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Modeling Permafrost in GSSHA with the Geophysical Institute Permafrost Lab Model, GIPL and Use Guidelines

Draft version

Nawa Raj Pradhan, Charles W. Downer, and Sergei Marchinko Submitting

Photo: "Provided by: Dr. Vladimir E. Romanovsky, Professor of Geophysics, University of Alaska Fairbanks, Alaska"

Coastal and Hydralics Laboratory

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Submitting

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Draft version

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Abstract: Climate warming is expected to degrade permafrost in many regions of the world, including Alaska. Degradation of permafrost has the potential to dramatically affect soil thermal, hydrological, and vegetation regimes. Projections of long-term effects of climate warming on high latitude ecosystems require a coupled representation of soil thermal state and hydrological dynamics. We developed such a coupled framework to explicitly simulate the soil moisture effects of soil thermal conductivity and heat capacity and its effects on hydrological response. In the coupled framework, Geophysical Institute Permafrost Laboratory (GIPL) model is coupled with the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model. The new permafrost heat transfer in GSSHA is computed through GIPL scheme that simulates soil temperature dynamics and the depth of seasonal freezing and thawing by numerically solving a 1D quasi-linear heat equation with phase change. All the GIPL input parameters are made consistent with the GSSHA input-output format and requirements, as well as GIPL parameters, and state variables are distributed in each GSSHA simulation grid unit. Test case simulated results showed freezing temperature reduced soil storage capacity, thereby producing higher peak and lower base flow. This report is a guideline for implementing GSSHA hydrologic simulation in permafrost active area. The report details the functions and format of required input variables and cards in GSSHA hydrologic analysis of permafrost active area.

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Introduction

The soil-freezing characteristic, a relationship between unfrozen water content and temperature, is relevant for any mass transfer processes in frozen porous media. To understand better the long-term effect of future climate scenarios, especially in the higher latitudes, interaction of soil thermal state and hydrological dynamics is significant. Thus, we develop a coupled framework to model interactive effects of soil thermal and hydrological dynamics.
Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model (Downer and Ogden, 2006) is a spatially explicit hydrologic model that simulates 2D overland flow, 1D (vertical) unsaturated groundwater flow, 2D saturated groundwater flow, and 1D flow in stream networks, all fully coupled. Past coupling framework, such as coupling of subsurface storm drainage and tile drain in GSSHA (Ogden et al. 2011; Pradhan et al. 2009), has demonstrated GSSHA ability to simulate important surface and subsurface runoff generation processes and to represent explicitly fully-coupled hydrodynamics. In this present framework, the GSSHA model is coupled with the Geophysical Institute Permafrost Laboratory (GIPL) model (Jafarov 2012; Marchenko 2008). The GIPL model simulates soil temperature dynamics and the depth of seasonal freezing and thawing by numerically solving a one dimensional (1D) quasi-linear heat equation with phase change. The coupled system utilizes the GIPL model to provide spatially and temporally varying soil temperature profiles that are used to adjust soil hydraulic properties used to compute infiltration, vertical unsaturated soil water movement and lateral saturated groundwater flow in GSSHA. GSSHA in turns provides GIPL spatially and temporally varying values of soil moisture, with depth, critical to the proper simulation of soil temperature. A continuous feedback loop links and improves the simulation of soil temperature and hydrology.

Purpose

The purpose of this report is to describe the new permafrost model in the hydrologic model GSSHA and to demonstrate the effects of seasonal freezing and thawing on hydrological dynamics. Details of theoretical background on coupling and linking GIPL and GSSHA are presented in Pradhan et al. (2013). The purpose of this report is to describe how to use the GIPL model as implemented in GSSHA to simulate permafrost active areas or include the effects of soil freezing and thawing on hydrology in any area where such processes occur. In this report we will describe the functioning of the GIPL model as it pertains to developing inputs for the model to simulate permafrost effects on heat transfer and soil physical properties. Details of numerical considerations in the use of the model are provided in Pradhan et al. (2013). This report describes the model inputs in detail and provides example problems with complete inputs to illustrate the points.

This document can be considered an addendum to the original GSSHA's User Manual (Downer and Ogden 2006) as it describes the details for developments after the user's manual was completed. Additional information on GSSHA can be found in the GSSHA's User's manual.

Permafrost Modeling in GSSHA and Use Guidelines

The GIPL is an implicit finite-difference numerical model which solves the one-dimensional (1D) quasi-linear heat equation with phase change. The process of soil freezing/thawing is treated in accordance with relationships between the soil unfrozen water content and temperature. The GIPL numerical model solves the Stefan problem (Alexiades and Solomon 1993; Verdi 1994) with phase change which is the problem of thawing or freezing via conduction of heat (Sergueev et. al. 2003; Nicolsky et. al. 2007).

The GSSHA model uses a 1D (vertical) finite-difference solution of Richards' Equation (Richards 1931) to simulate the unsaturated zone. The unsaturated zone is linked to a 2D (lateral) finite-difference representation of saturated groundwater flow (Downer 2002; Downer and Ogden 2004). The groundwater solution is fully coupled to surface flows using a 1D implicit finite difference solution to Richards' Equation. In GSSHA, infiltration may also be simulated using traditional Hortonian Green and Ampt (GA) (Green and Ampt, 1911) approaches which are simplifications of RE. There are three optional GA based methods to calculate infiltration for Hortonian basins: 1) traditional GA infiltration, 2) multi-layer GA (Ogden et al., 2011), and 3) Green & Ampt infiltration with redistribution (GAR) (Ogden & Saghafian, 1997). The traditional GA and multi-layer GA approaches are used for single event rainfall when there are no significant periods of rainfall hiatus. The GAR approach is used when there are significant breaks in the rainfall, or for continuous simulations. Therefore, GSSHA works in both event and continuous mode. When simulations are conducted in continuous mode, standard hydrometeorological inputs are provided hourly. Details of the frozen soil modeling with a specific infiltration scheme are provided later in Table 1 and Table 2.

Coupling GIPL to GSSHA

The GIPL model is a stand-alone permafrost model that is used to compute a one-dimensional (vertical) soil temperature profile over time using static values of soil moisture at daily intervals. As implemented in GSSHA, GIPL is a subroutine that is used to compute a profile of soil temperature in every 2D grid cell, including time-varying soil moisture and groundwater levels at varying time intervals (Pradhan et al. 2013). To accomplish this result several tasks were performed:

a) The original FORTRAN GIPL permafrost model source code was converted to a stand-alone C/C++ source code.
b) As the GIPL model was spatially lumped and the GSSHA model is spatially distributed, significant effort was expended to make all the GIPL state variables and parameters distributed as grid-based or permafrost soil type-based before merging the C/C++ version of GIPL into GSSHA.

Thus, the uni-dimensional limitations of GIPL were removed and GIPL becomes a multi-dimensional distributed application in the GSSHA distributed modeling framework.

c) Originally, the GIPL numerical model computed heat transport with daily or larger time-steps. While GSSHA loops on an overall model time-step, processes included for simulation are updated at user-specified or internally-derived time-steps. As implemented in GSSHA, GIPL can have any time-step, as specified by the user. The default time-step for GIPL is the infiltration time-step, which is on the order of seconds or minutes.

d) The coupling of GSSHA and GIPL is intended to provide a feedback between the two models with updated information from one model used to improve the simulation results from the other. Several thermo-hydrodynamic formulations and modeling concepts are implemented as a methodology in linking GIPL and GSSHA for the development of a coupled framework that simulates interactive effects of soil thermal hydrological dynamics in saturated/unsaturated permafrost layers. Details on linking GIPL and GSSHA in the coupled framework are presented in Pradhan et al. (2013). The following links in GIPL and GSSHA thermo-hydrodynamic formulations are implemented to exchange the information between GIPL and GSSHA:

    a) Linking GIPL and GSSHA computational nodes.
    b) Linking GIPL soil thermodynamics with GSSHA soil moisture hydrodynamics.
    c) Linking GIPL soil temperature and GSSHA hydraulic conductivity.
    d) Linking Soil Heat Transfer Effect on Effective Groundwater Transmissivity.

The spatial variability of land-surface and hydrodynamic parameters, including subsurface soil moisture state, is included in the GSSHA model and made available to GIPL during simulation (Figure 1). Theoretical and conceptual details of the linkage and exchange of information in GIPL and GSSHA coupled framework is provided in Pradhan et al. (2013).

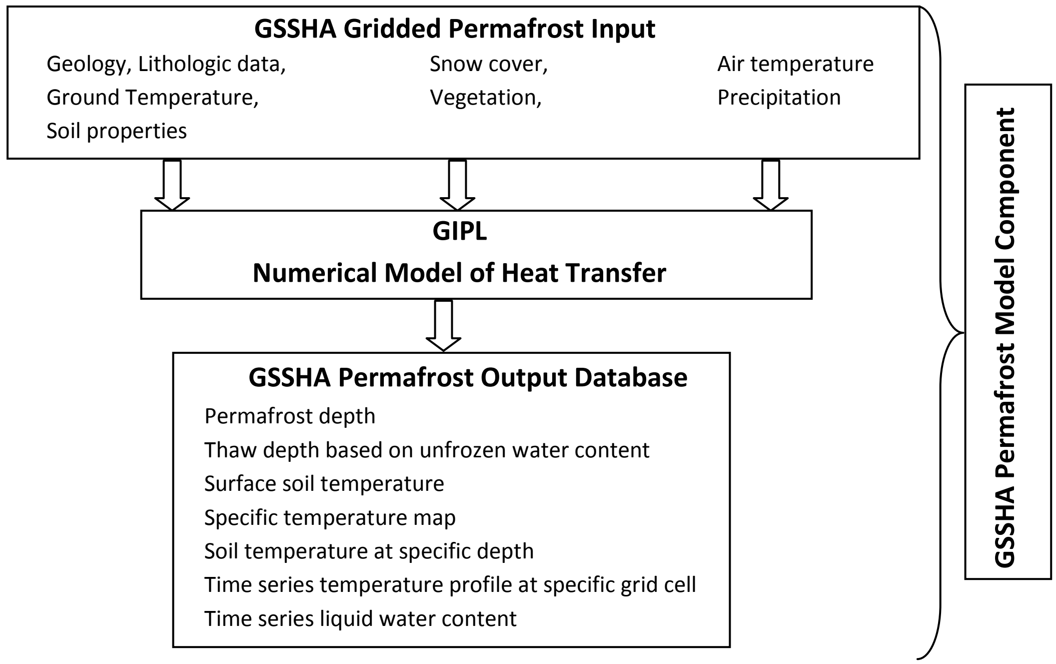


Figure 1. GIPL as a permafrost component in GSSHA

Use guidelines for permafrost modeling in GSSHA

General use guidelines of GSSHA are in GSSHA wiki: http://gsshawiki.com/gssha/Main_Page. The use guidelines in this document deal with GSSHA watershed hydrologic modeling that includes permafrost component, as well. Parametric values and cards along with the required input and output formats are in project file (file with the extension ".prj") and mapping table file (file with the extension ".cmt").

Project File

In GSSHA, the model simulation is controlled by a card based file called the project file with the extension ".prj". The following card is required in the project file for any GIPL simulation (Table 1).

Table 1. Card Required for GIPL Simulation.

Card	Input File	Card Description	File Description
PERMAFROST_GIPL	**Filename -*.pbd	This card is used when both saturated ground water and unsaturated vadose zone are hydro-dynamically affected by frozen soil. Therefore in the GSSHA project file, this card is accompanied by groundwater simulation card,	File containing permafrost mask map

		"GW_SIMULATION" and an infiltration option that represents the layers of the soil profile. The infiltration scheme may be 1D (vertical) finite-difference solution of Richards' Equation (Richards 1931) or multi-layer Green and Ampt (Ogden et al., 2011). Multi-layer Green and Ampt approaches is a simplification of Richards' Equation and is used for a single event case. For Richards' Equation, "INF_RICHARDS" card is used and for multi-layer Green and Ampt "INF_LAYERED_SOIL" card is used in the GSSHA project file. Details about those infiltration and groundwater cards in GSSHA are provided in GSSHAwiki.	
MULTI_LAYER_INFIL_GIPL		"MULTI_LAYER_INFIL_GIPL " card is used for the same condition as that for the "PERMAFROST_GIPL" except that "MULTI_LAYER_INFIL_GIPL " card does not account for the hydro-dynamic effect of the frozen soil in saturated groundwater portion.	File containing permafrost mask map
SINGLE_LAYER_INFIL_FROZEN_SOIL		This card is used when traditional GA infiltration scheme or Green & Ampt infiltration with redistribution (GAR) (Ogden & Saghafian, 1997) scheme is used . With this card, the multilayer heat transfer numerical solution does not apply and hence GIPL subroutine is not called. Instead of calling the heat transfer GIPL solution, the air temperature is applied directly in the unsaturated vadose zone frozen soil hydraulic conductivity estimation.	File containing frozen soil mask map

**Permafrost mask file, with the extension ".pbd", defines the boundary of the permafrost active zone. This GRASS GIS format map file defines which regions in the GSSHA grid are included in the active permafrost zone. In the mask file, permafrost active zone is 1, and outside the boundary is 0, as shown in Figure 2. Any heat transfer numerical solution is limited within the active zone.

```
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.

Figure 2. Freezing / thawing active mask index map.

Table 2 shows optional cards that can be used.

Table 2. Optional Cards.

Card	Input	Description
GIPL_TIMESTEP	Numerical value	GSSHA permafrost model user-defined numerical heat transfer time-step in seconds
OUT_GIPL_TEMP	Filename - *.tgi	Get the time series of soil temperature at location xyz

If the card GIPL_TIMESTEP is not used, GSSHA infiltration time-step is used as default for numerical heat transfer calculation.

Mapping Table File

In GSSHA the mapping table file is used to assign distributed parameter values for all processes selected for simulation as defined in the project file. The mapping table file contains tabulated parameter values linked with integer based index maps that describe the distribution of parameters within the GSSHA domain. If the project file contains the PERMAFROST card, the mapping table file must contain the card shown in Table 3.

Table 3. Card required for GIPL grid based parameter input in the mapping table.

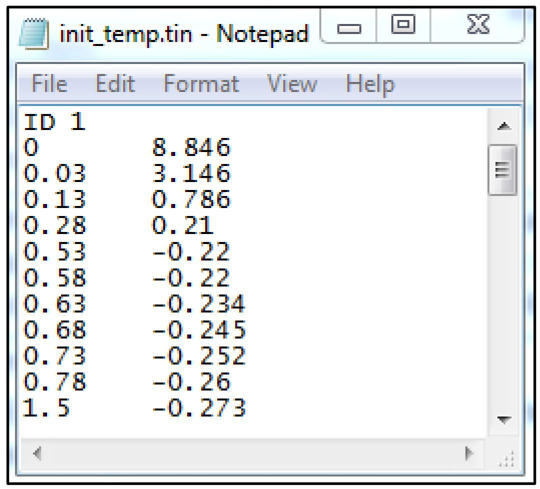
Card	Input	Description
PERMAFROST_LAYER_SOIL	**Referenced Filename - *.idx	File containing permafrost soil id map info

**Referenced Filename is the filename that is referred at INDEX_MAP. For example, in the following line extracted from the GSSHA mapping table (*.cmt), perma refers to the file name permafrost.idx.
INDEX_MAP “permafrost.idx” “perma”
PERMAFROST_LAYER_SOIL card in the *.cmt mapping table file appears as follows:

PERMAFROST_LAYER_SOIL "perma"

If there is PERMAFROST_LAYER_SOIL card in the mapping table, a series of other cards follows as shown in the following table 4.

Table 4. Permafrost mapping table inputs that follow after the main card PERMAFROST_LAYER_SOIL being read.

Card	Input	Description
NUM_IDS	Numerical value	Total number of permafrost soil IDs
MAX_NUMBER_LAYERS	Numerical value	Maximum number of soil layers in the permafrost active grid
DN_INIT_MAX	Numerical value	Maximum number of grid points in the vertical grid for initial conditions
Dn_max	Numerical value	Maximum number of nodes in the depth used for memory allocation. Dn_max should be bigger than Dn of any permafrost soil id in Table 6.
INIT_TEMP_FILE	Filename-*.tin	Initial temperature of soil profile. Format: Each soil id number followed by the depth and temperature for that soil id. Example of initial temperature profile file:  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 After soil id 1 (as shown in the example), soil id 2 follows in the similar way until all soil ids are complete, The depth may go to 100s of meters below the surface.
DEP_NODE_FILE	Filename-*.txt	Computational node depth file. Format: Each soil id number followed by the computational node depth for that soil id. Example of computational node depth file:

		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`
		After soil id 1 (as shown in the example), soil id 2 follows in the similar way until all soil ids are complete, The depth may go to 100s of meters below the surface.

OUT_NODE_FILE	Filename-*.txt	Time series state variable output node depth. Format: Soil id, followed by number of locations for that soil type, followed by row and column for each of those locations, followed by depth output node locations.
		Example of computational node depth file:
		out_node.txt - Notepad
		File Edit Format View Help
		`ID 1`
		`READ_OUT_ROW_COL_PAIRS 1`
		`6 6`
		`OUT_NODES_ADDRESS`
		`0.1`
		`1.5`
		`5.0`
		`ID 2`
		`READ_OUT_ROW_COL_PAIRS 1`
		`2 2`
		`OUT_NODES_ADDRESS`
		`0.1`
		`1.5`
		`5.0`
		All soil ids follow in the similar way as shown in the example.

Table 4 is followed by the parametric value input. After defining the overall inputs with the cards in Table 4, parameter values must be assigned for each specified soil layer within each of the specified GIPL soil types. An example input format is shown in Table 5. The parameter values in this table are taken from the example project at the end of this document.

Table 5. Permafrost parametric value input format in GSSHA mapping table.

ID	DESCRIPTION1	LAYERNUMS	Dn_init	Dn	Dn_out	thick	tfr	wvol	wunf	aclv	bclv	cclv	cond_th	cond_fr	Cvol
1	Permafrost ID	3	20	200	4	0.080	0.0	0.87	0.11	0.034	-0.32	0.00	0.0201	0.055100	2800
						3.500	0.0	0.87	0.11	0.034	-0.32	0.00	0.0201	0.055100	2800
						101.0	0.0	0.87	0.11	0.034	-0.32	0.00	0.0201	0.055100	2800
2	Permafrost ID	3	20	200	4	0.080	0.0	0.87	0.11	0.034	-0.32	0.00	0.0201	0.055100	2800
						3.500	0.0	0.87	0.11	0.034	-0.32	0.00	0.0201	0.055100	2800
						101.0	0.0	0.87	0.11	0.034	-0.32	0.00	0.0201	0.055100	2800

Description of items in Table 5 is in Table 6.

Table 6. Description of items in Table 5.

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	$Jm^{-1}m^{-1}m^{-1}k^{-1}$

Thermal parametric value range

Table 7 shows the thermal conductivity parametric value range for different types of soils.

Table 7 Thermal conductivity parametric value range.

Soil type	Thermal conductivity range [$wm^{-1}k^{-1}$]
Clay	0.5 - 3.1
Silt	0.8 – 2.4
Peat	0.05 – 0.9
Sandstone	0.5 – 4.2
Coal	0.15 – 2.2
Sand	0.75 – 2.1
Bedrock (granite)	1.2 – 3.9
Bedrock (basalt)	1.5 – 3.5
Marble	1.6 – 4.1
Quartz	2.7 – 7.6

Illustration of Permafrost Modeling in GSSHA

The example case in this section illustrates is modeling a permafrost active area with GIPL coupled in GSSHA. The simplified example is conceptual, but the permafrost parametric values represent Alaskan woodland and tundra ecosystem sites in a permafrost active region. This example project includes surface/ subsurface runoff where infiltration and groundwater components are simulated within GSSHA. The soil moisture and soil physical state are simulated with the Richards' Equation. The model is run in continuous simulation mode. Hydrometeorological data are input hourly.

Test Model

The test model, shown in Figure 3, is comprised of a gridded 10 × 10 domain. As seen in Figure 3, the test watershed drains from the northeast corner to the southwest corner, as illustrated by the contour lines, blue for higher elevations and red for lower elevations. A stream network, indicated by the dark blue lines (arrows indicate direction of flow), collects the overland flow and directs it to the watershed outlet.

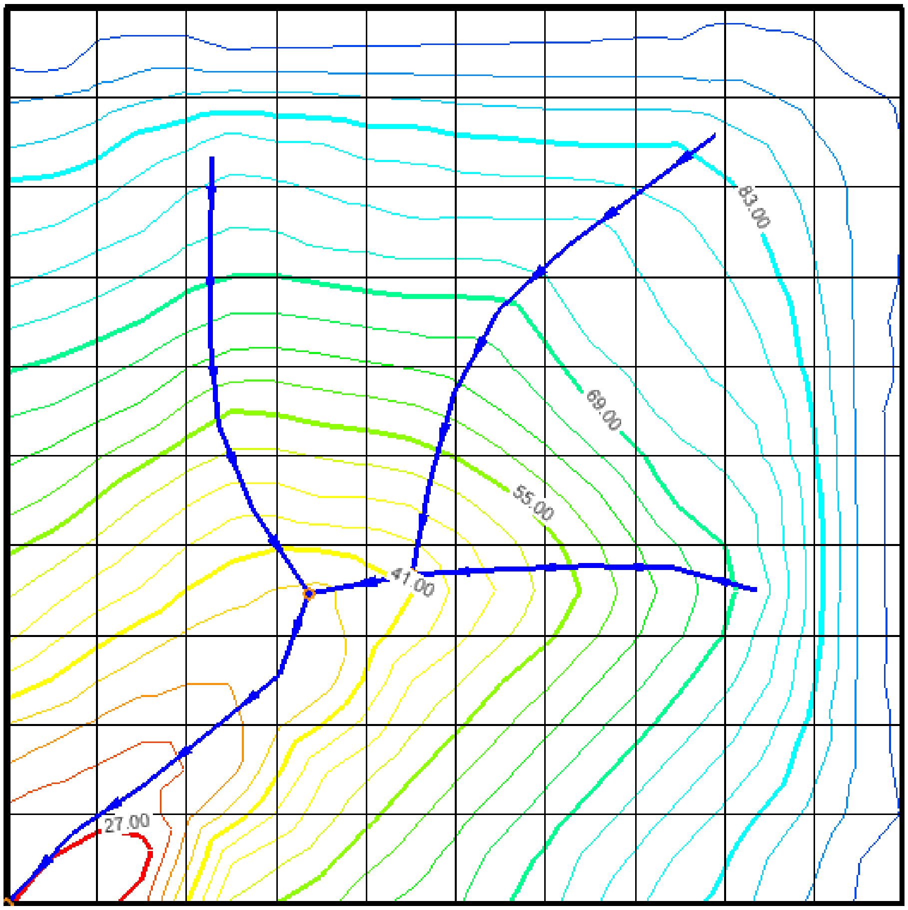


Figure 3. Test case example project of coupled GSSHA and GIPL where the permafrost parametric values represent woodland and tundra ecosystem sites in permafrost active Alaskan region.

Cards and Index Maps

Following cards are included in the GSSHA project file:

PERMAFROST_GIPL	"permabound.pbd"
MULTI_LAYER_INFIL_GIPL	
GIPL_TIMESTEP	900
OUT_GIPL_TEMP	temp_out.gip

The active permafrost mask map, "permabound.pbd", for this test case was presented in Figure 2, where the index value of 1 refers to the permafrost active grid, and index values of 0 indicate that the region falls outside the active zone and no GIPL computations are performed in these computational cells. Figure 4 is an example of the permafrost soil index map indicated in the GSSHA mapping table file presented in Table 3. In this permafrost soil index map, index value 1 refers to woodland areas and index value 2 refers to tundra areas, with the physical parameter values defined in Tables 5 and 6, as shown above.

```
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

Figure 4. Permafrost soil index map.

Initial Condition

Figure 5 shows the initial temperature profile taken from an Alaskan permafrost woodland and tundra site. As shown in the figure, the initial temperature is defined at irregular intervals to a depth of 100 m. The initial condition data of Figure 5 is in the file ”*.tin” indicated by the card INIT_TEMP_FILE in table 4.

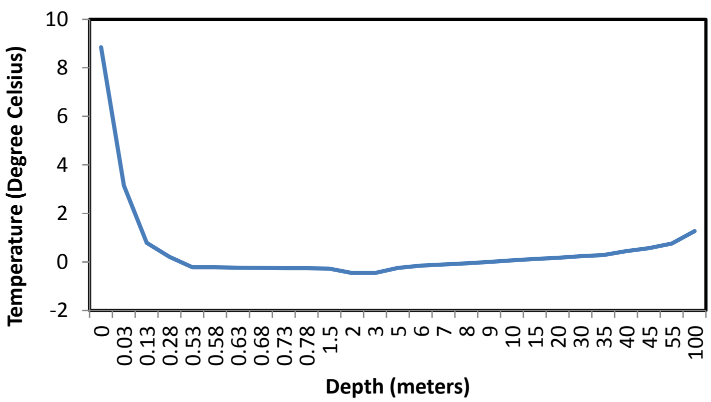


Figure 5. Soil temperature profile as an initial condition for the thermodynamics numerical simulation.

Model Results

The model was run for a period of 12 months. Figure 6 shows simulated soil temperature profile extracted from the time series.

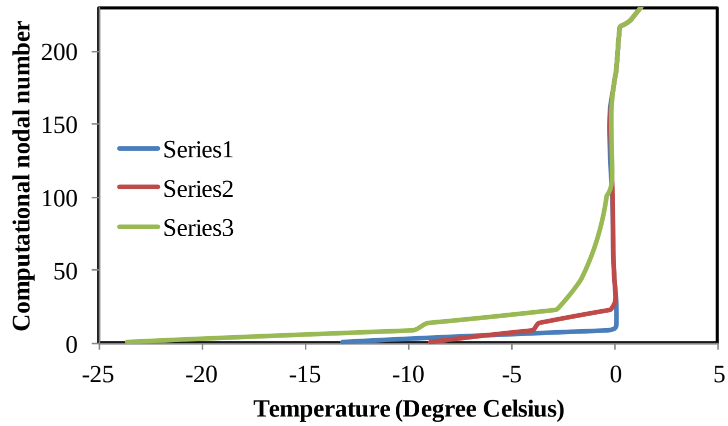


Figure 6. Soil temperature profiles.

Figure 6 shows the vertical soil temperature at computational nodal points and, Figure 7 shows the corresponding depths for the nodal points.

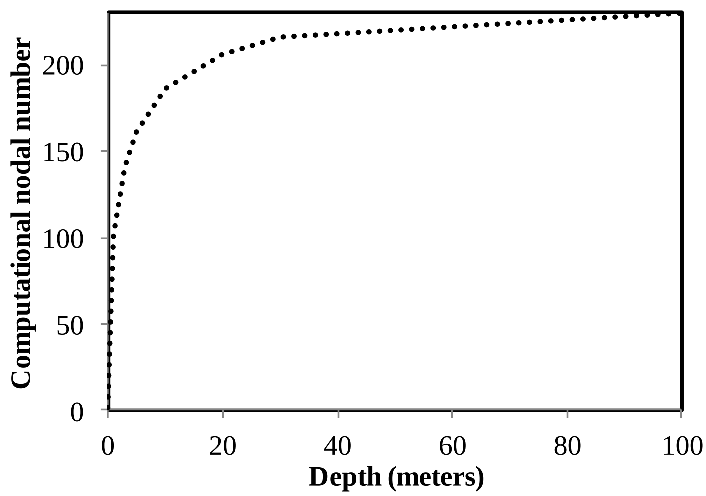


Figure 7. Depth information of the computational nodal number.

Figure 8 shows the soil temperature at various depths. The time-series of soil temperature in Figure 8 is the output data in the file defined by the card OUT_GIPL_TEMP in Table 2. The output data has the columns of time-series, temperature for each location and depth defined in the file defined by the card OUT_NODE_FILE in Table 4. Figure 8 shows that the air temperature has most significant influence in the near-surface soil layer. As the soil layer depth increases, air temperature influence in soil thermo-dynamics is diminished along with the increase in the time lag influence.

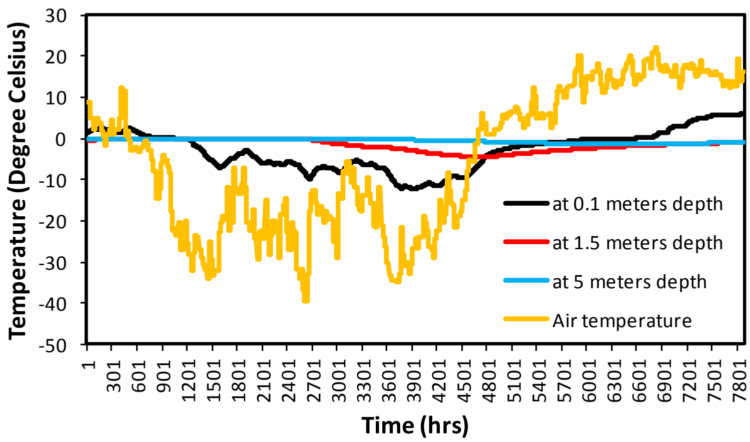


Figure 8. Time-series of temperature at various depths.

Figure 9 shows the change in effective hydraulic conductivity due to frozen soil condition.

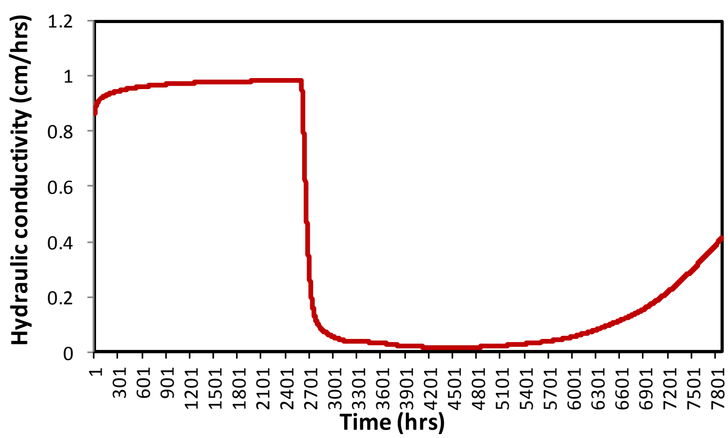


Figure 9. Hydraulic conductivity under active permafrost soil layer.

Figure 10 shows the comparison of GSSHA simulated discharge with and without permafrost model for some events within the simulation duration.

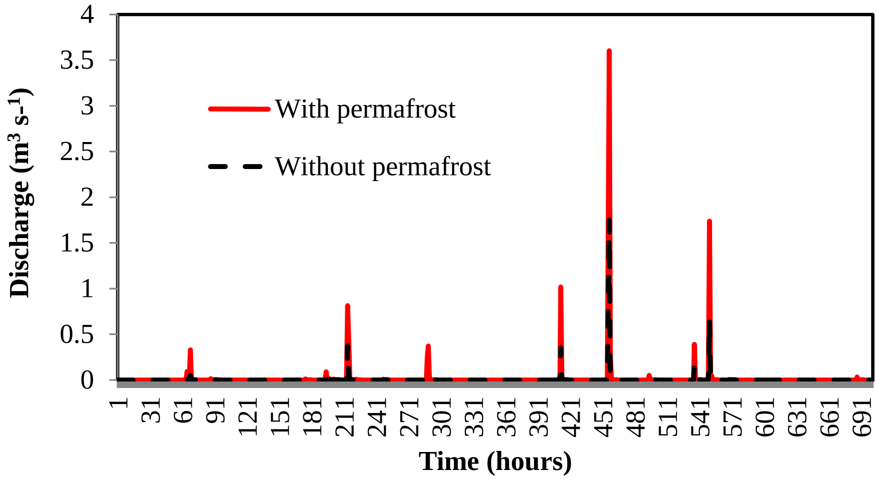


Figure 10. Hydrograph with and without active permafrost.

Discussion

It is apparent from Figure 10 that the increased coverage of permafrost in high permafrost basin leads to less soil-pore water storage and a flashier response to the precipitation event. On the other hand, loss of permafrost will likely lead to enhanced connectivity between the surface and ground water storage regimes.

Summary

This report is an application guideline for implementing GSSHA hydrologic simulation in permafrost active area. Details of theoretical guideline of linking GIPL and GSSHA Thermo-hydrodynamic information are provided in Pradhan et al. 2013.

The new permafrost heat transfer in GSSHA is computed through a scheme called GIPL. All the GIPL input parameters are made consistent with the GSSHA input format and requirements. GIPL parameters and variables along with the GIPL-GSSHA linking variables are distributed in each GSSHA simulation grid unit. Timeseries output at a specific depth along with the profile based outputs are made accessible as per the requirement of a model user. In this document, the coupled GSSHA GIPL is demonstrated on a contrived watershed around a previous GIPL test site. GIPL and GSSHA-coupled simulation results showed that the effect of soil thermal properties obtained from GIPL play a significant role in the GSSHA hydrological dynamics and vice versa. GSSHA hydrodynamics includes vadose zone soil moisture and ice content information feedback and its effects on hydraulic conductivity and transmissivity.

References

Alexiades, V., A. D. Solomon, 1993. *Mathematical modeling of melting and freezing processes, Washington, Hemisphere*, 325 pp.

Downer, C. W. 2002. Identification and modeling of important stream flow producing processes in Watersheds. PhD diss., University of Connecticut.

Downer, C. W., F. L. Ogden. 2004. *Appropriate vertical discretization of Richards' equation for two-dimensional watershed-scale modelling*. *Hydrol. Process.* 18, 1–22 (2004). DOI: 10.1002/hyp.1306 HYDROLOGICAL PROCESSES.

Downer, C. W., and F. L. Ogden. 2006. *Gridded Surface Subsurface Hydrologic Analysis (GSSHA) User's Manual, Version 1.43 for Watershed Modeling System 6.1, System Wide Water Resources Program*. ERDC/CHL SR-06-1. Vicksburg, MS: US Army Engineer Research and Development Center.

Jafarov, E. E., S. S. Marchenko, and V. E. Romanovsky. 2012. *Numerical modeling of permafrost dynamics in Alaska using a high spatial resolution dataset*. The Cryosphere Discuss., 6, 89–124, 2012. www.the-cryosphere-discuss.net/6/89/2012/, doi:10.5194/tcd-6-89-2012.

Marchenko, S., V. Romanovsky, and G. Tipenko. 2008. *Numerical modeling of spatial permafrost dynamics in Alaska*. In, *Proceedings of the Eighth International Conference on Permafrost*. 190–204, Willey, , Fairbanks, AK: Institute of Northern Engineering, University of Alaska. 2008. 91, 95.

Nicolsky, D. J., V. E. Romanovsky, and G. S. Tipenko. 2007. "Using in-situ temperature measurements to estimate saturated soil thermal properties by solving a sequence of optimization problems." *The Cryosphere* (1): 41–58. doi:10.5194/tc-1-41-2007, 2007. 93, 95, 98.

Ogden, F. L., N. R. Pradhan, C. W. Downer, and J. A. Zahner. 2011. "Relative importance of impervious area, drainage density, width function, and sub-surface storm drainage on flood runoff from an urbanized catchment." *Water Resources Research* (47): W12503. doi: 10.1029/2011WR010550.

Pradhan, N. R., F. L. Ogden, and C. W. Downer. 2009. Uncertainty in tile drain locations: implications for hydrologic modeling of agricultural watersheds. Transactions of the American Geophysical Union, 90, 52.

Pradhan, N. R., C. W. Downer., S. Marchenko,, A. Liljedahl, , T. A. Douglas, and A. Byrd. 2013. *Development of a Coupled Framework for Simulating*

Interactive Effects of Frozen Soil and Hydrological Dynamics in Permafrost Regions. 2013. Technical Report ERDC TR-13-15.Vicksburg, MS: US Army Engineer Research and Development Center.

Richards, L. A. 1931. Capillary conduction of liquids in porous mediums. *Physics* (1): 318-333.

Sergueev, D., G. Tipenko, V. Romanovsky, and N. Romanovskii. 2003. *Mountain permafrost thickness evolution under the influence of long-term climate fluctuations (results from numerical simulation)*: In 8th International Conference on Permafrost, edited by Swets & Zeitlinger: Lisse, Z., edited by Phillips, M., Springmanm S., and Arenson, L., 1017–1021, 2003. 94, 95.

Verdi, C. 1994. “Numerical aspects of parabolic free boundary and hysteresis problems.” *Lecture Notes in Mathematics.* New York: Springer-Verlag, 213-284.