

Development of a Coupled Framework for Simulating Interactive Effects of Frozen Soil Hydrological Dynamics in Permafrost Regions

GSSHA/GIPL theory

ERDC TR-13-15

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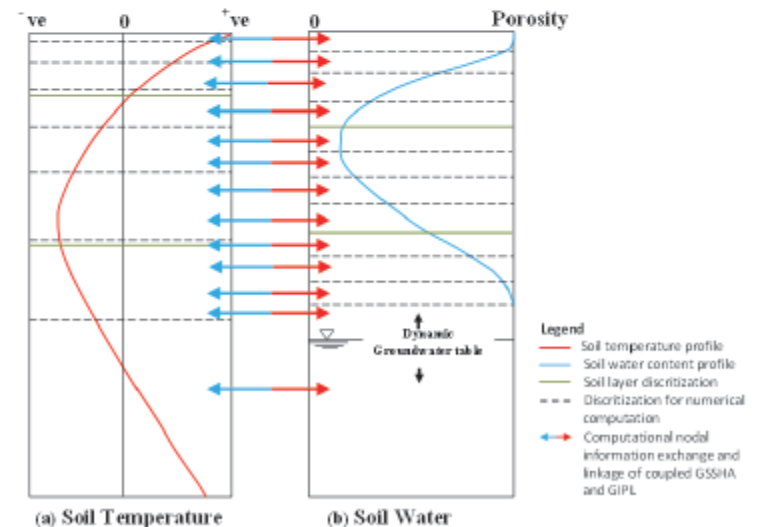
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Strategic Environmental Research and Development Program (SERDP)

Development of a Coupled Framework for Simulating Interactive Effects of Frozen Soil Hydrological Dynamics in Permafrost Regions

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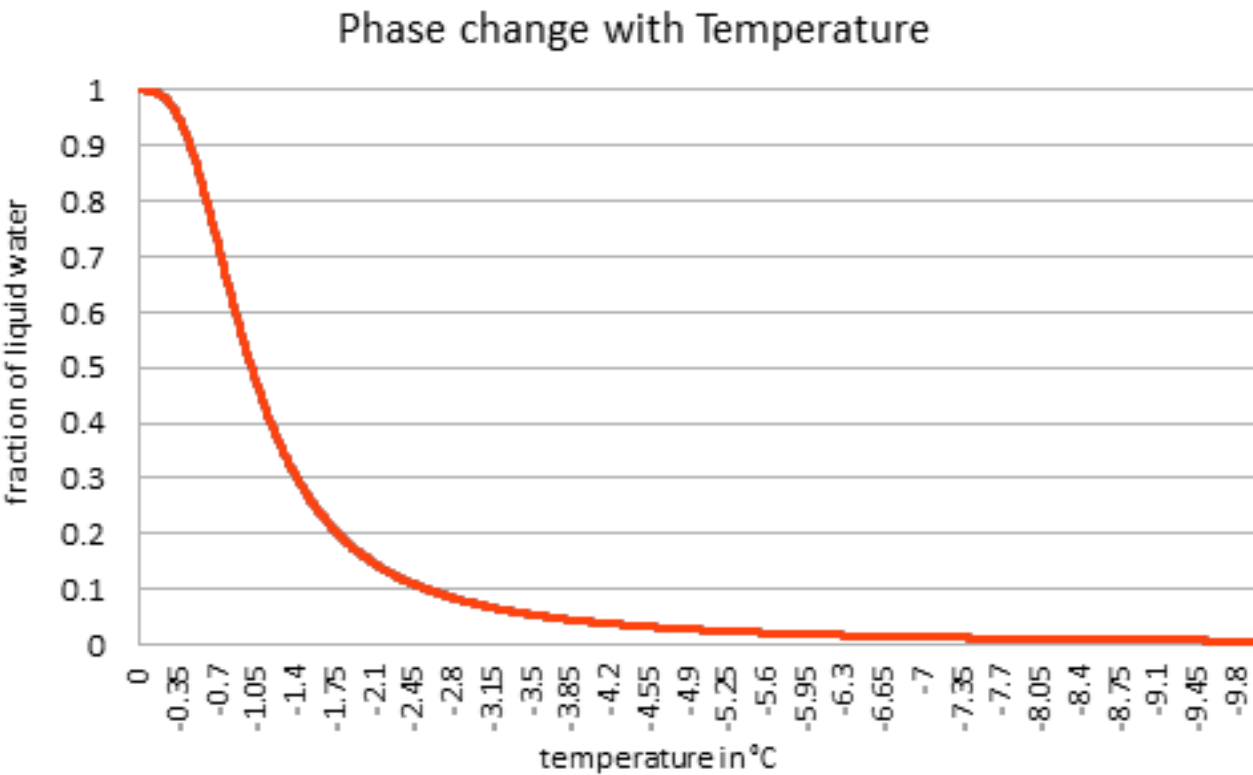
Permafrost is land that remains frozen (at or below 32°F or 0°C) for two or more consecutive years. Permafrost covers about one-fifth of the earth's land surface.



In general, permafrost mainly occurs at latitudes higher than 60°N and is most abundant and continuous throughout Alaska, the northern portions of Canada, parts of Greenland, and a large portion of Eastern Russia and Siberia. It also occurs sporadically in alpine regions in lower latitudes such as the Himalaya, the Alps, the Rockies, and even in the tropics in portions of the Andes and on Mount Kilimanjaro above 16,404 feet (5,000 m).

The effective hydraulic conductivity decreases with an increasing fraction of ice, i.e. a decreasing S_E -value. The effective hydraulic conductivity changes with several orders of magnitude as the soil freezes/thaws

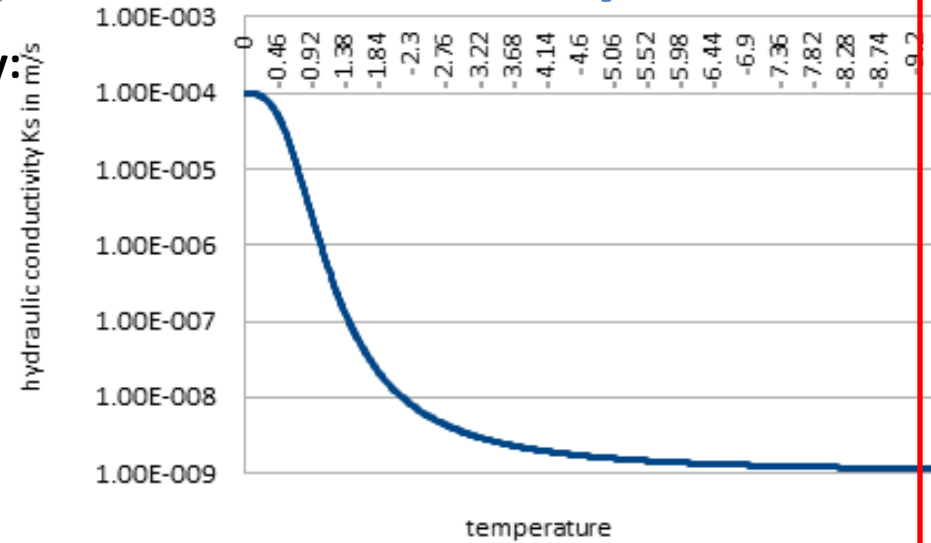
Ice rich soil



Influence of temperature on hydraulic conductivity

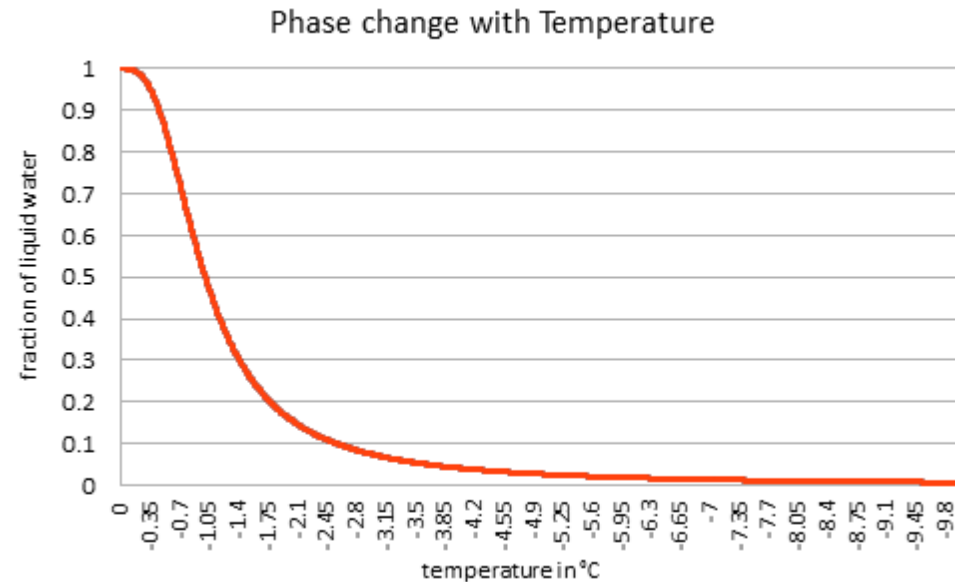
Estimation of the effective hydraulic conductivity:

$$k(T) = e^{SE \cdot \ln(kt(\Theta)) + (1-SE) \cdot \ln(kf)}$$



where S_E is the relative fraction of liquid water of the total soil moisture; n , m and α are the van-Genuchten-Parameters as used in the Richards equation; T is soil temperature in °C

$$S_E = \left(\frac{1}{1 + (\alpha \cdot |1.22 \cdot T|)^n} \right)^m \text{ for } T \leq 0^\circ\text{C}$$



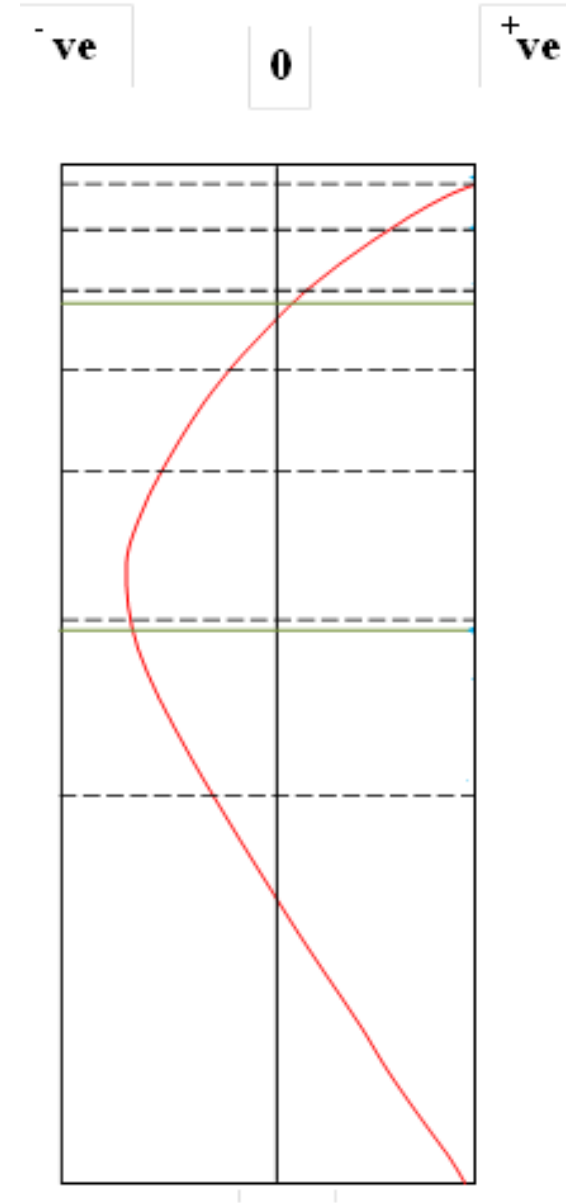
Geophysical Institute Permafrost Lab, GIPL

1D vertical heat conductive equation

$$\frac{\partial H(x,t)}{\partial \tau} = \nabla \cdot (k(x,t) \nabla t(x,\tau))$$

$$\frac{H(t_i^{n+1}) - H(t_i^{n+1/2})}{\Delta \tau_n} = \frac{2}{(\Delta h_{i+1} + \Delta h_i)} \times \left(\lambda_{i+1/2}^{n+1} \frac{(t_{i+1}^{n+1} - t_i^{n+1})}{\Delta h_{i+1,y}} - \lambda_{i-1/2}^{n+1} \frac{(t_i^{n+1} - t_{i-1}^{n+1})}{\Delta h_{i,y}} \right)$$

Where, λ , thermal conductivity is a function of soil moisture.



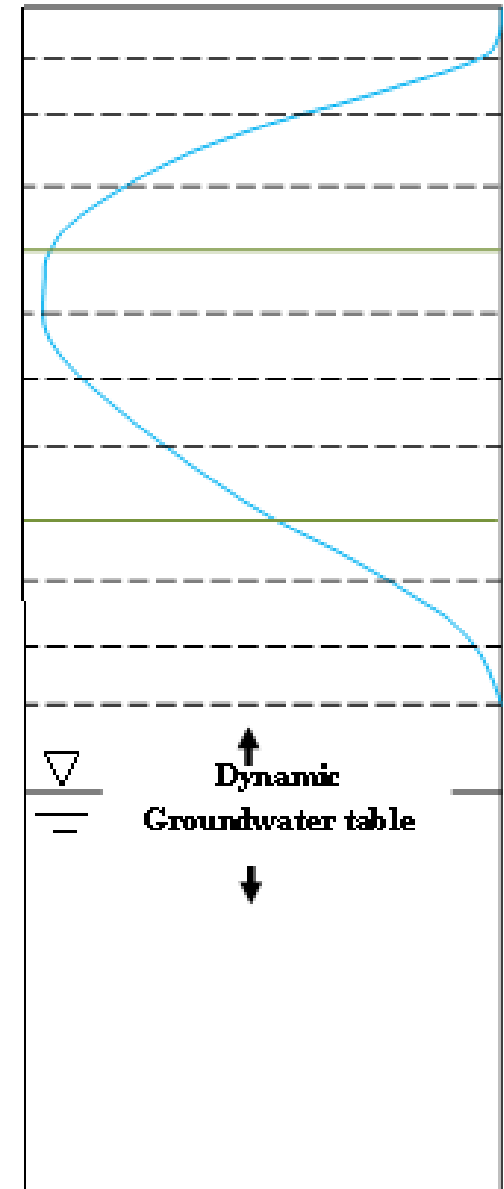
Gridded Surface Subsurface Hydrologic Analysis, GSSHA

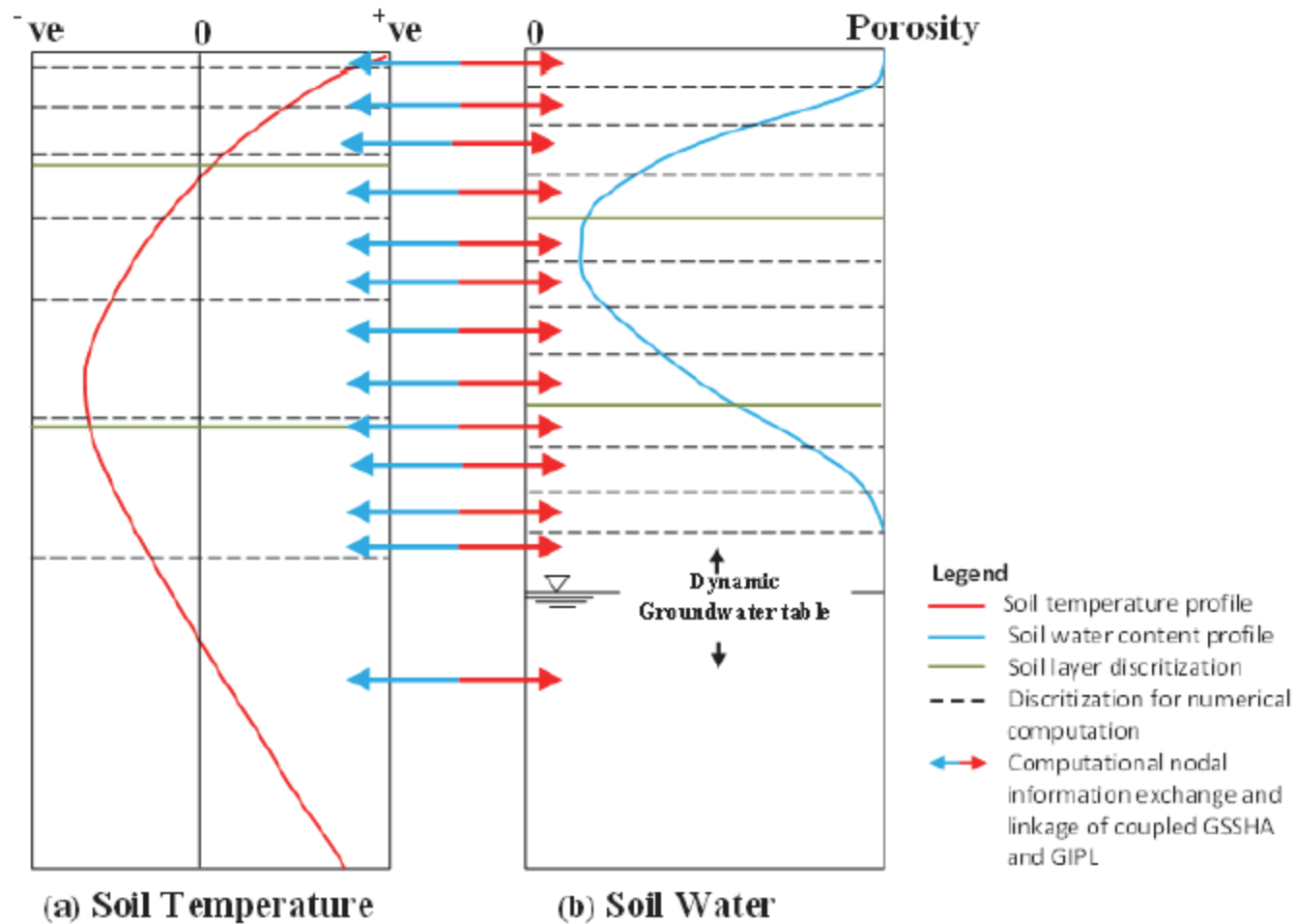
1D Vertical head-based formulation of Richards Equation

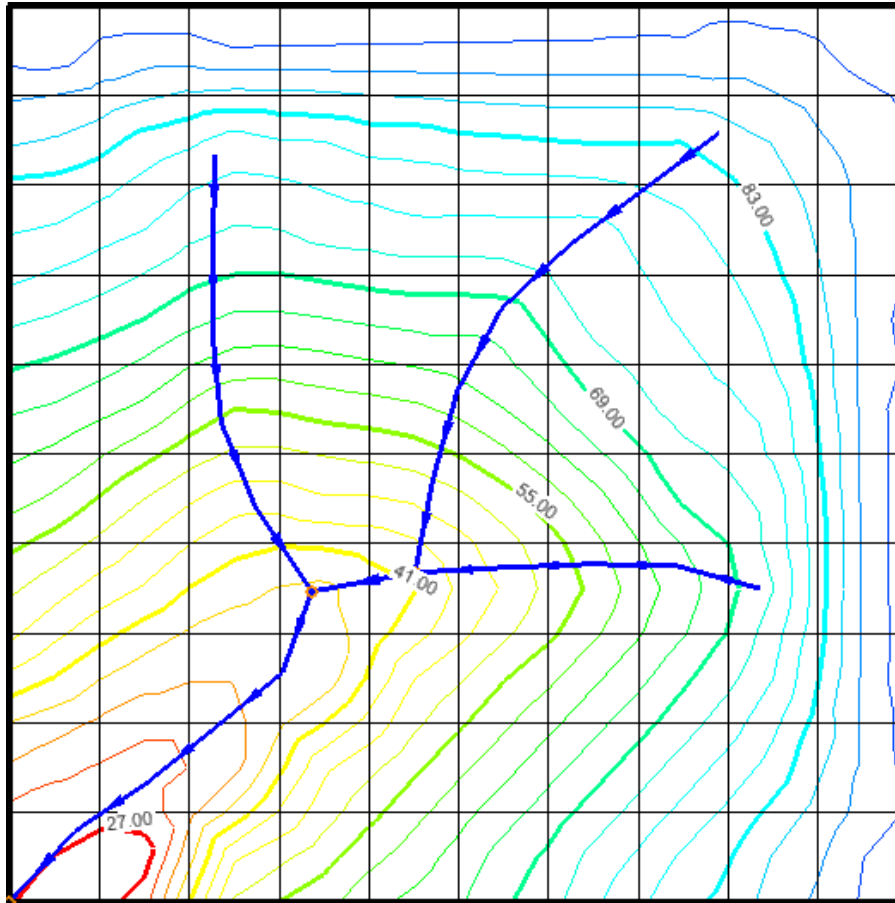
$$C_m(\psi) \frac{\partial \psi}{\partial \tau} - \frac{\partial}{\partial z} \left[K_{soil}(\psi) \left(\frac{\partial \psi}{\partial z} - 1 \right) \right] - W = 0$$

$$C_j^i \frac{\varphi_j^{n+1} - \varphi_j^n}{\Delta t} = \frac{1}{\Delta z_j} \left[K_{j+1/2}^n \left(\frac{\varphi_{j+1}^{n+1} - \varphi_j^{n+1}}{\Delta z_{j+1/2}} \right) - K_{j-1/2}^n \left(\frac{\varphi_j^{n+1} - \varphi_{j-1}^{n+1}}{\Delta z_{j-1/2}} \right) \right] + W_j^n$$

Where, K , hydraulic conductivity is a function of temperature.







Test case project of coupled GSSHA and GIPL where the permafrost parametric values represent woodland and tundra ecosystem sites in permafrost active Alaskan region.

Input database

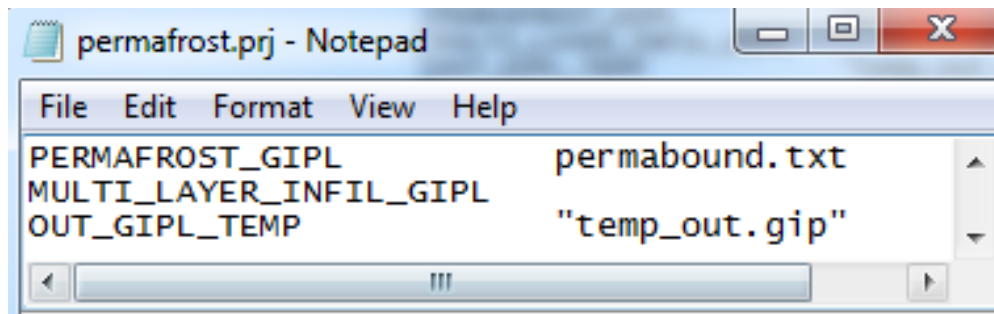
*Geology,
Lithologic Data,
Ground Temperatures,
Soil Properties*

*Snow Cover,
Vegetation*

*Air Temperature,
Precipitation*

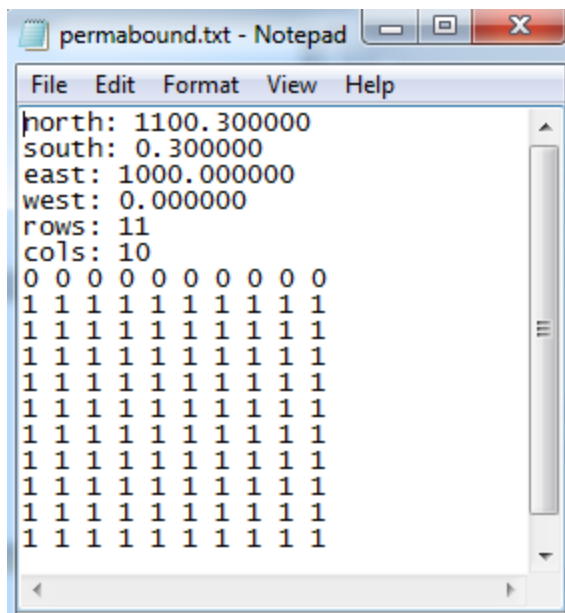
Numerical Model of Heat Transfer

Ground Temperatures with Daily Resolution
Active Layer Thickness
Unfrozen Water Content
Permafrost Extent
Time of Freeze-Up



```
File Edit Format View Help
PERMAFROST_GIPL      permabound.txt
MULTI_LAYER_INFIL_GIPL
OUT_GIPL_TEMP        "temp_out.gip"
```

**Optional project card:
GIPL_TIMESTEP**



```
File Edit Format View Help
north: 1100.300000
south: 0.300000
east: 1000.000000
west: 0.000000
rows: 11
cols: 10
0 0 0 0 0 0 0 0 0 0
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
```

GRASS type header
format

Index 1 refers to freezing / thawing active area.
Index 0 refers to grids without permafrost activity.

dep_node.txt - Notepad

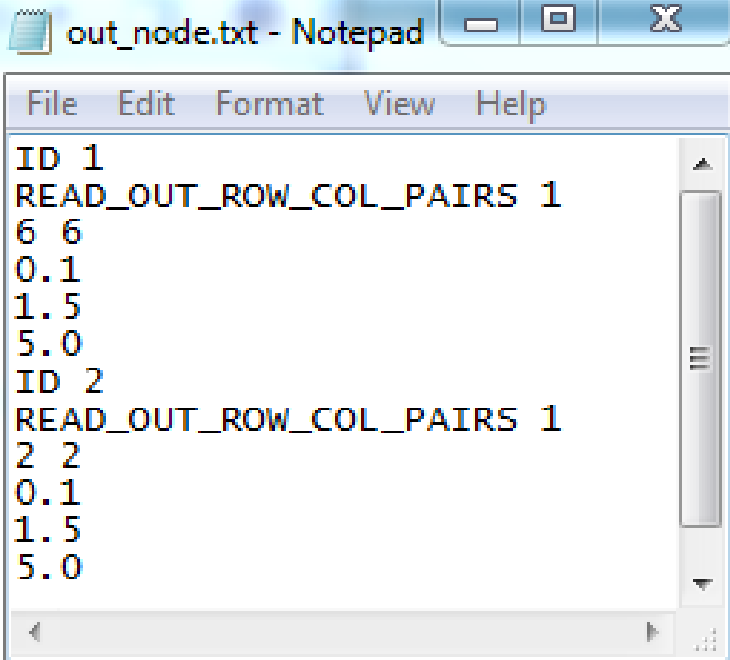
File Edit Format View Help

ID 1
0.0
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2
0.21
0.22
0.23
0.24
0.25
0.26
0.27
0.28
0.29
0.3
0.31
0.32
0.33
0.34
0.35
0.36
0.37
0.38
0.39
0.4
0.41
0.42

init_temp.tin - Notepad

File Edit Format View Help

ID 1	
0	8.846
0.03	3.146
0.13	0.786
0.28	0.21
0.53	-0.22
0.58	-0.22
0.63	-0.234
0.68	-0.245
0.73	-0.252
0.78	-0.26
1.5	-0.273



out_node.txt - Notepad

File Edit Format View Help

```
ID 1
READ_OUT_ROW_COL_PAIRS 1
6 6
0.1
1.5
5.0
ID 2
READ_OUT_ROW_COL_PAIRS 1
2 2
0.1
1.5
5.0
```

```

north: 1100.300000
south: 0.300000
east: 1000.000000
west: 0.000000
rows: 11
cols: 10
0 0 0 0 0 0 0 0 0 0
1 2 1 1 1 1 1 1 1 1
1 1 2 1 1 1 1 1 1 1
1 1 1 2 2 2 1 1 1 1
1 1 1 1 1 1 2 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
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1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1
1 1 1 1 1 1 1 1 1 1

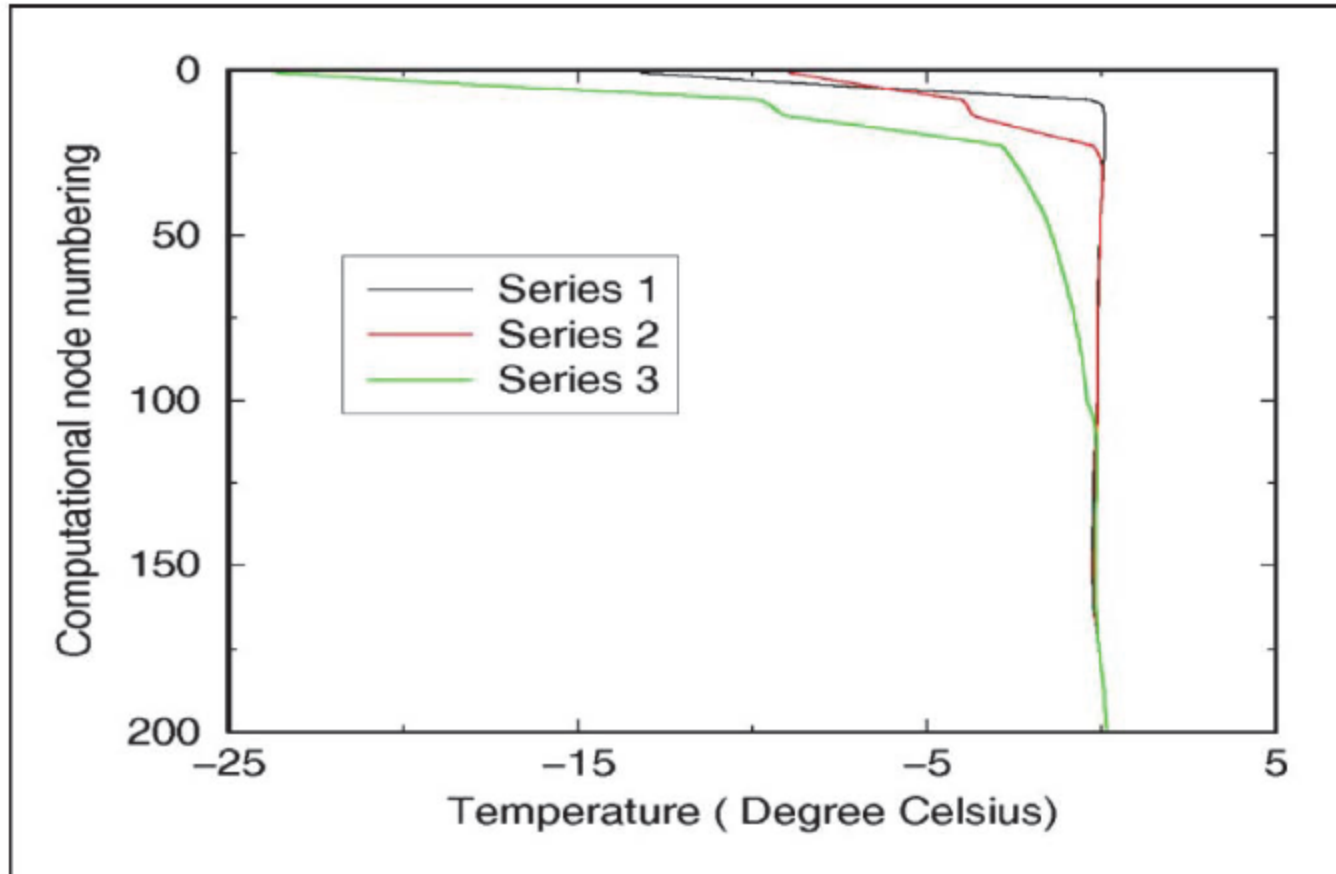
```

GRASS type header
format

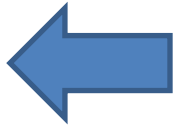
- Id 1 refers to a type of permafrost soil
- Id 2 refers to another type of permafrost soil

Depth(m)	Soil	Temp(C)	Depth(m)	Soil	Temp(C)
1.5000		-0.2733	5.0000		-0.2430
1.5000		-0.2817	5.0000		-0.2432
1.5000		-0.2859	5.0000		-0.2434
1.5000		-0.2890	5.0000		-0.2435
1.5000		-0.2916	5.0000		-0.2436
1.5000		-0.2938	5.0000		-0.2438
1.5000		-0.2959	5.0000		-0.2439

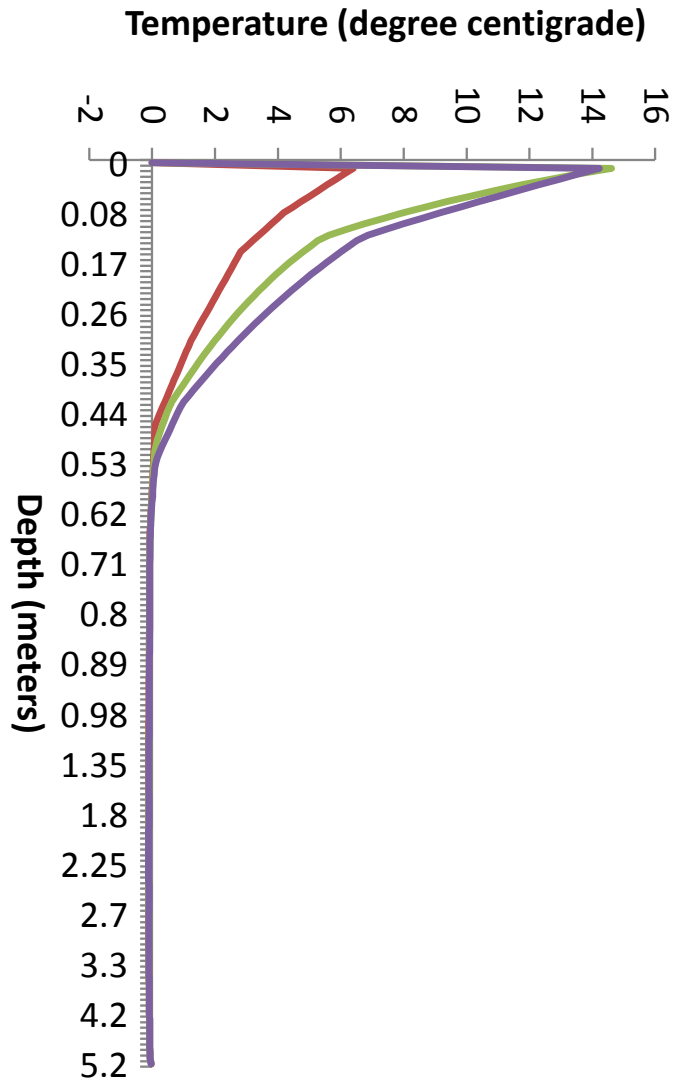
Simulated Temperature profile



Decreasing temperature with time

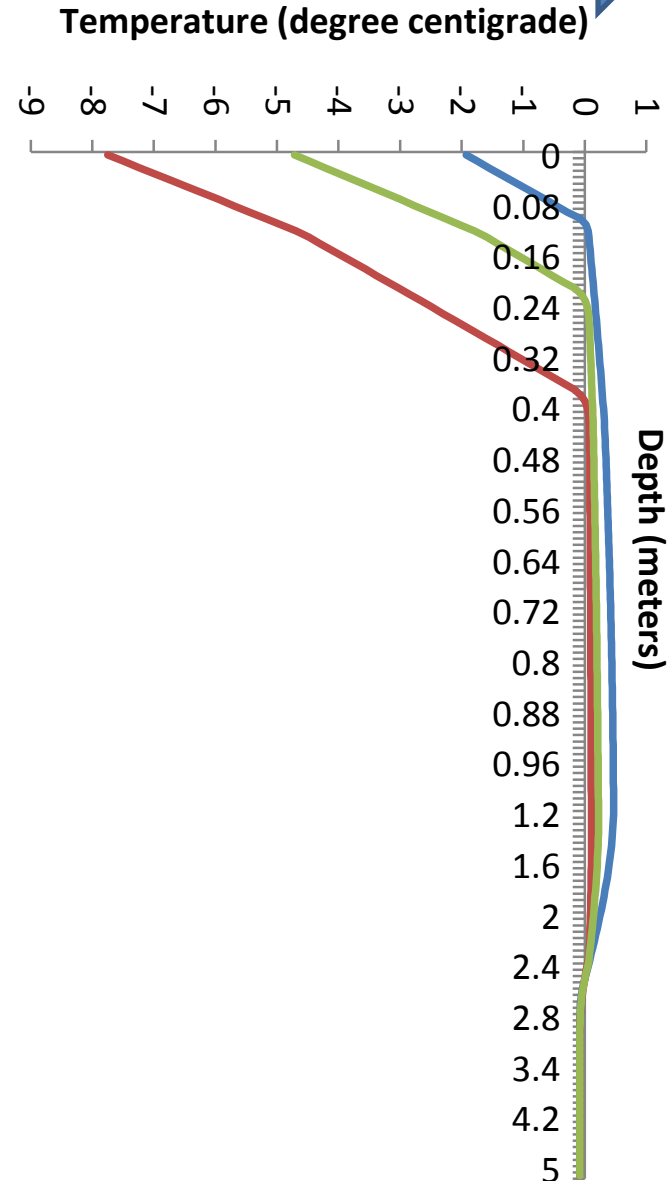


Heading towards freezing condition

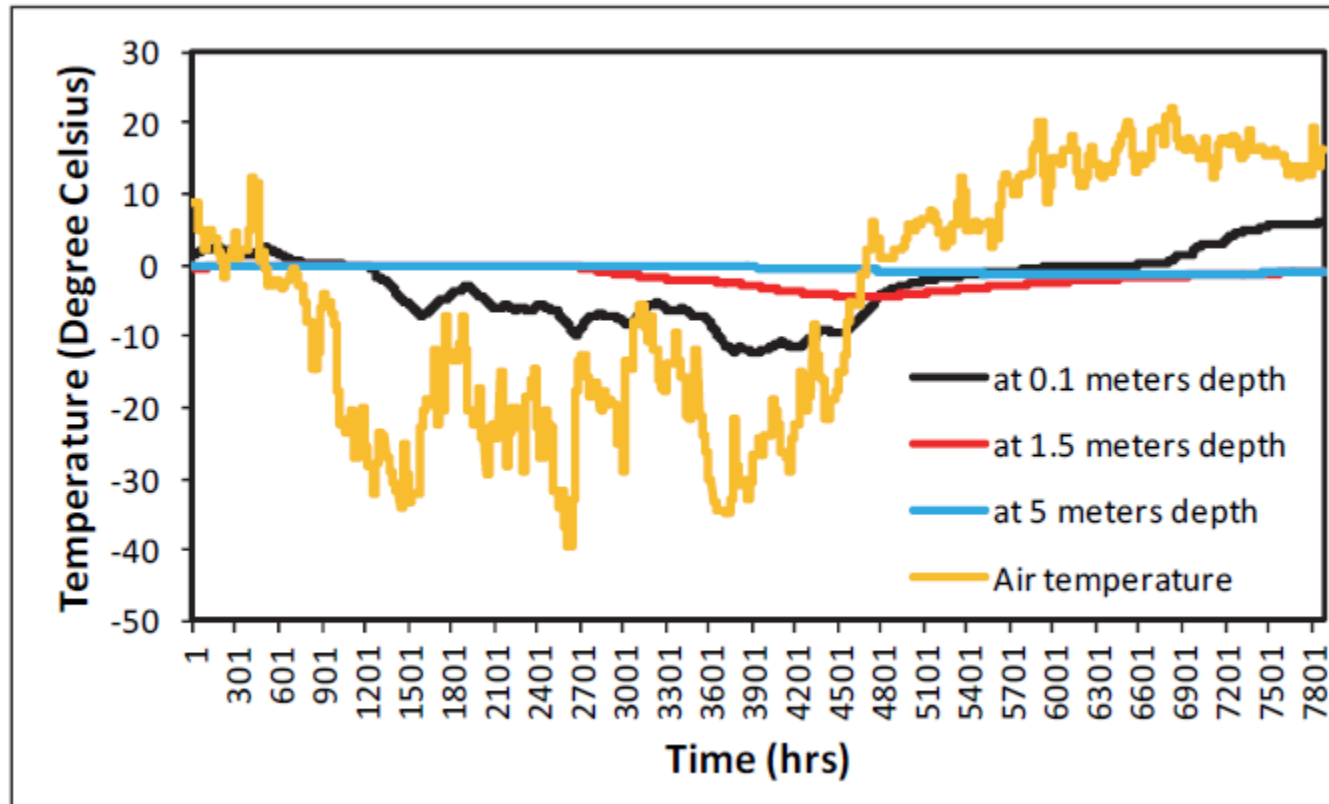


Increasing temperature with time

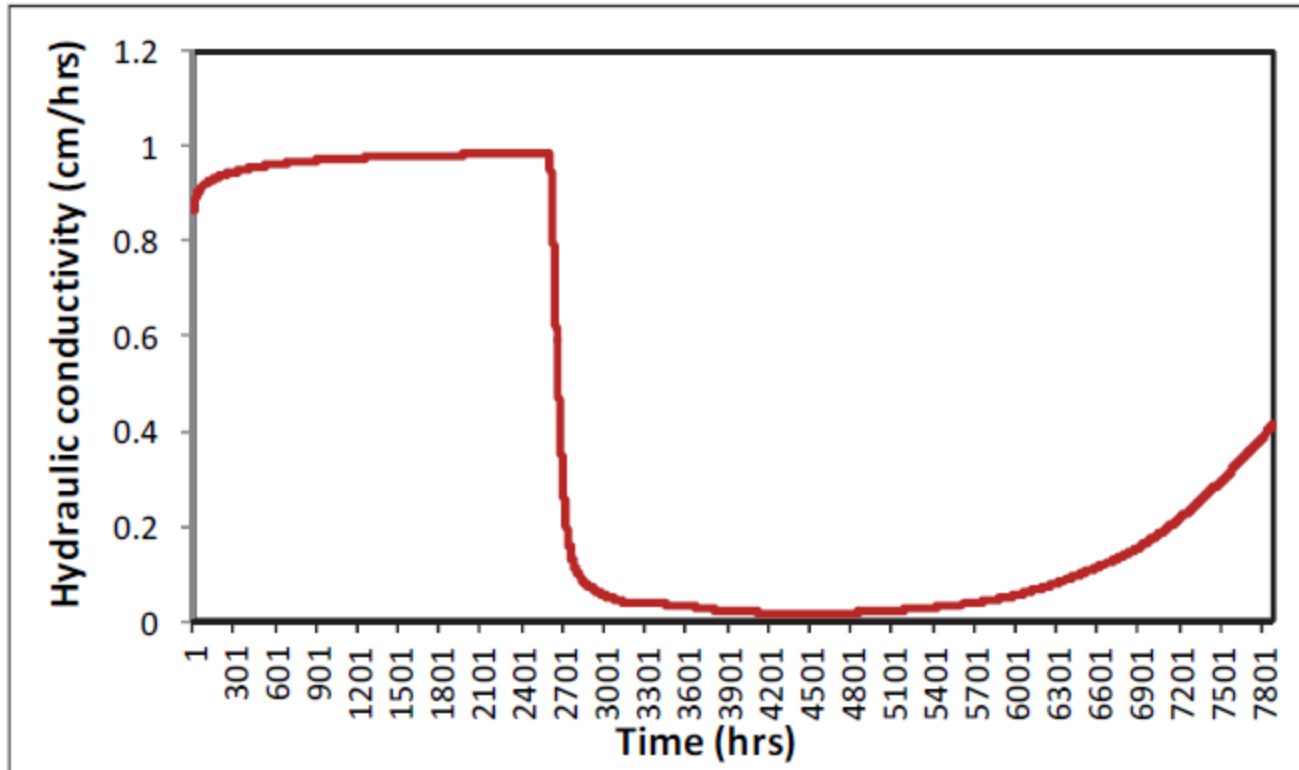
Heading towards thawing condition



Simulated Temperature series



Simulated Hydraulic conductivity



How to set up a model?
User guidelines.

NEXT STEP

