Hydro-thermodynamics: Hydrological Modeling with Soil Thermal Dynamics

ERDC/CHL TR-24-4

Coastal and Hydraulics Laboratory

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User Guidelines on Catchment Hydrological Modeling with Soil Thermal Dynamics in Gridded Surface Subsurface Hydrologic Analysis (GSSHA)

Nawa Raj Pradhan, Charles W. Downer, and Sergey Marchenko

March 2024

ERDC TR-13-15

Engineer Research and Development Center

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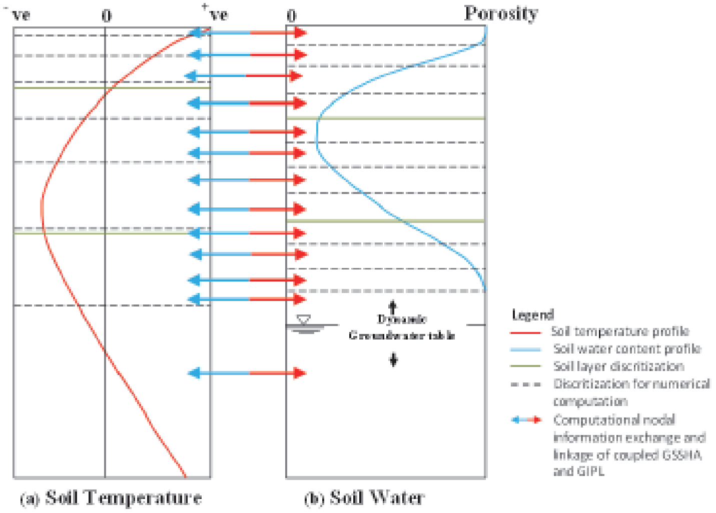
Strategic Environmental Research and Development Program (SERDP)

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

Nawa Raj Pradhan, Charles W. Downer, Sergei Marchenko, Anna Liljedahl, Thomas A. Douglas, and Aaron Byrd

November 2013



HH&C Science & Engineering Technology

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).

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Influence of temperature profile on hydraulic conductivity

T ≥ 0 ℃

$$K(\theta) = K_s\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)^{3+2/\lambda}$$

where

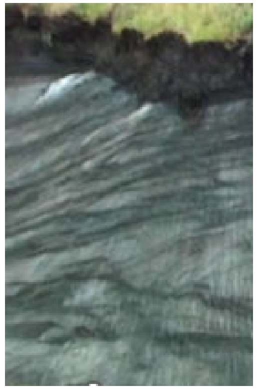
$K(\theta)$ = soil moisture dependent hydraulic conductivity of the soil (m/s);
K_s = saturated hydraulic conductivity of the soil (m/s);
θ = water content of the soil;
θ_s = saturated water content of the soil;
θ_r = residual water content of the soil; and
λ = is soil distribution index.

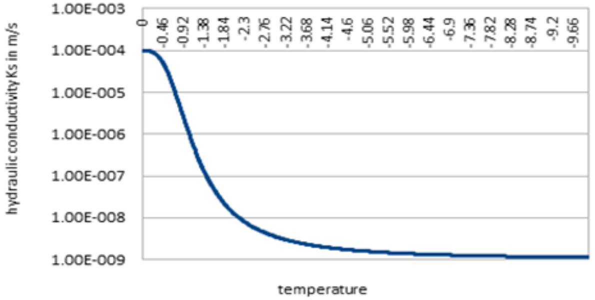
(Brooks and Corey, 1964)

T ≤ 0 ℃

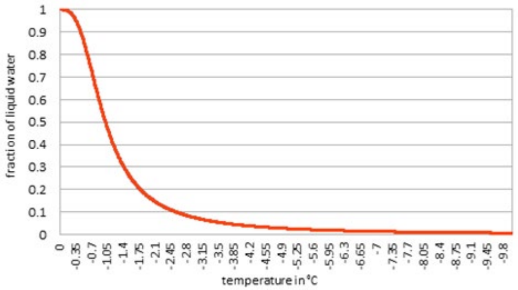
$$K(T) = e^{S_E \ln(K_t(\Theta)) + (1 - S_E) K_f}$$

S_E is relative fraction of liquid water





$$S_E = \left(\frac{1}{1 + (\propto |1.22t|)^n}\right)^m \text{ for } T \le 0\,^{\circ}\mathrm{C}$$



water

Article

Catchment Hydrological Modeling with Soil Thermal Dynamics during Seasonal Freeze-Thaw Cycles

Nawa Raj Pradhan [1,*], Charles W. Downer [1] and Sergei Marchenko [2]

[1] Coastal and Hydraulics Laboratory, U.S. Army Engineer Research and Development Center, 3909 Halls Ferry Road, Vicksburg, MS 39180-6199, USA; Charles.W.Downer@erdc.dren.mil
[2] Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA; ssmarchenko@alaska.edu
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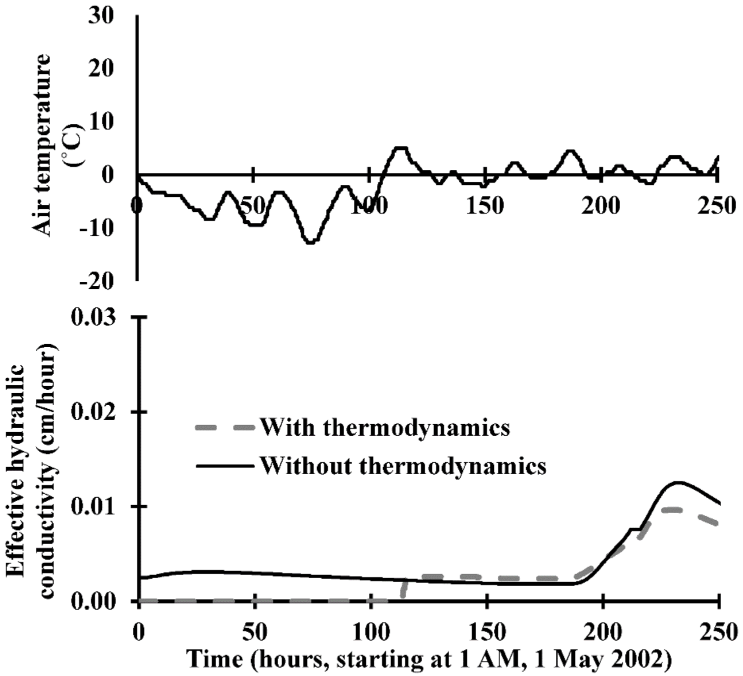
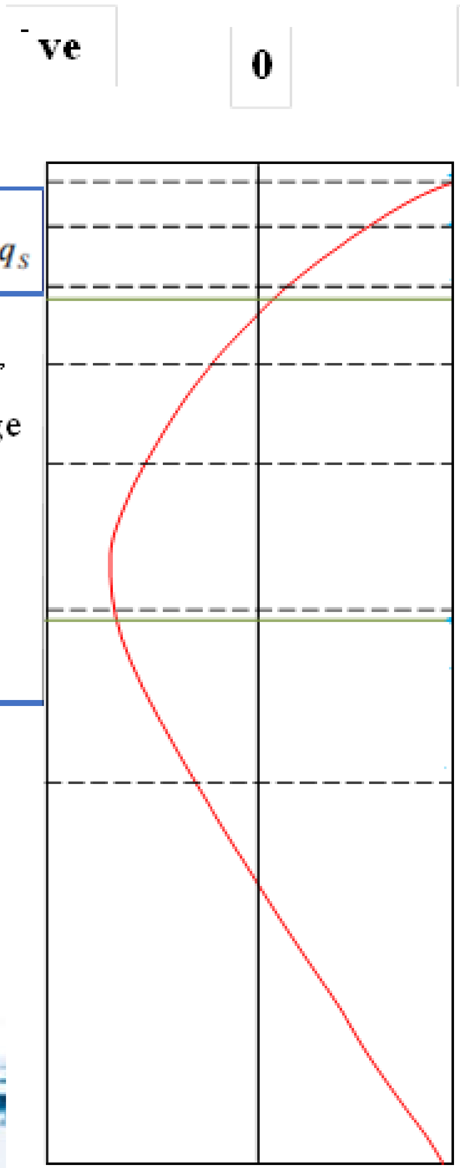


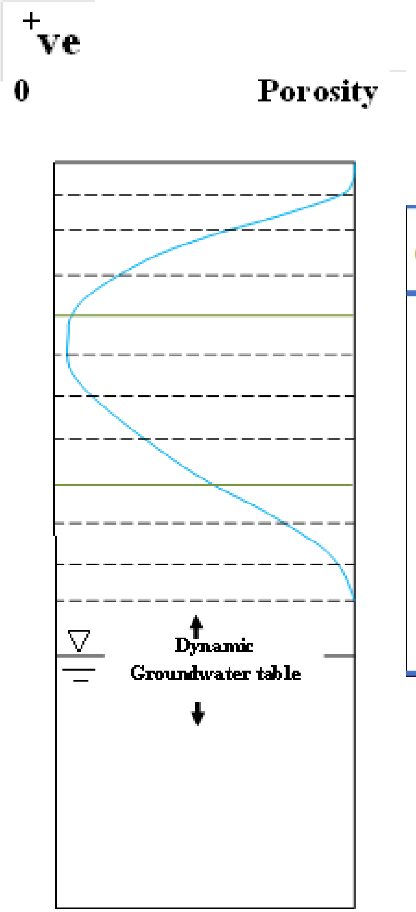
Physical processes

Numerical equation of heat transfer in GIPL

$$C(T)\cdot\frac{\partial T}{\partial t}=\operatorname{div}\left(\lambda(T)\cdot grad\,T\right)+q_s$$

where $C(T)$ is the specific heat capacity of the soil, $\partial T/\partial t$ is the temperature change in time,
$\lambda(T)$ is the temperature dependent thermal conductivity. and
q_s is the source/sink term



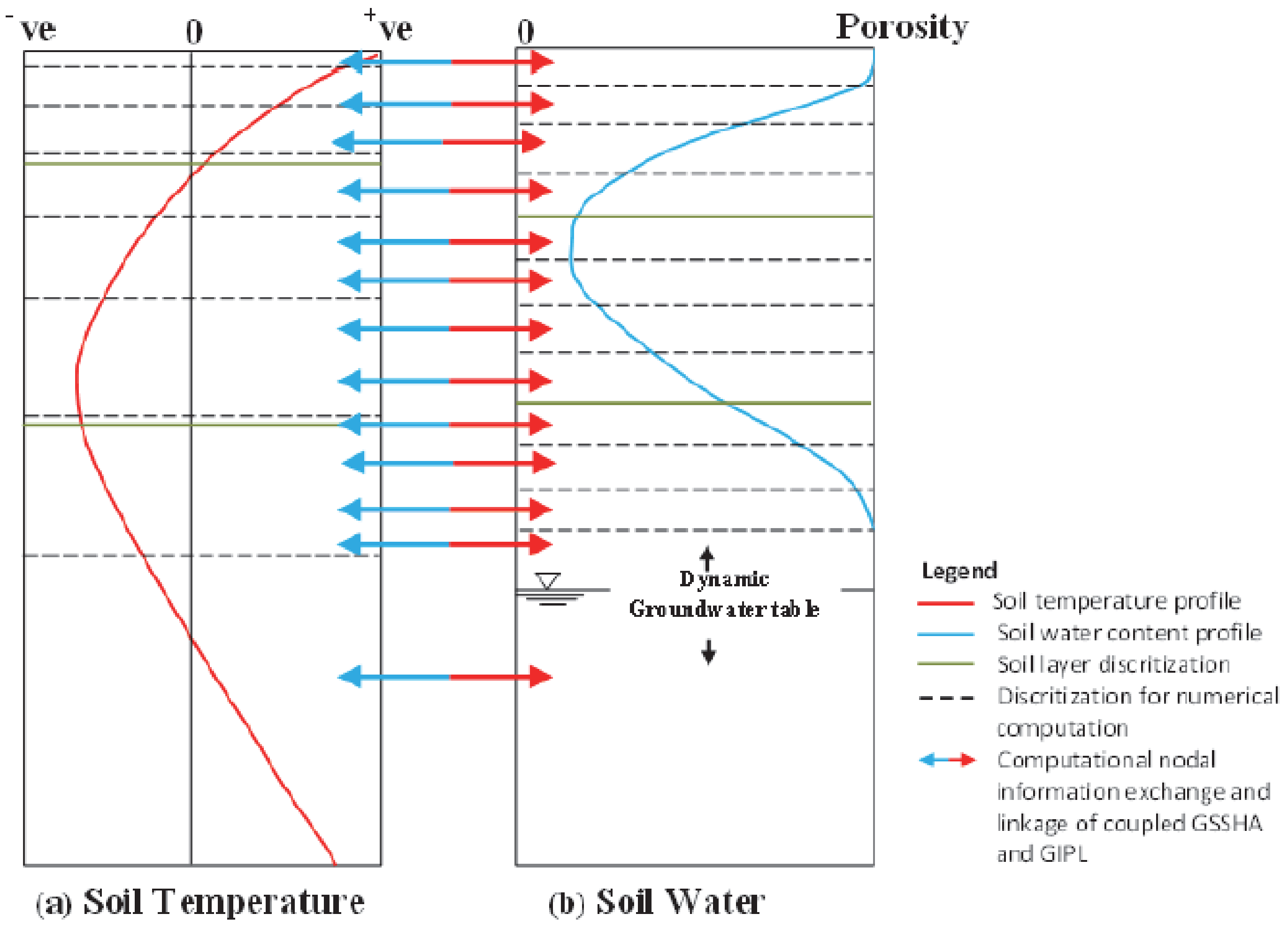


Numerical equation of soil moisture in GSSHA

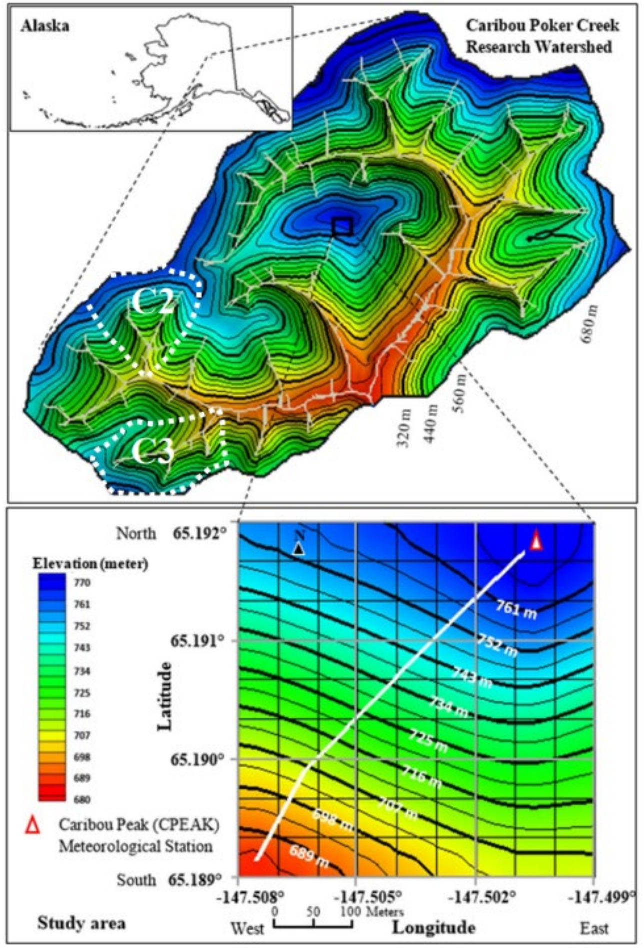
$$C_m(\psi)\frac{\partial\psi}{\partial\tau}-\frac{\partial}{\partial z}\left[K_{soil}(\psi)\left(\frac{\partial\psi}{\partial z}-1\right)\right]-W=0$$

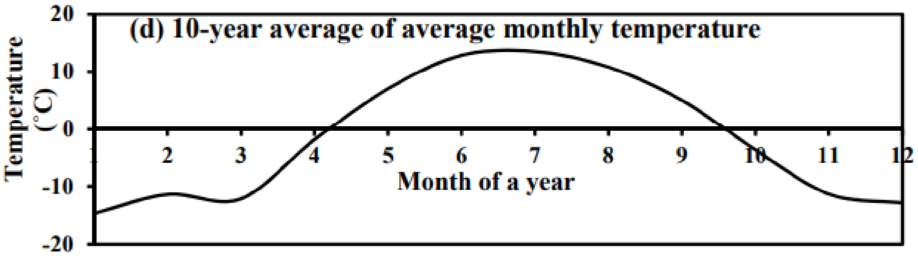
where, C_m, the specific moisture capacity,
ψ is the soil capillary head (cm),
z is the vertical coordinate (cm),
τ is time (h),
$K_{soil}(\psi)$ (cm) is the effective hydraulic conductivity and
W is a flux term added for sources and sinks ($cm\ h^{-1}$),

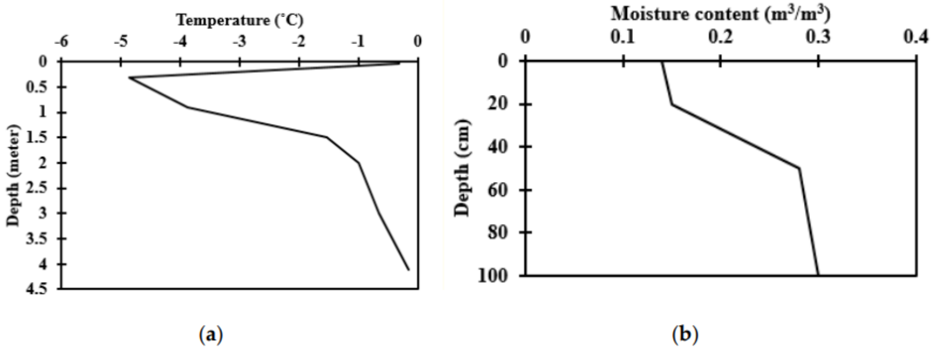
Coupling architecture



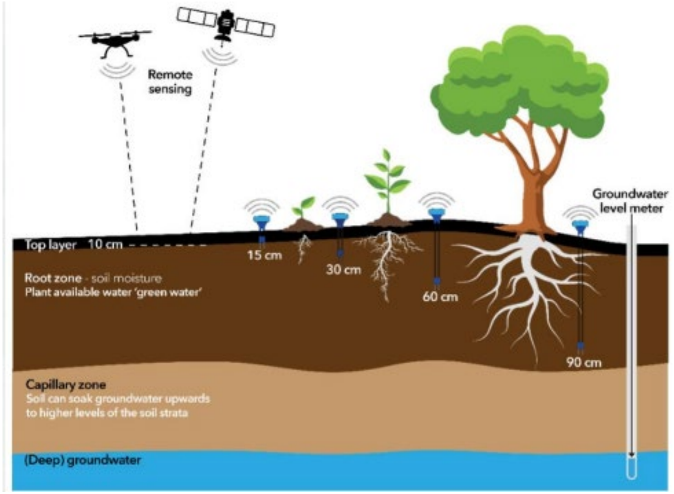
Initial conditions and boundary conditions







Site-based and Satellite-based



$$\theta_i = (1.33NDVI - 0.049)\,(\theta_{fci} - \theta_{wpi}) + \theta_{wpi}$$

θ = soil moisture content;

θ_{fc} = field capacity soil moisture content; and

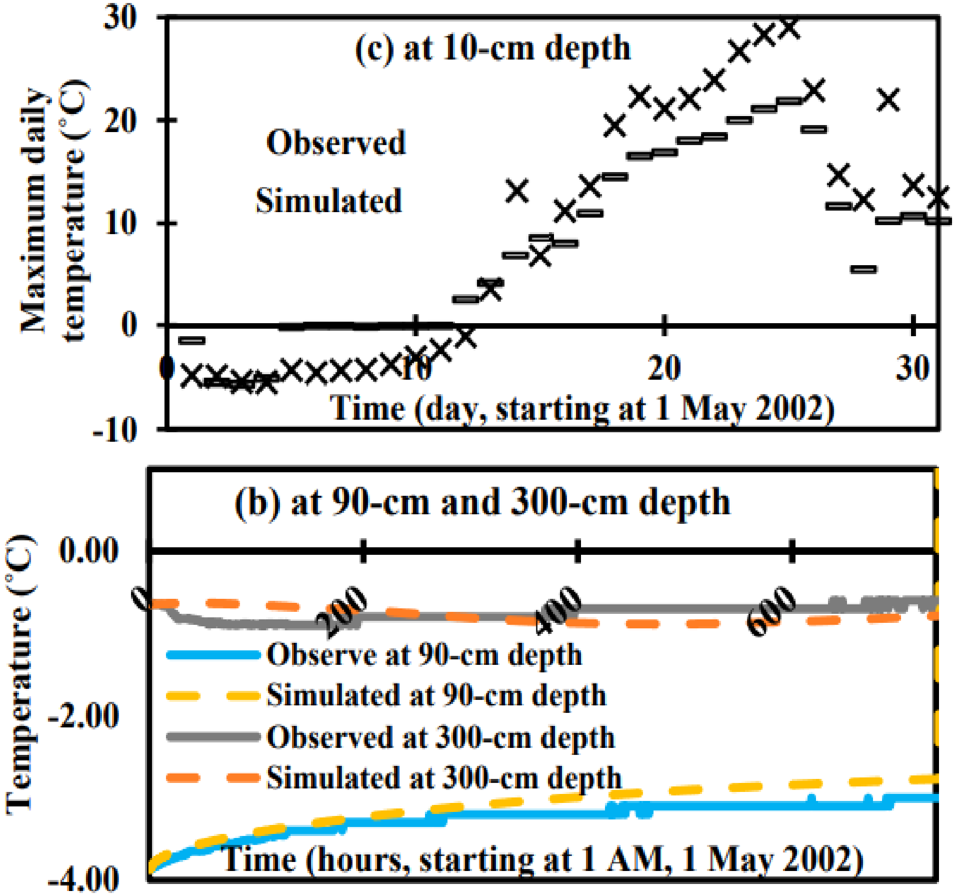
θ_{wp} = wilting point soil moisture content;

i = any spatial location or grid/tin address for a numerical model.

NDVI is the vegetation index **'SERVES Method'** (*Pradhan, 2019*)

Simulated results of soil profile heat transfer

Time-series of observed and simulated temperature



water

Article

Catchment Hydrological Modeling with Soil Thermal Dynamics during Seasonal Freeze-Thaw Cycles

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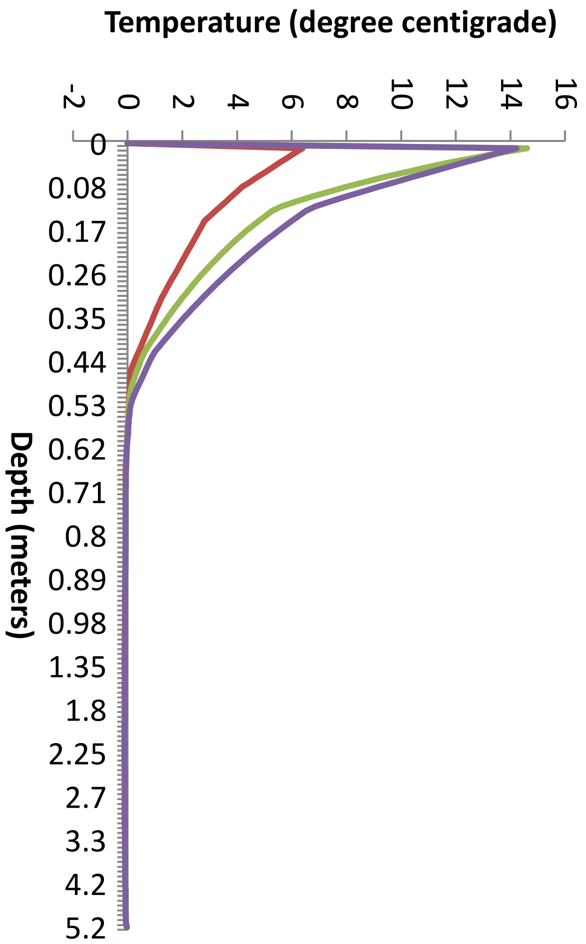
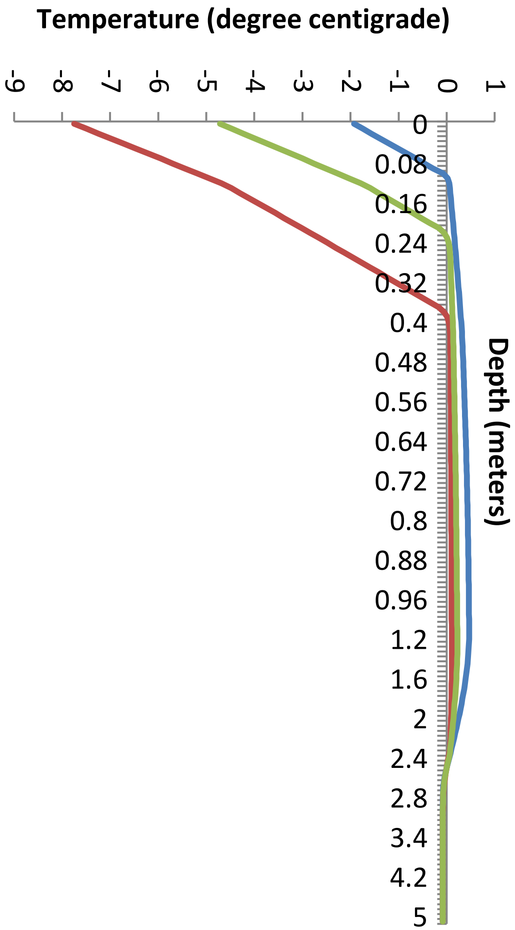
2 Geophysical Institute, University of Alaska Fairbanks, Fairbanks, AK 99775, USA; ssmarchenko@alaska.edu
* Correspondence: Nawa.pradhan@usace.army.mil

Freeze/Thaw

Heading towards freezing condition

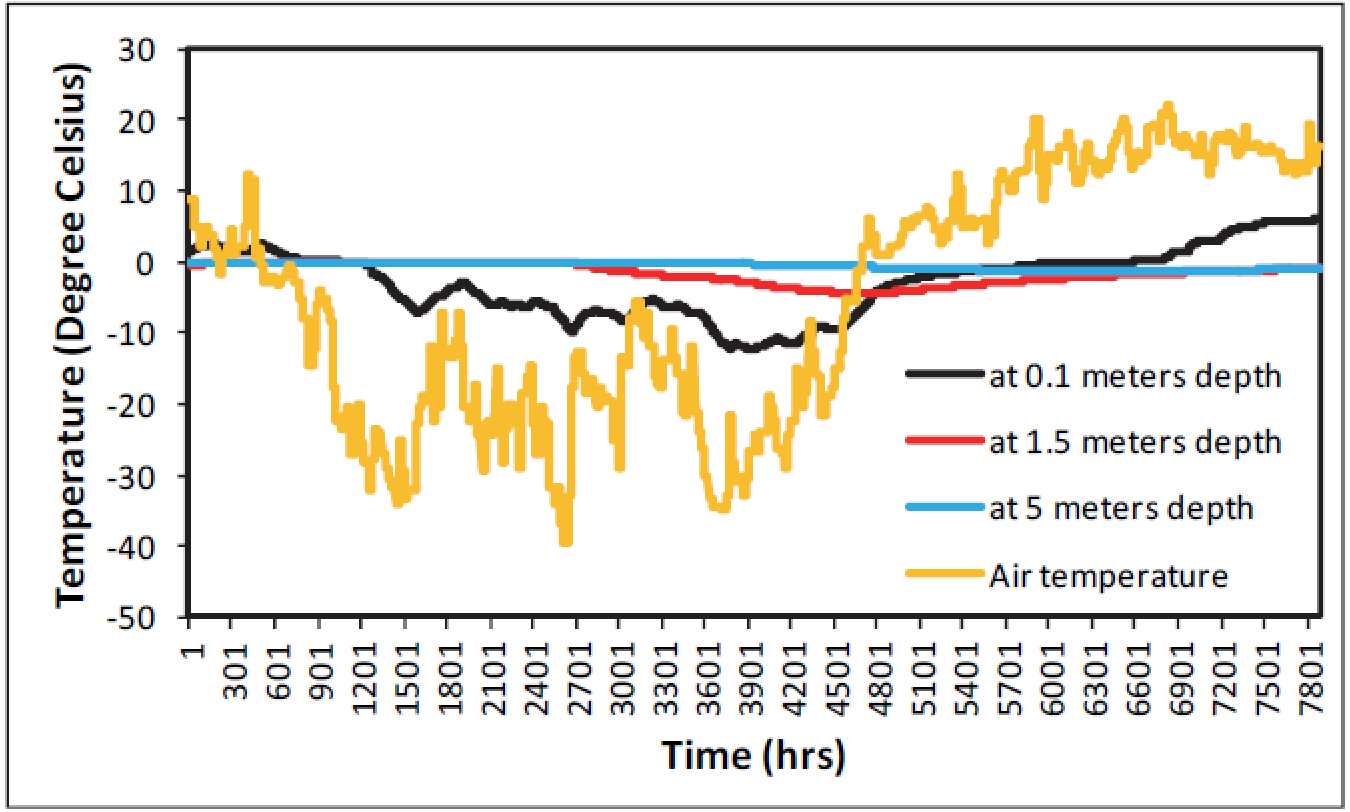
Heading towards thawing condition



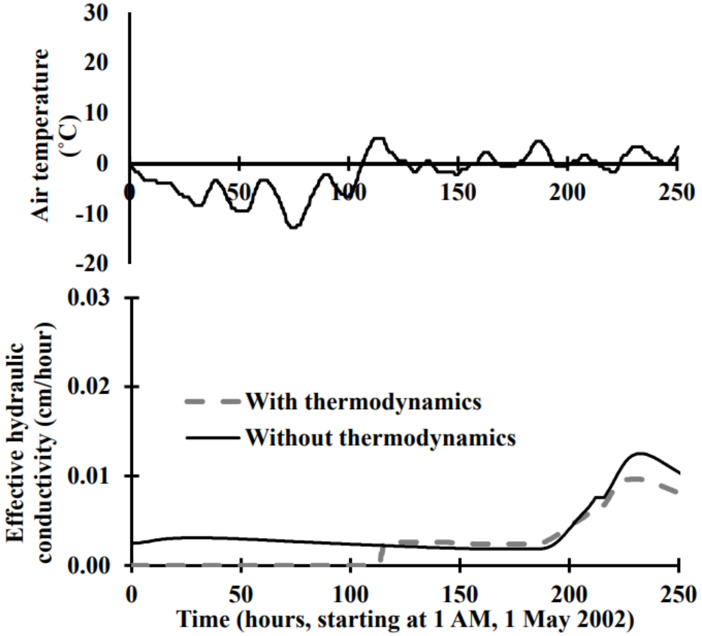


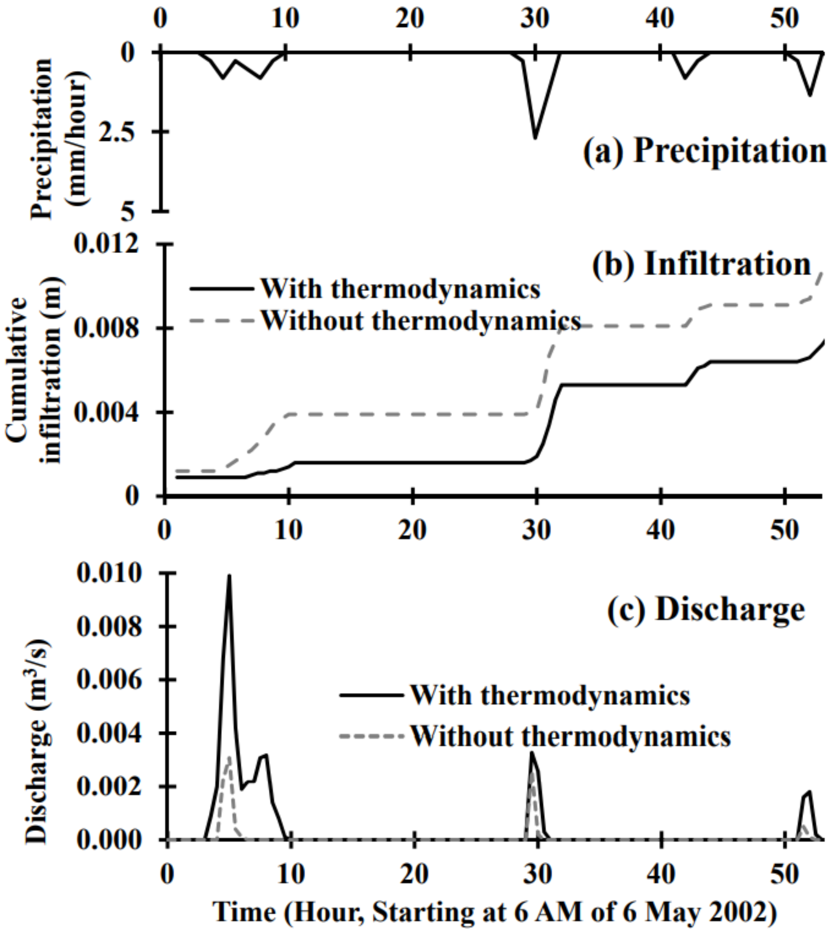
Seasonal Freeze-Thaw Cycles
https://doi.org/10.3390/w11010116

Long-term simulation



Simulation results and analysis





Figures from:

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Article

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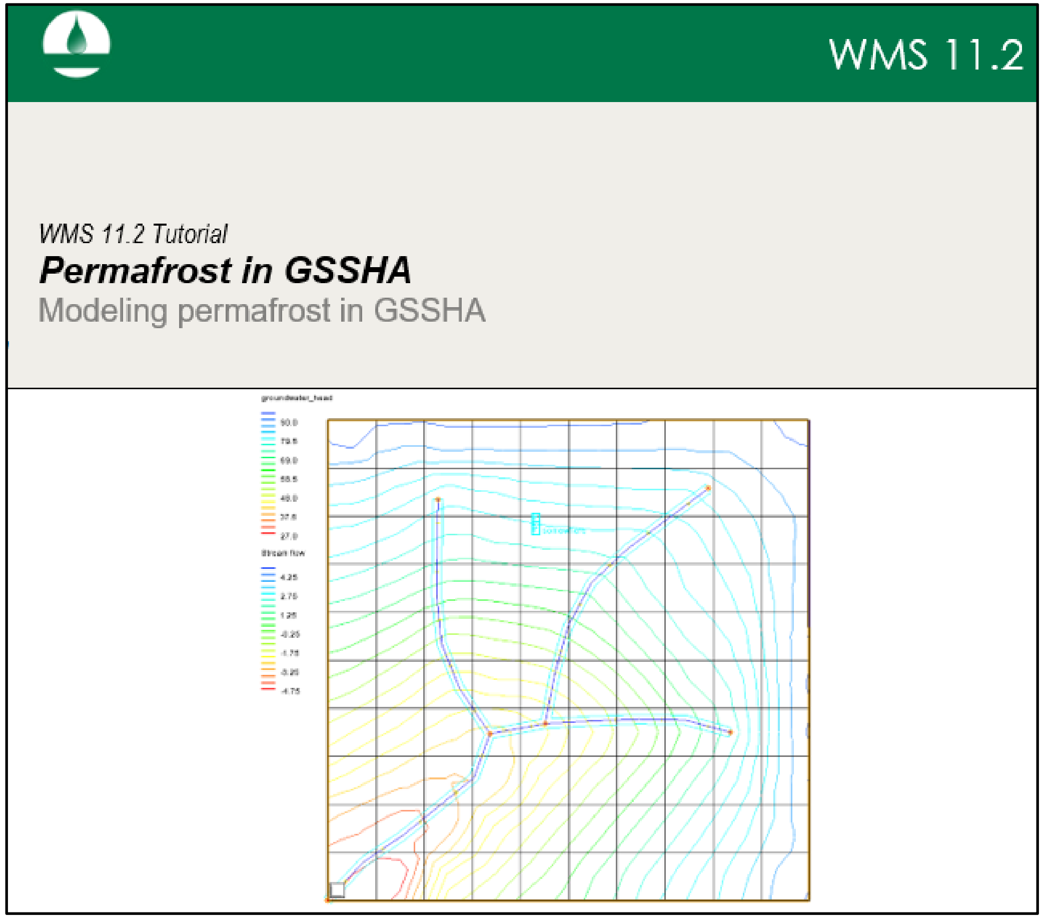
Setting up hydro-thermodynamic model

WMS Tutorial


WMS 11.2

WMS 11.2 Tutorial

Permafrost in GSSHA

Modeling permafrost in GSSHA

User guidelines report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Data input/output

Figure 3. Permafrost parametric value input format in the GSSHA mapping table.

```
PERMAFROST_LAYER_SOIL  "perma"
NUM_IDS 2
MAX_NUMBER_LAYERS 17
DN_INIT_MAX 30
DN_MAX 500
INIT_TEMP_FILE  init_temp.txt
DEP_NODE_FILE   dep_node.txt
OUT_NODE_FILE   out_node.txt
ID   DESCRIPTION1    LAYERNUMS  Dn_init   Dn    Dn_out  thick tfr  wvol  wunf   aclv bclv  cclv cond_th cond_fr  Cvol
1    Permafrost ID      8        27       230    3      0.080 0.0  0.87  0.107  0.03 -0.32 0.0  0.02    0.02     2800000
                                                        0.220 0.0  0.43  0.027  0.02 -0.23 0.0  0.01    0.02     2900000
                                                        0.320 0.0  0.20  0.053  0.04 -0.27 0.0  0.01    0.05     2700000
                                                        0.380 0.0  0.36  0.014  0.01 -0.23 0.0  0.01    0.05     2800000
                                                        0.500 0.0  0.32  0.072  0.06 -0.29 0.0  0.01    0.05     2700000
                                                        3.500 0.0  0.34  0.014  0.01 -0.13 0.0  0.01    0.05     2800000
                                                        5.000 0.0  0.44  0.021  0.01 -0.10 0.0  0.01    0.05     2800000
                                                        101.0 0.0  0.07  0.020  0.01 -0.12 0.0  0.01    0.05     2800000
2    Permafrost ID      3        27       230    3      0.120 0.0  0.48  0.020  0.00 -0.10 0.0  0.01    0.05     2800000
                                                        0.420 0.0  0.42  0.020  0.03 -0.32 0.0  0.01    0.05     2800000
                                                        101.0 0.0  0.31  0.010  0.06 -0.35 0.0  0.01    0.05     2800000
```

Figure (above) and table (right) is from: http://dx.doi.org/10.21079/11681/48331

Figure (below) is from: http://dx.doi.org/10.21079/11681/48331

Figure 1. Geophysical Institute Permafrost Laboratory (GIPL) as a permafrost component in the Gridded Surface Subsurface Hydrologic Analysis (GSSHA).

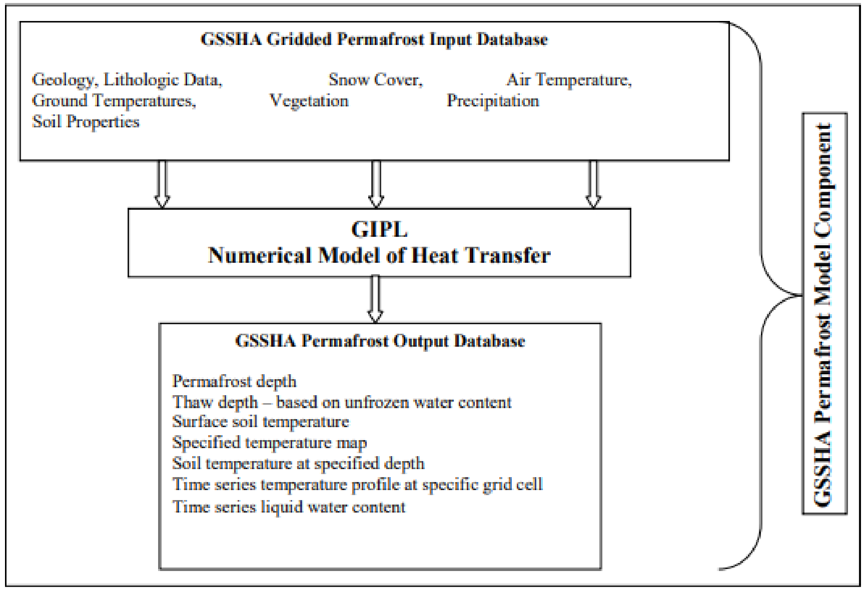

Table 6. Description of items in Figure 3.

Item	Description	Unit
ID	Permafrost soil ID	—
LAYERNUMS	Total number of soil layers in a soil ID type	—
Dn_init	Number of initial temperature inputs in the vertical soil profile	—
Dn	Total number of computational nodes	—
Dn_out	Total number of permafrost state variable output.	—
thick	Thickness of soil layer	M
tfr	Temperature of phase change	Degree Celsius
wvol	Volumetric soil water content	Fraction of 1
wunf	Volume of unfrozen water	Fraction of 1
aclv	A—parameter of unfrozen water	—
bclv	B—parameter of unfrozen water	—
cclv	C—parameter of unfrozen water	—
Cond_th	Soil thermal conductivity thawed	W m^{-1} k^{-1}
Cond_fr	Soil thermal conductivity frozen	W m^{-1} k^{-1}
cvol	Volumetric heat capacity	J m^{-1} m^{-1} m^{-1} k^{-1}

permafrost.prj - Notepad

```
PERMAFROST_GIPL           permabound.txt
MULTI_LAYER_INFIL_GIPL
OUT_GIPL_TEMP             "temp_out.gip"
```

Optional project card:
GIPL_TIMESTEP

permabound.txt - Notepad

```
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

```
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

```
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
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

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

temp_out.gip - Notepad

File Edit Format View Help

Time	Air Temp(C)	Depth(m)	Soil Temp(C)	Depth(m)	Soil Temp(C)	Depth(m)	Soil Temp(C)
2454000.50000000	8.889	0.1000	1.4935	1.5000	-0.2733	5.0000	-0.2430
2454000.54166667	8.889	0.1000	1.4376	1.5000	-0.2817	5.0000	-0.2432
2454000.58333333	8.889	0.1000	1.4274	1.5000	-0.2859	5.0000	-0.2434
2454000.62500000	8.889	0.1000	1.4294	1.5000	-0.2890	5.0000	-0.2435
2454000.66666667	8.889	0.1000	1.4354	1.5000	-0.2916	5.0000	-0.2436
2454000.70833333	8.889	0.1000	1.4426	1.5000	-0.2938	5.0000	-0.2438
2454000.75000000	8.889	0.1000	1.4500	1.5000	-0.2959	5.0000	-0.2439

Thank you

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