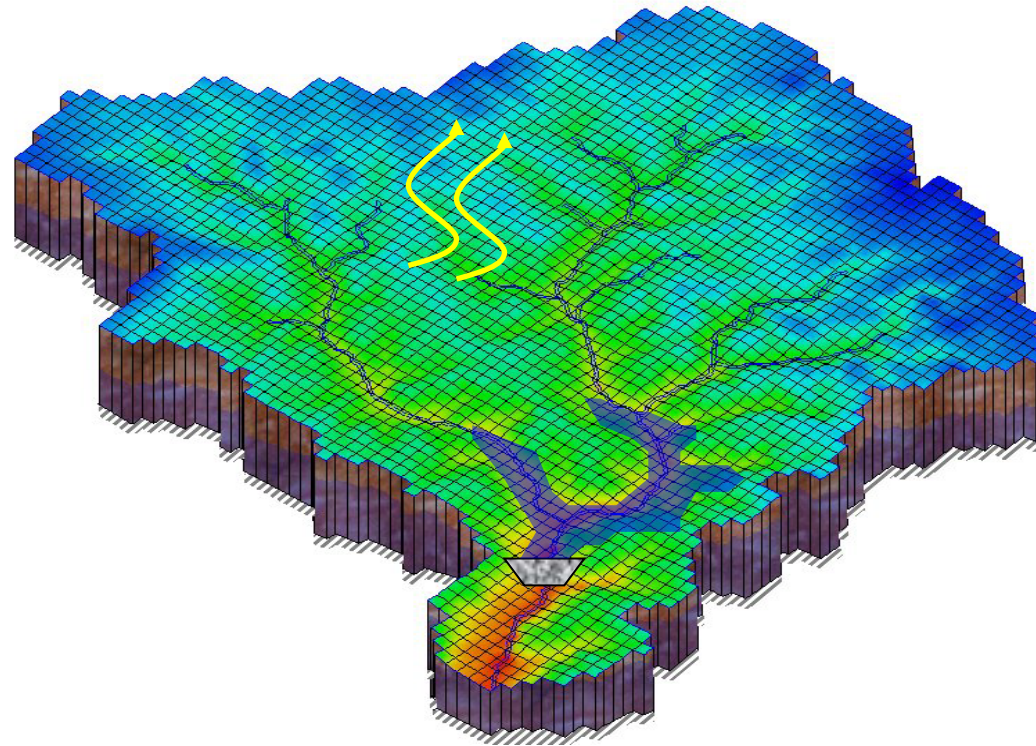
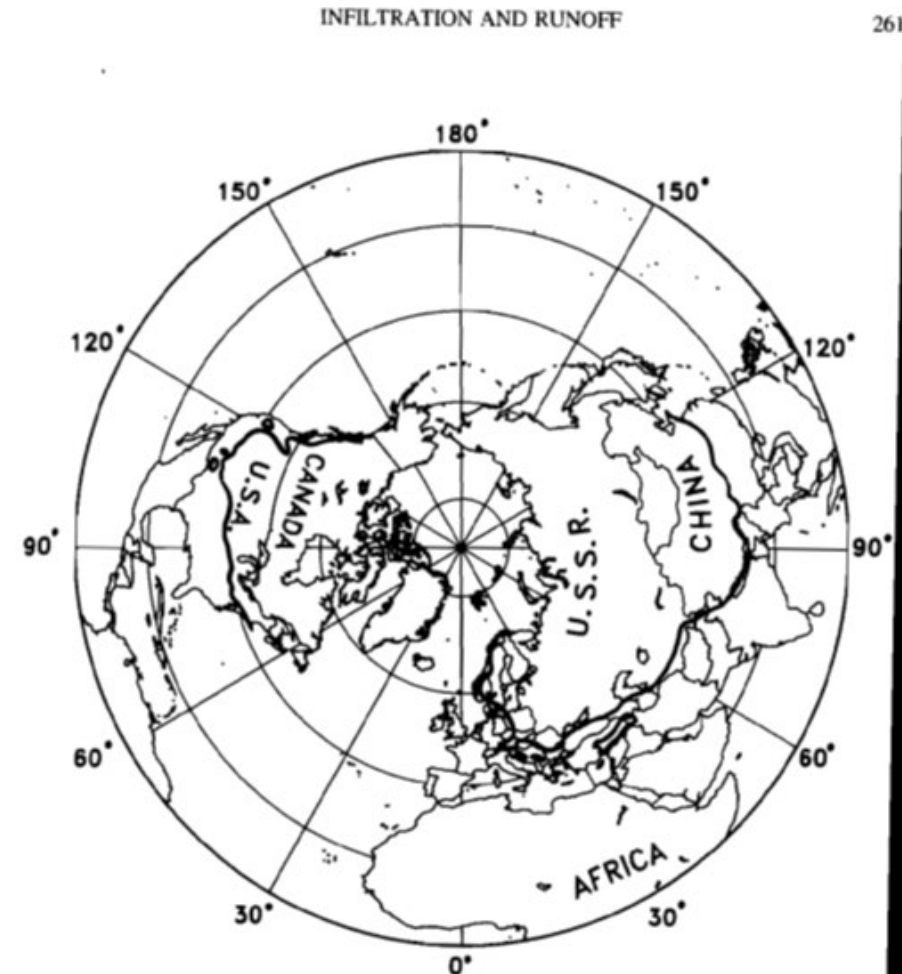


Effects of Temperature on Hydrology

Simulating Arctic Hydrology in GSSHA



- In cold regions soil pore water can freeze
 - Seasonally
 - Permanently- more northern climates



— Limit of significant frost penetration based on a mean of 100 degree days of freezing ($^{\circ}\text{F}$) or 55.5 degree days of freezing ($^{\circ}\text{C}$).



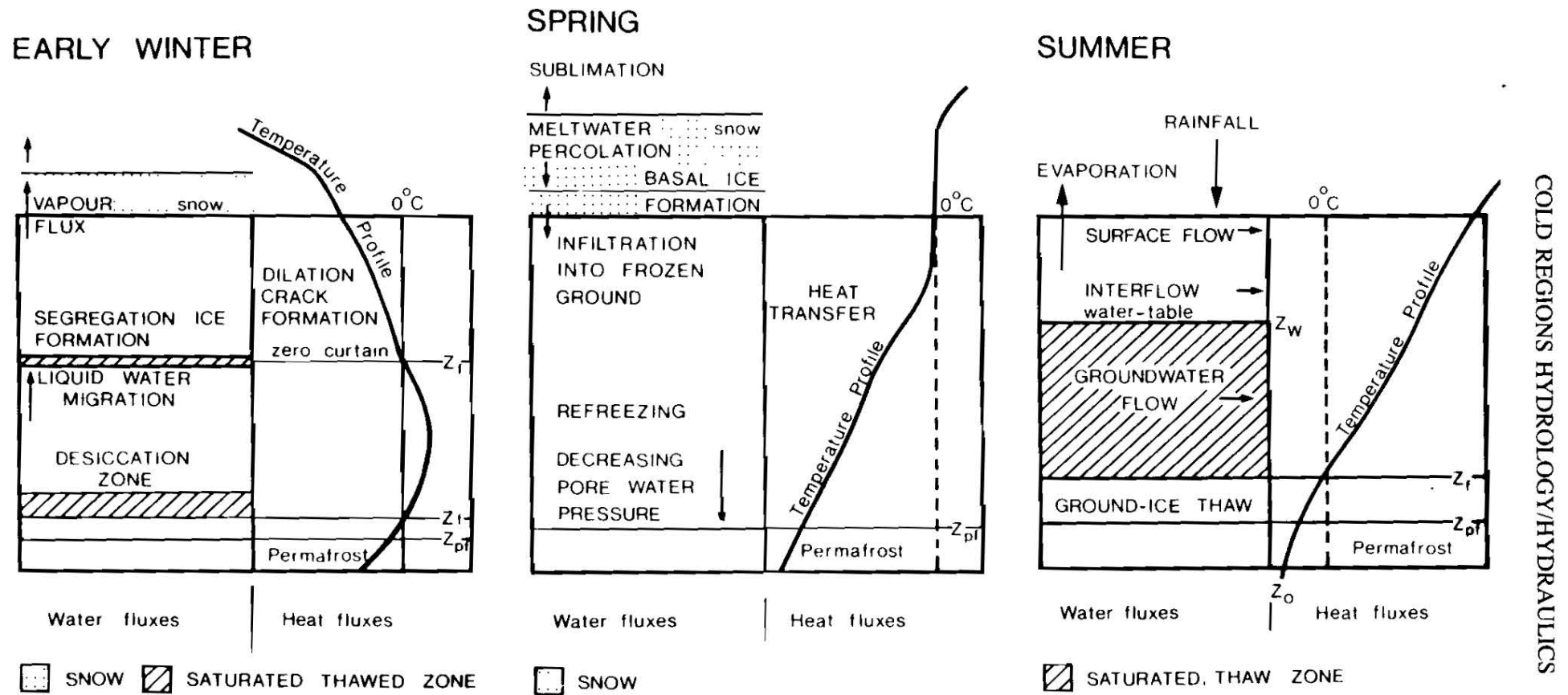
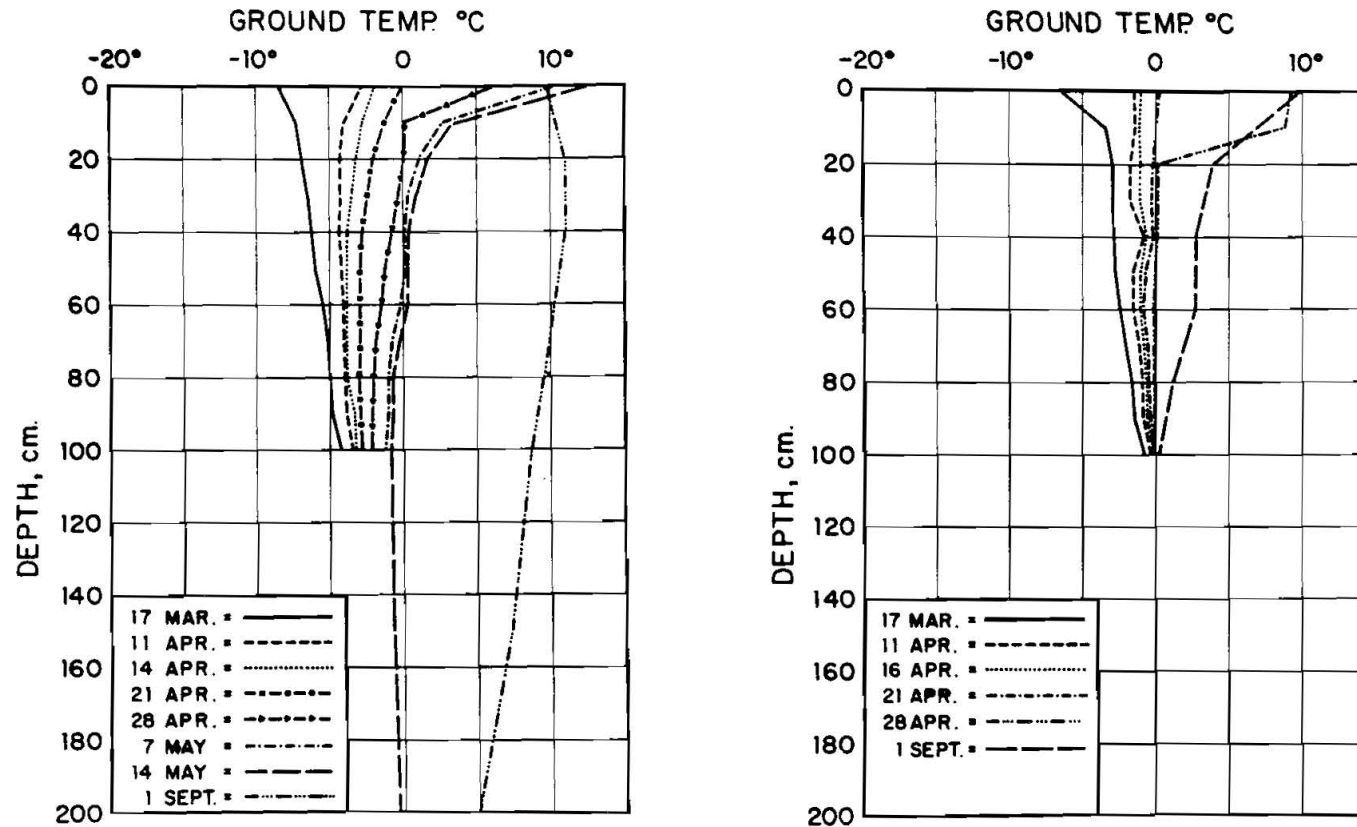


Figure 3. Water and heat fluxes of a permafrost site. Z_f is a frost table; Z_{pf} is the permafrost (Woo, 1986).



INFILTRATION AND RUNOFF

Figure 4. Temperature profiles (near-surface) in a sub-arctic setting, Fairbanks, Alaska (Kane, et al., 1978).

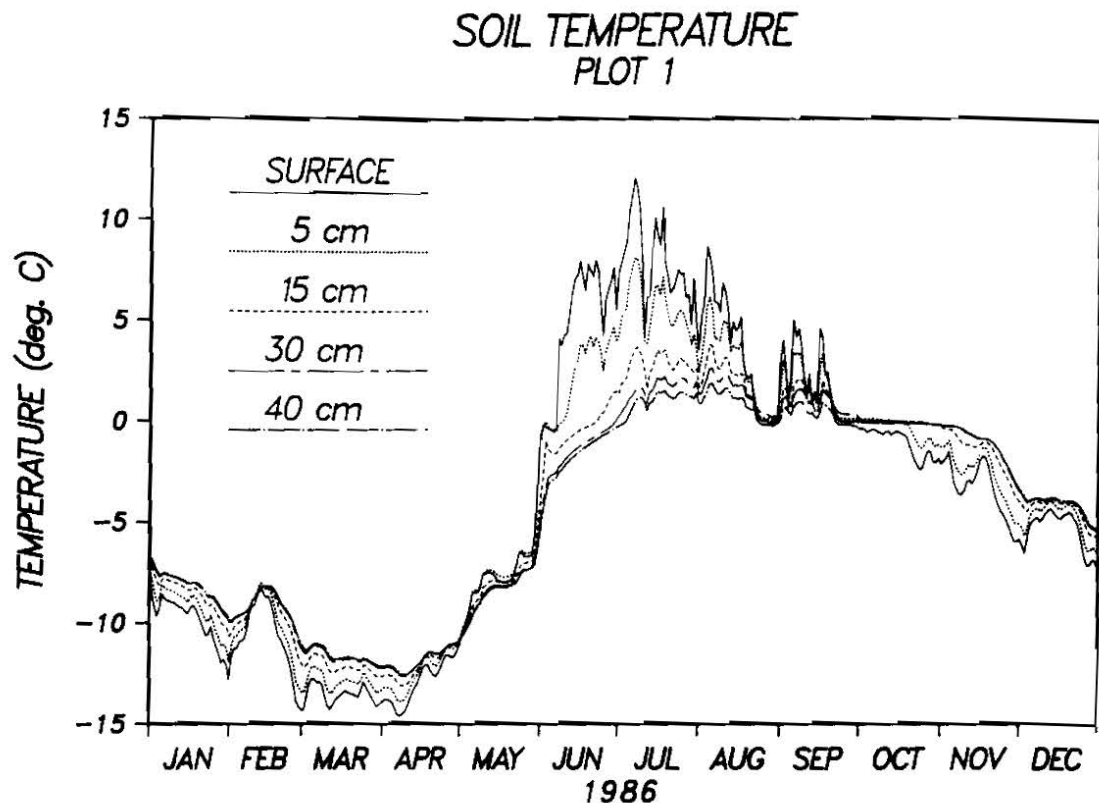


Figure 5a. Variation in soil temperature for several depths in 1986, Imnavait Creek (Hinzman et al., 1990).

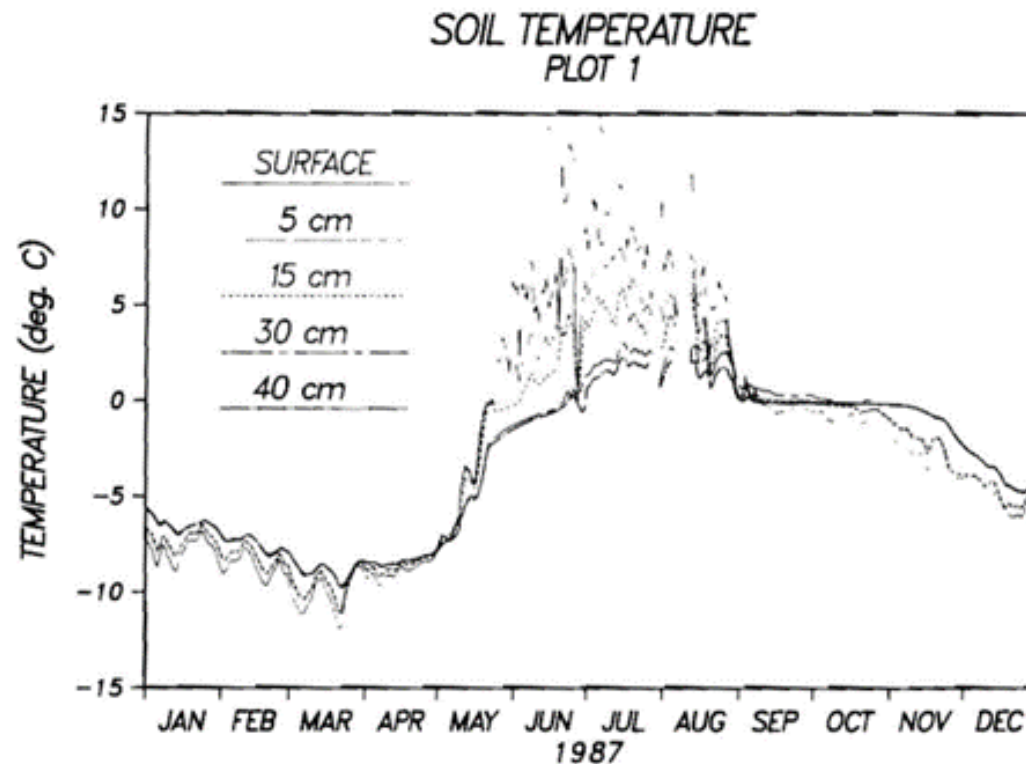
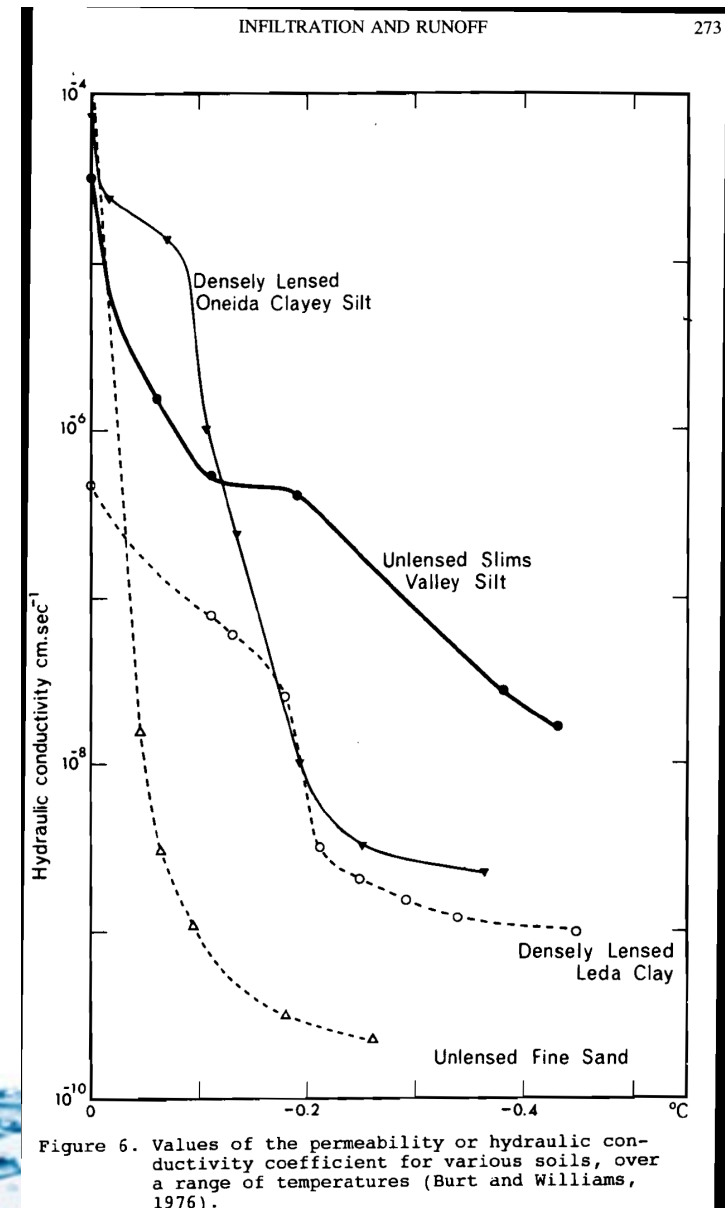


Figure 5b. Variation in soil temperature for several depths in 1987, Imnavait Creek (Hinzman et al., 1990).

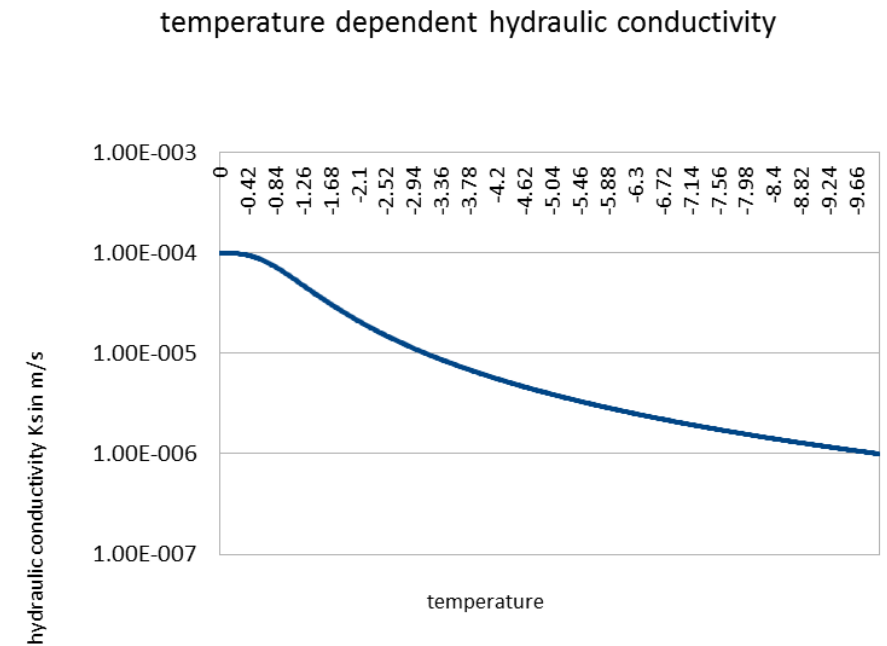
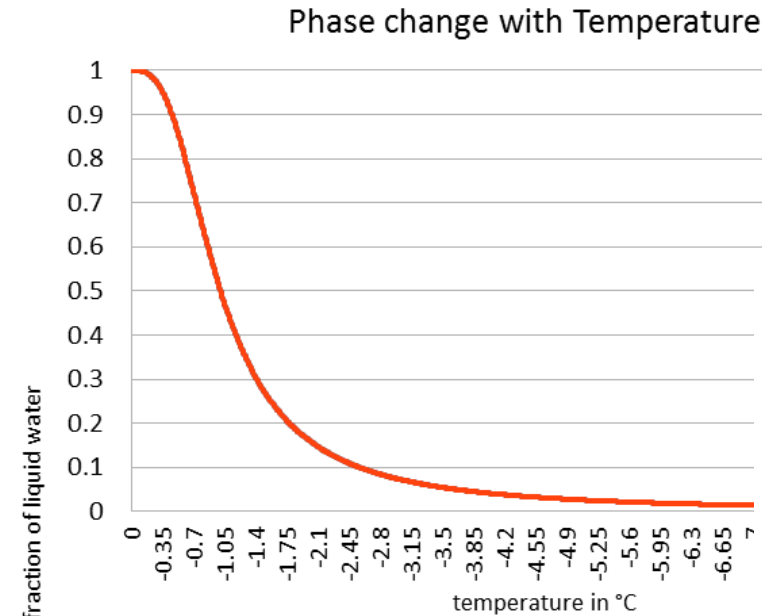
- Frozen soil, either seasonally or permafrost, significantly affects hydrology in affected regions.
- Frozen soils have reduced infiltration due to
 - Reduction in porosity, especially in permafrost
 - Reduction in hydraulic conductivity
- Frozen soils alter the movement of groundwater
 - Reduce the depth of the transmissive zone
 - Impede recharge
 - Impede daylighting (surfacing of groundwater)



- Hydraulic conductivity decreases as soil temperature drops
- Response in soils depends on the soil properties
 - Texture
 - Thermal conductivity
 - Thermal capacity
 - Moisture content
 - Infiltration rate



- Normally soil hydraulic conductivity depends on soil moisture and soil properties
- As soils freeze, the ice content becomes an additional consideration
- Ice in the soil column is essentially impenetrable
- As the ice content increases, the soils become less permeable



Infiltration Rate

- A. Saturated frozen soil
- B. Water thawing soil
- C. Unfrozen soil
- D. Water freezing as it enters soil

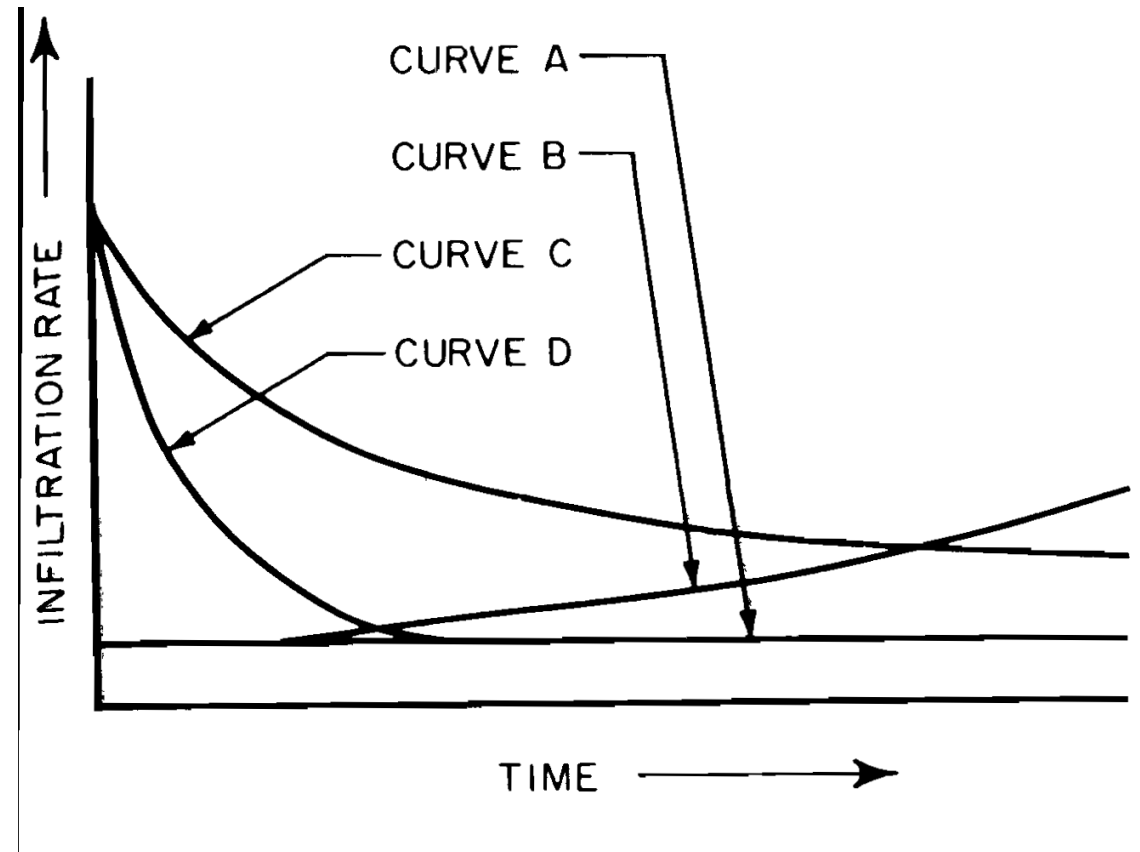


Figure 7. Schematic diagram of infiltration rates of frozen soils (Gray, et al., 1970).

1. Snow cover
2. Continuous Frozen Ground Index
3. Adjustments to soil properties based on soil skin temperature
4. GSSHA/GIPL with soil thermal profile modeling and effects on soil properties



- Simplest method
- If there is snow in a cell, there is no infiltration
- Use the card "SNOW_NO_INFILTRATE" in your project file



- Based on an hourly summation of below freezing temperatures
- Computed for each cell
- Threshold limit for frozen soil
- Once the CFGI exceeds the threshold, infiltration ceases in that cell
- Accounts for
 - Snow cover
 - Feedback from ground
- Original formulation by Molanau and Bissell is daily and applied to the entire domain



Formulation

$$CFGF = A(CFGF) - (T/24.0)e^{(-0.4Kd)}$$

Where:

- CFGF is the index in negative degree days
- A accounts for the degradation due to the ground
 - $0.99875 (1.0 - 0.99875)(1.0 - e^{(-0.4Kd)})$
- T is the air temperature in the cell (C)
 - Divided by 24 because in GSSHA the CFGF is updated hourly
- K is a factor related to the insulating effect of snow
 - Default is 0.5
- d is the depth of snow in the cell (cm)

- To use the CFGF model put the card “CFGF” in the project file
- Soil is assumed to be frozen once the CFGF hits the threshold value
 - Default value is 83 (from Molanau and Bissel, 1983)
 - Results are sensitive to this value
 - To vary the value include the card “CFGF_INDEX” followed by the value
 - Higher values result in later freezing, earlier thawing, and generally less runoff
 - Lower values results in earlier freezing, later thawing, and generally more runoff
- The snow index value can be changed by including the card “CFGF_K” in your project file
 - Default is 0.5
 - Increasing K increases the effect of the snow in insulating the soil

- Soil hydraulic conductivity can be adjusted based on the ice content of the soil
- $k(T) = S_E \cdot k_t(\Theta) + (1 - S_E) \cdot k_f$
- Where
 - $k(T)$ is the effective hydraulic conductivity (m/s)
 - T is temperature (K)
 - $k_t(\Theta)$ is the actual (thawed soil) hydraulic conductivity for liquid water content Θ (m^3/m^3)
 - K_f is the hydraulic conductivity of the ice (0.0036 cm/hr)
 - SE is the relative fraction of the liquid water
 - $SE = (dH \cdot (T - 273.15) / T) / (GBP)^{-1/\lambda}$
 - Where dH is the change in enthalpy from ice to liquid 334000 J/Kg
 - G is gravity, BP is the soil bubbling pressure, and λ is the Brooks and Corey soil pore distribution index

- Used by specifying the card “GTFSM” in the project file
- Works with any Green and Ampt infiltration model
- Not fully verified
- Method also used with GSSHA/GIPL to adjust soil hydraulic conductivity of the soils
- Unless used with GIPL the soil skin temperature is used for at the ground temperature



- Computed using the Clausius-Clapeyron equation

$$\frac{dq_s(T_g)}{dT_g} = \left[\frac{P}{P - (1 - \epsilon) e_s} \right] \frac{L}{R_{water} T_g^2} q_s(T_g)$$

where: R_{water} is the gas constant for water vapor ($461 \text{ J kg}^{-1} \text{ } ^\circ \text{ K}^{-1}$) and L is the latent heat of evaporation ($2.50036 \text{ MJ kg}^{-1}$). Following Williamson et al. (1987), the latent heat of evaporation, known to vary with ground temperature, is a constant, and q_s is the saturation specific humidity (kg/kg). The ground temperature can be obtained iteratively using the following relationship:

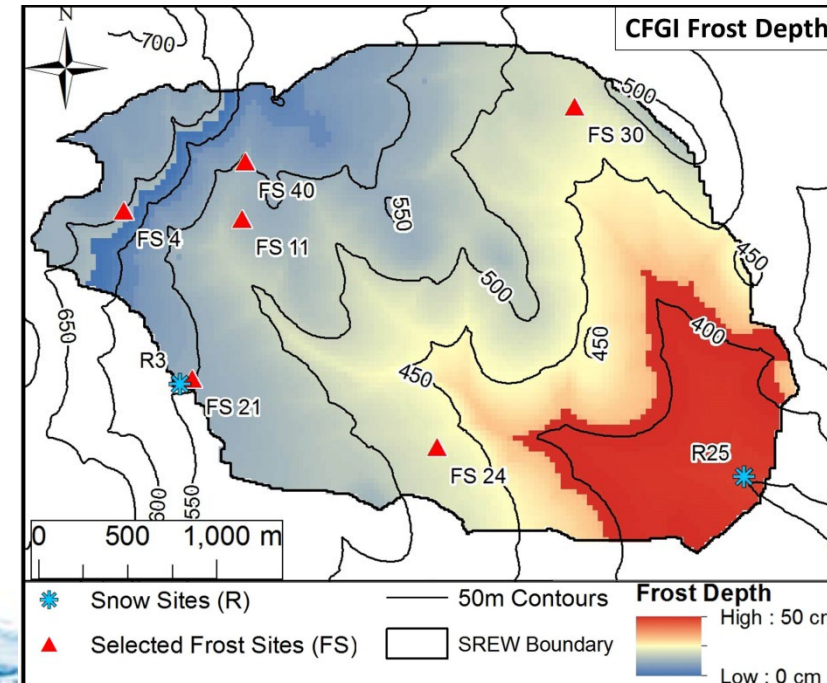
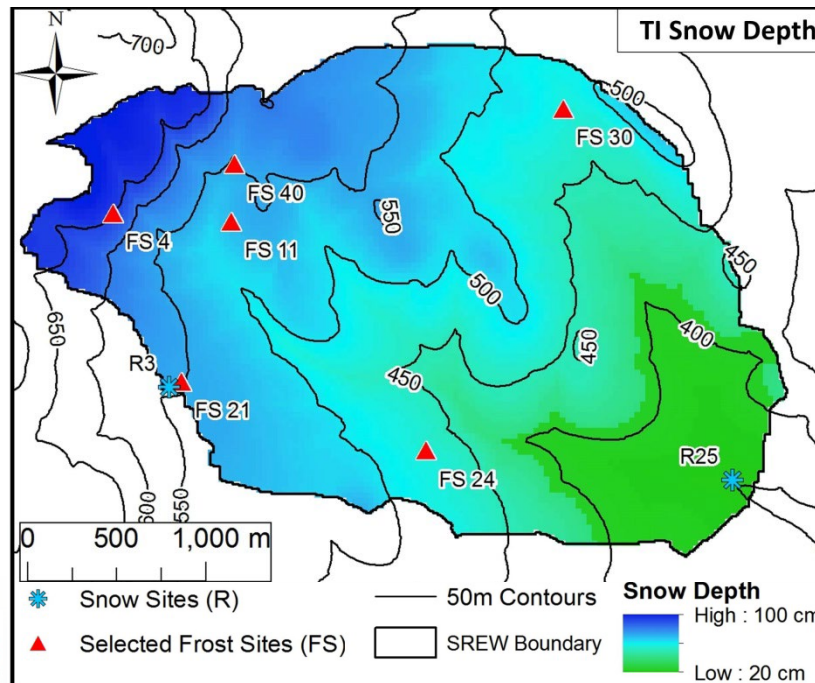
$$T_g^{K+1} = T_g^K - \frac{f(T_g^K)}{f'(T_g^K)}$$



- Rerun the snow model using the "SNOW_NO_INFILTRATE" card
- Rerun the snow model using the "GTFSM" card
- Rerun the snow model using the "CFGF" card
- Vary the parameters
 - CFGF_INDEX 120
 - CFGF_INDEX 40
 - CFGF_K 1.0
 - CFGF_K 0.25
- Plot the outlet hydrographs and see how the various methods affect the runoff



- Any Issues with CFGI?
 - Frozen ground is only dependent on elevation (via air temperature) and snow depth.
 - Land Cover and Soil Moisture not considered.
 - Difficult to validate model with field measurements.



- modCFG model (not in release version of GSSHA...yet)
 - CFG Model: $CFG = CFG_{t-1}A - T_a e^{-0.4(K_s D_s)}$
 - modCFG Model: $CFG = CFG_{t-1}A - T_{rad} e^{-0.4(K_s D_s + K_{GC} D_{GC})}$
 - T_{rad} is the radiation-derived proxy temp (C) (same as in RTI snow model)
 - K_{GC} is the ground cover reduction coefficient (cm)
 - D_{GC} is the depth of ground cover (cm)
- Modified Berggren Equation:
 - $Z_d = \lambda(48 (CFG - CFG_Index) \delta^{-1} K_m)^{1/2}$
 - Z_d is depth of frozen ground (m)
 - λ accounts for changes in sensible heat, based on temperature & soil moisture
 - δ latent heat of fusion of soil, based on dry soil density & soil moisture
 - K_m is the mean thermal conductivity of the soil, based on soil moisture

