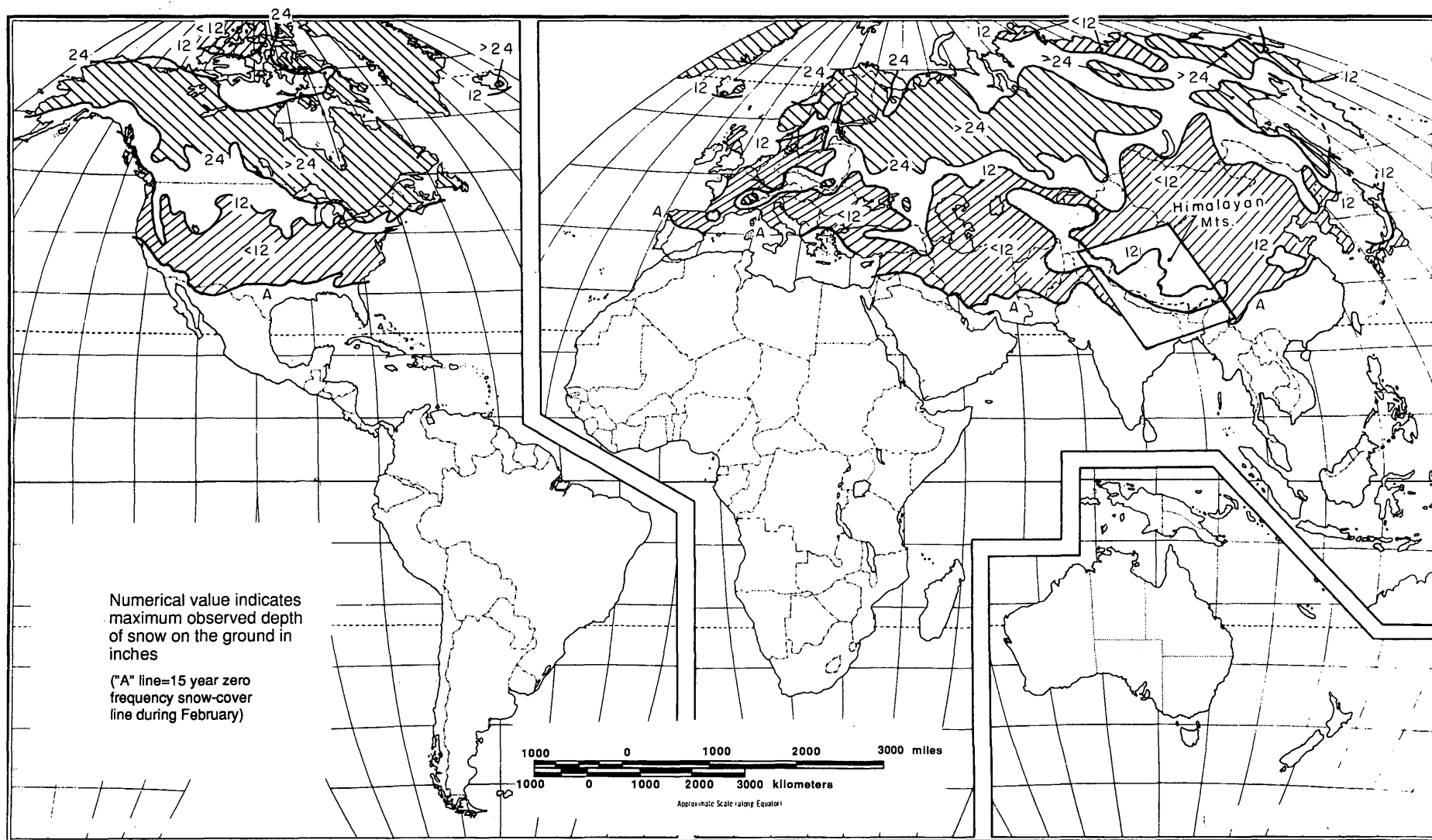


FIGURE 1 Cold-regions boundaries as determined by snow depths (1).

affected areas presented here in Figure 2 (1). Understandably, the southernmost isogram, that for frost penetration, is similar to that for snow cover. However, several areas (mostly in the western United States) with low rates of annual precipitation are now included. These areas are all or parts of Arizona, Colorado, Kansas, Maryland, Missouri, New Mexico, and Rhode Island.

Discontinuous Permafrost

In the United States, discontinuous permafrost is found only in Alaska. Discontinuous permafrost or permafrost is found under most of the land surface of the state.

Permafrost

Areas of permafrost, in which no seasonally thawed land occurs, are found in the northernmost parts of Alaska.

Importance to Contaminant-Transport Modeling

A model is a mathematical expression of the developer's understanding of the system being simulated. Accordingly, contaminant-transport models valid for cold regions differ from those appropriate for warmer climates because the system being described is conspicuously different. Below is a list of modeling aspects that differentiate contaminant-transport models valid in cold regions:

1. Much of what is understood about the hydrology of cold regions is qualitative. Because there have been comparatively few studies in cold regions, the physical, chemical, and biological processes that determine contaminant hydrology of cold regions are not completely understood. This lack of quantitative knowledge hinders the development of physically based contaminant-transport models valid for cold regions. Much basic research is needed to support the development of simulation models that are appropriate for these regions.

2. The flow of heat and aqueous-solution phase transitions must be included explicitly in the development of solute transport models.

3. In unfrozen porous media, liquid water moves largely in response to hydrostatic gradients. In frozen porous media, liquid water movement in response to osmotic or thermal gradients may be dominant.

4. The physical chemistry of electrolyte solutions in natural porous media above freezing temperatures is well understood, and models describing them are generally available. For systems below 0°C, there are comparatively few physical chemical data (aside from freezing-point depression determinations) for even simple electrolyte solutions.

5. Much of the groundwater in areas with permafrost is brackish and impotable. Contamination of currently exploited aquifers that are potable can effectively deprive communities of potable subterranean water supplies.

How these effects are incorporated in mathematical models of contaminant transport can be outlined with the differential equations that form the basis of many of these models. Water in a porous medium flows in a linearly proportional response to the

hydrostatic gradient across that medium. This observation has been formalized as Darcy's law, the vector form of which is

$$\mathbf{v} = -\frac{\mathbf{k}}{\nu} + (\nabla p - \rho g \nabla z) = -\mathbf{K} \cdot \nabla h \quad (1)$$

where

\mathbf{v} = Darcian flow velocity vector (m sec^{-1});

\mathbf{k} = permeability tensor (m^2);

ν = viscosity of the fluid ($\text{Pa} \cdot \text{sec}$);

p = fluid pressure (Pa);

ρ = fluid density (kg m^{-3});

z = vertical distance above datum (m);

g = acceleration due to gravity ($\text{m} \cdot \text{sec}^{-2}$);

\mathbf{K} = hydraulic conductivity tensor, which in this treatment will be assigned dimensions of square meters per pascal second; and

h = total head (Pa).

[The formulas presented here are from Mangold and Tsang (2).] As will be discussed in later sections, low temperatures dramatically affect three of the parameters in Equation 1: ν , p , and \mathbf{K} . The viscosity of the aqueous solution in freezing soils is affected directly by lowering temperatures, which cause the viscosity of pure water to increase by an order of magnitude (an effect presented in Figure 3), and by solutes excluded from ice forming in the soil solution, which cause the viscosity of the remaining liquid-water solution to be increased still further (an effect presented in Figure 4). The pressure of vicinal water in frozen porous media is controversial and an active area of basic research (4). It is clear that the liquid-pressure gradients accompanying differences in temperature may be much more important than pressure gradients due to elevation or water content [see, for example, Perfect et al. (5)]. Finally, because ice occupies some of the pore space, the conductivity of the porous material is reduced.

Once the flow of water is established, the more challenging problem of solute flows through porous media can be addressed. In many cases, the appropriate partial differential equation to describe the transport of the solute j is

$$\nabla \cdot (\mathbf{v}c_j) - \nabla \cdot (\mathbf{D} \cdot \nabla c_j) = \Phi \frac{\partial c_j}{\partial t} + Q_{c_j} \quad (2)$$

where

c_j = aqueous concentration of the j th solute (mol m^{-3}),

\mathbf{D} = dispersivity tensor ($\text{m}^2 \text{sec}^{-1}$),

Φ = porosity of the porous medium (L), and

Q_{c_j} = source-sink term for j th solute ($\text{mol m}^{-3} \text{sec}^{-1}$).

As would be expected, most of the geochemical reactions that contribute to the term Q_{c_j} are affected by temperature. The most pronounced of these effects are on the chemical-thermodynamic state of the solutes and consequently their solubility, miscibility, speciation, and reactivity.

PHYSICS OF FROZEN POROUS MEDIA

Moderately cool temperatures affect the physical-chemical state of water and its propensity to flow through porous media. For

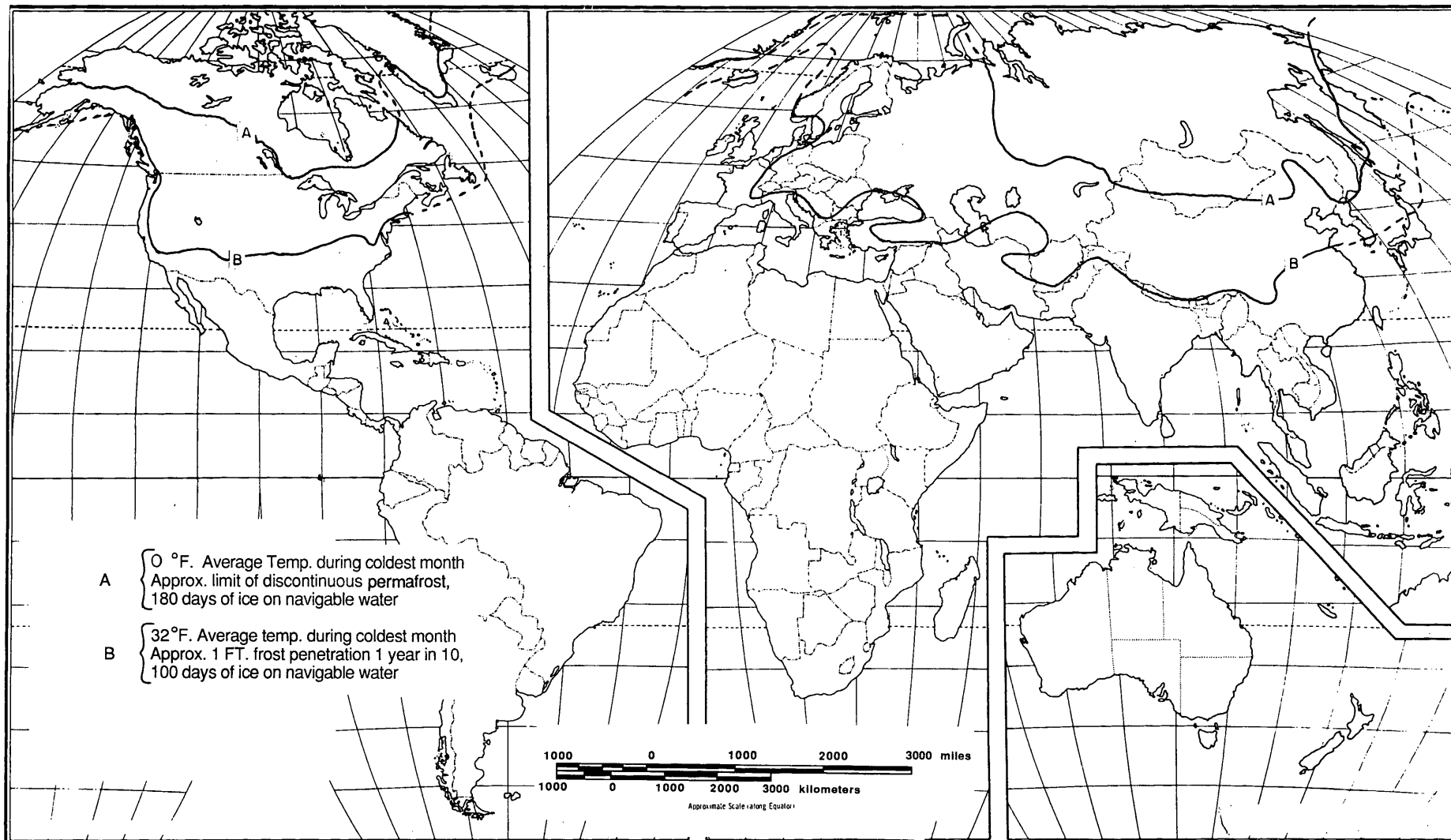


FIGURE 2 Cold-regions boundaries as determined by frozen ground (1).

contaminant transport, changing temperatures affect the chemical potentials of the solvents and solutes in the pore solutions and therefore the solubility and reactivity of the solutes. These changes in the physical properties of the solvent and chemical properties of the solutes can dramatically affect the mobility of contaminants in cold regions.

At low temperatures, at which surficial, vadose, and aquifer waters freeze, the nature of flow changes dramatically. First, at a macroscopic level, because the effective volume of voids is reduced, the ground has a much lower permeability when frozen. This affects the basin-scale hydrology in cold regions in sometimes unpredictable ways. Second, although frozen ground is less permeable, it is not impermeable. The mathematical description of transport of solutes through frozen ground is inherently more complex than that for unfrozen ground for the following reasons:

1. The solvent, water, is partitioned into two phases, liquid water and ice, which are intimately comingled in the pores of the ground.

2. As the ice forms, the solutes (including the contaminants) are largely excluded from the ice, concentrating the remaining liquid-water solutions in a thin film at the colloid surfaces. The chemical potentials of the solutes in these solutions, used to estimate the effects of solute-solute and solute-surface interactions, are not understood well enough to be modeled accurately.

3. In unfrozen coarse-grained soils, the movement of solutes is controlled by the Darcian flow of water in response to gravitational and pressure gradients. In frozen ground, solutes may also move appreciably in response to thermal and osmotic gradients—transport mechanisms that are less well understood and more difficult to parameterize than flow in response to gravitational and pressure gradients.

Darcy's Law

An alternative form of Darcy's law, with which water flows in porous media can be described, can be stated as follows:

$$q \equiv \frac{Q}{A} = - \left(\frac{k}{\nu} \right) \frac{(p_2 - p_1 + \rho gh)}{h} \quad (3)$$

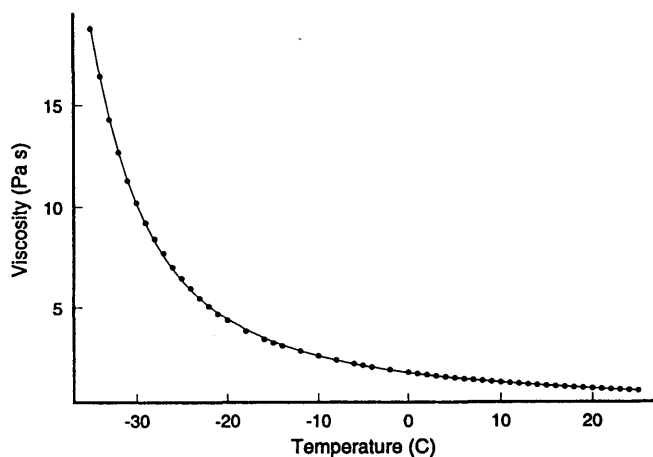


FIGURE 3 Viscosity of supercooled water [data from Osipov et al. (3)].

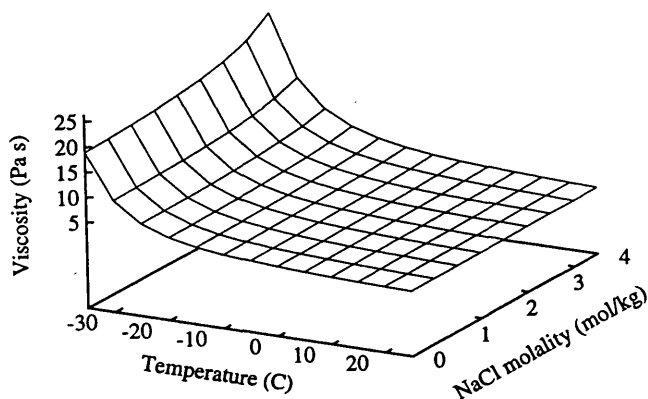


FIGURE 4 Predicted viscosity of aqueous NaCl solutions as affected by temperature and solution concentration.

which states simply that a length h of a porous medium, over which a hydrostatic gradient [equal to $(p_2 - p_1 + \rho gh)$] is posed, will transmit water at a rate that is directly proportional to its permeability k and its cross-sectional area A and inversely proportional to the viscosity of the fluid, ν . Low temperatures reduce water flows through porous media. As has been discussed, low temperatures increase the viscosity of water. Freezing reduces the permeability of soils and ground dramatically. Geochemical solutions do not freeze uniformly at 0°C . The equilibrium freezing temperature of pore water is a function of pore geometry, freezing-point depressing effects of solutes, and the charge behavior of the porous matrix (6). The quantitative description of these effects, which is discussed below, is an active research area.

Soil-Water Retention Curve

The permeability of a frozen porous medium is affected by its liquid water content. Accordingly, a discussion of the physics of unsaturated porous media is appropriate.

Matric Potential

Two factors have been identified in determining the relationship between matric potential and water content in unsaturated soils. The first is the pressure difference between the soil atmosphere and the liquid water bound to soil particles. The second factor is the work required to expand the liquid water-air interface as soil-water content decreases. When a stable interface is established, these two factors are balanced and the water content is stable. For a given matric potential, any environmental event that changes one of these balanced factors relative to the other can be expected to cause the water content to change.

Effect of Temperature

An obvious, and pertinent, example is temperature, which decreases the interfacial tension of water against air. The effect of temperature on the soil-water retention curve may be estimated

via

$$\left(\frac{\partial \theta}{\partial t}\right)_\Psi = - \left(\frac{\partial \theta}{\partial \Psi}\right)_t \left(\frac{\partial \Psi}{\partial t}\right)_\theta \quad (4)$$

where θ is the volumetric water content of the porous medium in liters, and Ψ is the matric potential of the water in the porous medium in pascals.

For a given pore radius, the relationship between capillary pressure and interfacial tension is direct:

$$\Psi = - \frac{2\gamma^{wa} \cos \phi}{r} \quad (5)$$

where r is the pore radius in meters and ϕ is contact angle of the water-air interface with the solid in radians.

The interfacial tension of water against air (in newtons per meter) from the triple-point of water (0.01°C) to the critical point of water (374.15°C) has been fitted to

$$\gamma^{wa} = \gamma_0 \left(\frac{T_e - T}{T_e}\right)^u \left(1 - v \frac{T_e - T}{T_e}\right) \quad (6)$$

in which the parameters have the following recommended values: $\gamma_0 = 0.2358$, $T_e = 647.15$, $u = 1.256$, and $v = 0.625$. Although there have been few reported measurements of γ^{wa} below 0°C, these data indicate that Equation 6 is approximately valid to at least -8°C (7). The complexity of Equation 6 belies the fact that the interfacial tension of water against its vapor is virtually linear from -10°C to 50°C, as can be seen in Figure 5. Accordingly, one would expect that the following relationship would hold exactly:

$$\frac{[\partial \Psi(t, \theta) / \partial t]}{[\partial \gamma^{wa}(t) / \partial t]} = \frac{\Psi(t, \theta)}{\gamma^{wa}(t)} \quad (7)$$

In fact it does not, requiring the definition of an empirical variable $[G(\theta)]$ introduced by Nimmo and Miller (8) to account for the discrepancy:

$$G(\theta) = \frac{\frac{\Psi(t_2, \theta)}{\Psi(t_1, \theta)} - 1}{\frac{\gamma^{wa}(t_2)}{\gamma^{wa}(t_1)} - 1} \quad (8)$$

where $t_2 > t_1$.

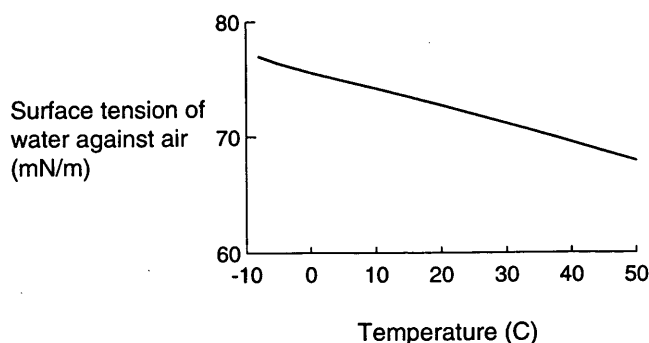


FIGURE 5 Measured values of interfacial tension of water against its vapor at a range of temperatures.

Soil Freezing Characteristic Curve

Liquid water (albeit generally very small amounts) exists in frozen soil at temperatures significantly below 0°C. For water-saturated frozen soils, an approximation of the liquid-water content can be calculated from the soil-water retention curve, if known. The physics of the two situations are similar: in the unsaturated, unfrozen soil, the liquid-water content is determined by balancing the pressure difference across the interface between the soil water and the soil atmosphere with the work necessary to deform this interface against the interfacial tension of water against air. The validity of this hypothetical mechanism for controlling the soil-water retention curve is supported by the observation that, for a given matric potential, the quantity of water held by the soil decreases as the temperature increases; that is, as interfacial tension decreases with increasing temperatures, less work is required to deform the water-air interface.

In frozen, water-saturated soils, there is a water-ice interface between the liquid water surrounding the soil particles and the ice. This situation is qualitatively similar to the water-air interface in unsaturated soils. A schematic displaying these parallel physical systems is presented in Figure 6. For a single soil sample of unaltered internal structure, liquid water contents in a frozen, unsaturated state should be a function of the pressure gradient across the water-ice interface. This function should be similar to the empirical equation that describes the soil-water retention curve.

Clapeyron Equation

For two phases at equilibrium (e.g., water and ice), the following expression applies:

$$\Delta_s^l H_m^* = T^{l+s} \Delta_s^l S_m^* \quad (9)$$

where

$\Delta_s^l H_m^*$ = molar enthalpy of fusion (J mol⁻¹),

$\Delta_s^l S_m^*$ = the molar entropy of fusion (J K⁻¹ mol⁻¹), and

T^{l+s} = melting temperature (K) (9).

When the Gibbs-Duhem equation is applied to Equation 9, the following relation is obtained:

$$\frac{dp^{l+s}}{dT} = \frac{\Delta_s^l H_m^*}{T^{l+s} V_m^{*l}} \quad (10)$$

where p^{l+s} is the pressure at which the solid and liquid phases coexist (in pascals) and V_m^{*l} is the molar volume of the liquid phase. Equation 10 is known generally as the *Clapeyron equation*.

Following the suggestion of Koopmans and Miller (10), the Clapeyron equation has been applied to soil systems to estimate the matric potential of the liquid-water fraction of frozen soils.

This argument begins with the standard definition of capillary pressure (in pascals):

$$p_c = p(\text{liquid soil water}) \quad (11)$$

$$- p(\text{ambient atmospheric pressure})$$

which is related to matric potential by (11)

$$\Psi = \frac{p_c}{\rho g} \quad (12)$$

A similar pressure, p_i , may be defined for frozen ground to express the pressure gradient across the water-ice interface in frozen ground:

$$p_i = p(\text{liquid soil water}) - p(\text{ice}) \quad (13)$$

A term similar to matric potential can be defined for the pressure gradient across the water-ice interface in frozen ground:

$$\Psi_i = \frac{p_i}{\rho g} \quad (14)$$

If the volumetric content of soils for a given matric or supercooling potential is assumed to be dependent solely on the ratios of pressure gradients to interfacial tensions,

$$\theta\left(\frac{\Psi}{\gamma^{wa}}\right) = \theta\left(\frac{\Psi_i}{\gamma^{wi}}\right) \quad (15)$$

Then moisture-release and soil-freezing curves should be related by

$$\theta(\Psi) = \theta\left(\frac{\gamma^{wa}}{\gamma^{wi}} \frac{p_i}{\rho_{H_2O} g}\right) \quad (16)$$

The value of p_i as a function of temperature can be estimated by Equations 10 and 16 if it is assumed that $p_i = dp^{l+s}$ and $t - 0 = dT$. The necessary data are (12,7)

$$\gamma^{wa}(p = 0.1 \text{ MPa}, t = 0.01^\circ\text{C}) = 0.7564 \text{ N m}^{-1}$$

$$\gamma^{wi}(p = 0.1 \text{ MPa}, t = 0^\circ\text{C}) = 0.033 \text{ N m}^{-1}$$

$$\Delta_s^l H_m^* = 6007.0 \text{ J mol}^{-1}$$

$$V_m^l = 18.018 \text{ cm}^3 \text{ mol}^{-1}$$

$$V_m^s = 19.650 \text{ cm}^3 \text{ mol}^{-1}$$

This implies that the pressure gradient across the water-ice interface changes with temperature according to

$$\frac{dp^{l+s}}{dT} = 1.221 \text{ MPa K}^{-1} \equiv 1.221 \text{ MPa}^\circ\text{C}^{-1} \quad (17)$$

Making the proper substitutions into Equation 16,

$$\theta(\Psi) \approx \theta\left(-\frac{\gamma^{wa}}{\gamma^{wi}} \frac{\Delta_s^l H_m^*}{T_{fus} V_m^l \rho_{H_2O} g} t\right) \quad (18)$$

the following equation is derived:

$$\theta(\Psi) \approx \theta(ft) \quad (19)$$

where f is a constant approximately equal to $285.3 \text{ m H}_2\text{O } ^\circ\text{C}^{-1}$.

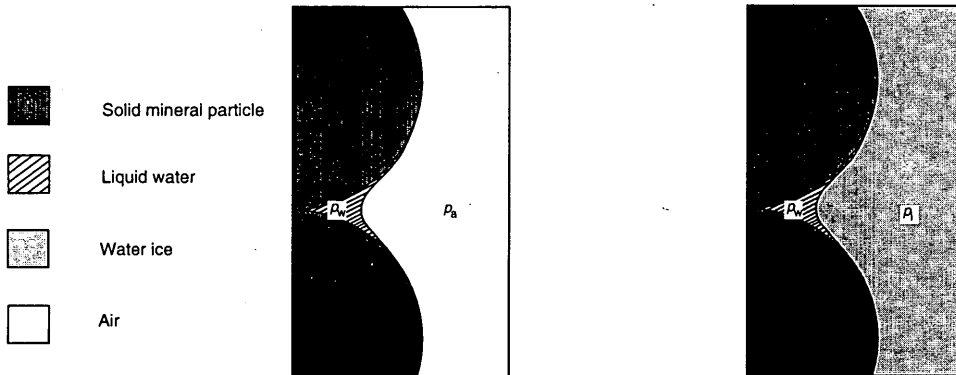
Changes in Hydraulic Conductivity with Soil-Water Content

The relative-hydraulic-conductivity model proposed by van Genuchten (13) has been adopted by many investigators. With some changes in notation, van Genuchten's model represents reduced water content, Θ (in liters), as a function of soil-water matric potential by

$$\Theta = \left[\frac{1}{(\Psi\alpha)^\lambda + 1} \right]^{\frac{\lambda-1}{\lambda}} \quad (20)$$

where α (m^{-1}) and λ (L) are empirical parameters. The reduced water content is defined by

$$\Theta = \frac{(\theta - \theta_r)}{(\theta_s - \theta_r)} \quad (21)$$



Simplified microscopic schematic illustration of unfrozen, unsaturated soil

Simplified microscopic schematic illustration of frozen, water-saturated soil

FIGURE 6 Schematic drawing showing the hypothetical similarity between water contents of unsaturated, unfrozen soils and of saturated, frozen soils.

where θ is the volumetric water content (L), and θ_s and θ_r are the saturated and residual volumetric water content (L). The resulting empirical equations for volumetric water content are as follows; for unsaturated, unfrozen soils:

$$\theta = \theta_r + (\theta_s - \theta_r) \left[\frac{1}{(\Psi\alpha)^\lambda + 1} \right]^{\frac{\lambda-1}{\lambda}} \quad (22)$$

and, by extension, for frozen, saturated soils:

$$\theta = \theta_r + (\theta_s - \theta_r) \left[\frac{1}{(ft\alpha)^\lambda + 1} \right]^{\frac{\lambda-1}{\lambda}} \quad (23)$$

Similarly, the van Genuchten model proposed the following equations to calculate changes in relative permeability; for unsaturated, unfrozen soils:

$$K_r(\Psi) = \frac{\left\{ 1 - \frac{(\alpha\Psi)^{\lambda-1}}{[1 + (\alpha\Psi)^\lambda]^{\frac{\lambda-1}{\lambda}}} \right\}^2}{[1 + (\alpha\Psi)^\lambda]^{\frac{\lambda-1}{2\lambda}}} \quad (24)$$

and for frozen, saturated soils:

$$K_r(t) = \frac{\left\{ 1 - \frac{-(\alpha ft)^{\lambda-1}}{[1 + (-\alpha ft)^\lambda]^{\frac{\lambda-1}{\lambda}}} \right\}^2}{[1 + (-\alpha ft)^\lambda]^{\frac{\lambda-1}{2\lambda}}} \quad (25)$$

CONCLUSION

A surprisingly large number of sites in cold regions in the Northern Hemisphere are contaminated. There is a need to incorporate the fundamental physical, chemical, and hydrological processes that govern contaminant hydrology into the numerical models that are used to assist in the remediation of these sites. It is hoped that this paper assists in that process. The physical and chemical processes that determine the fate of contaminants in cold regions are just now being understood comprehensively. As with any new area of understanding, this is a challenging process, but it is also an exciting area at the limits of the understanding of the dynamic behavior of complex, heterogeneous materials.

RESEARCH PRIORITIES

The literature survey presented here has revealed important gaps in scientific information that will impede the development of contaminant-transport models for cold regions:

1. A consistent thermodynamic treatment of the hydrostatics of liquid water in frozen porous media, a critical need, has yet to be developed.

2. Aside from permeability, the capillary pressure-saturation relation for fluids in porous media is the most critical physical function for modeling the transport of fluids in variably saturated me-

dia. It has yet to be resolved entirely how temperature affects this relationship. A satisfactory understanding of the effect of temperature on soil retention curves for water and other liquids needs to be developed.

3. A coordinated research effort should be pursued to determine the temperature effects on the physics of insoluble and sparingly soluble nonaqueous phase liquids in porous media.

4. In frozen ground, the movement of solutes and water in response to osmotic and thermal gradients may be significant. Relations by which the transport of water, solutes, and nonaqueous phase liquids in response to thermal and osmotic gradients may be estimated reliably should be derived or developed.

5. The Pitzer model provides a powerful method by which to model the thermophysical behavior of electrolyte solutions below the freezing point of water. Unfortunately, there are few measurements with which to apply this tool. Physical-chemical properties of aqueous electrolyte solutions at subzero temperatures (constant-pressure heat capacities, molar volumes, and viscosities) are needed.

NOTATION

Symbol/Name (Definition)	Equation First Cited
A cross-sectional area	(3)
c_j aqueous concentration of the j th solute	(2)
D dispersivity tensor	(2)
g acceleration due to gravity	(1)
h height or width of a system	(3)
h total head	(1)
$\Delta_s^* H_m^*$ molar enthalpy of melting, pure substance	(9)
k (specific) permeability	(3)
\mathbf{k} permeability tensor	(1)
\mathbf{K} hydraulic conductivity tensor	(1)
p pressure	(1)
p_c capillary pressure	(11)
p_i pressure gradient across ice-liquid-water interface in water-saturated porous media	(13)
q seepage velocity	(3)
r mean radius, largest undrained pore class	(5)
t Celsius temperature ($\equiv T - 273.15$)	(17)
T thermodynamic temperature	(9)
T^{l+s} freezing temperature of pure solvent	(9)
\mathbf{v} Darcian flow velocity vector	(1)
V_m^α molar volume of α phase	(9)
$\Delta_s^* V_m^*$ molar volumetric change with fusion	(9)
z vertical distance above datum	(1)
α parameter in van Genuchten equation	(20)
γ^{wa} interfacial tension of water against air	(6)
γ^{wi} interfacial tension of ice against water	(15)

θ_r	residual liquid-water content	(21)
θ_s	saturated liquid-water content	(21)
θ	reduced liquid-water content	(20)
λ	parameter in van Genuchten equation	(20)
ν	viscosity	(1)
ρ	density	(1)
ϕ	water-air contact angle at solid	(5)
Φ	porosity	(2)
θ	volumetric liquid-water content	(4)
Ψ	matric potential	(4)
Ψ_i	p_i expressed in terms of height of liquid water	(15)

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