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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

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Abstract

Climate warming is expected to degrade permafrost in many regions of the world. Degradation of permafrost has the potential to 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. Such a coupled framework was developed to explicitly simulate the soil moisture effects of soil thermal conductivity and heat capacity and its effects on hydrological response. In the coupled framework, the 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 with the GIPL scheme that simulates soil temperature dynamics and the depth of seasonal freezing and thawing by numerically solving a one-dimensional quasilinear heat equation with phase change. All the GIPL input and output parameters and the state variables are set up to be consistent with the GSSHA input-output format and grid distribution data input requirements. Test-case simulated results showed that freezing temperatures reduced soil storage capacity, thereby producing higher peak and lower base flow. The report details the functions and format of required input variables and cards, as a guideline, in GSSHA hydrothermal analysis of frozen soils in permafrost-active areas.

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Preface

This study was performed for the US Army Engineer Research and Development Center (ERDC) through the Strategic Environmental Research and Development Program, under Project Number 11 SI01-016, Addressing the Impacts of Climate Change on US Army Alaska with Decision Support Tools Developed through Field Work and Modelling, under Program Element No. 622182; Project No. CX3. Continuation and enhancement of this work is supported by Intelligent Environmental Battlespace Awareness under Department of Defense Research, Development, Test, and Evaluation 6.2 Applied Research program.

The work was performed by the Hydrologic Systems Branch of the Flood and Storm Protection Division, ERDC Coastal and Hydraulics Laboratory (CHL). At the time of publication of this report, Dr. Hwai-Ping Cheng was the branch chief; Mr. David May was the division chief; and Dr. Julie Rosati was the technical director for Civil Works Research and Development. The deputy director of ERDC-CHL was Mr. Keith W. Flowers, and the director was Dr. Ty V. Wamsley.

The commander of ERDC was COL Christian Patterson, and the director was Dr. David W. Pittman.

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1 Introduction

1.1 Background

Both the Intergovernmental Panel on Climate Change latest full assessment (IPCC 2014) and the US National Climate Assessment (USGCRP 2017) unequivocally state that climate change is occurring due to anthropogenic factors, that significant warming has already occurred, and that both data trends and climate modeling indicate that climate change and the problems associated with climate change will only worsen in the future.

One of the many issues related to climate change is how it directly affects soil temperature and trends in soil temperature. After analyzing 50 yr* of soil temperature profile data at 5, 10, 20, 50, 100, and 150 cm depths across Canada, Qian et al. (2011) found a soil temperature warming trend of +0.30°C/decade. Warming was especially prevalent during spring. Qian et al. (2011) also found that the increasing trend of soil temperature was directly associated with the increasing trends in air temperature. A change in soil temperature has a determinative role on the response of biochemical processes that control the soil biological cycle of plant nutrient and carbon use and production (Schipper et al. 2014). An increasing trend in the soil temperature has a key role on the emission of greenhouse gases in Alaska and other arctic and subarctic ecosystems (Zhuang et al. 2007; Davidson et al. 2006). Melvin et al. (2017) showed widespread damages to Alaska public infrastructure from increased soil temperature due to climate change.

Seasonal changes in air temperature have led to analogous changes in the soil thermal regime, thereby affecting the hydrological response (ICAT 2017; Dunne and Black 1971). Plot-scale studies by Dunne and Black (1971), and Stähli et al. (1999) showed that storm-runoff generation processes of a watershed are altered as the soil water phase transitions from a nonfrozen state to a freezing state with reduced infiltration and enhanced runoff. Without physical processes that explicitly simulate such seasonal changes in hydrological regime, calibrated parameter values

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* For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-252, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

alone may not be sufficient to simulate the rainfall-runoff response, especially in a long-term numerical simulation of projected future global warming scenarios in higher latitude regions (ICAT 2017). Note that the freezing condition is highly variable in space and time (Stähli 2017), which a simple conceptual model, or even a physics-based numerical model lacking the required process, may fail to account for the complexities of the freezing condition. To fully analyze the effects of climate change on soil thermal dynamics, as well as associated hydrologic response for the future climate change scenarios on the response of watersheds with permafrost and a seasonally frozen soil regime, an understanding and application of soil thermal dynamics interaction with soil hydrological dynamics are required.

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, the interaction of soil thermal state and hydrological dynamics is important to consider. Thus, a coupled framework was developed to model interactive effects of soil thermal and hydrological dynamics. A previous coupling framework, such as coupling of subsurface storm drainage (Ogden et al. 2011) and tile drains (Pradhan et al. 2009) in Gridded Surface Subsurface Hydrologic Analysis (GSSHA) (Downer and Ogden 2006), has demonstrated GSSHA's ability to simulate important surface and subsurface runoff generation processes and to represent explicitly fully coupled hydrodynamics. The GSSHA model is also coupled with a thermodynamic model (Pradhan et al. 2013; Pradhan et. al. 2020), namely 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. GSSHA model is a spatially explicit hydrologic model that simulates 2D overland flow, 1D infiltration, 2D groundwater flow, and 1D flow in stream networks, all fully coupled.

1.2 Objective

The purpose of this document is to describe how to use the GIPL model as implemented in GSSHA to simulate soil hydrothermal dynamics in permafrost active areas. In this report, the functioning of the GIPL model will be described as it pertains to developing inputs for the model to simulate permafrost effects on heat transfer and soil physical properties.

Numerical considerations in the use of the model will be discussed, the model inputs in detail will be described, and example problems with complete inputs to illustrate the points will be provided.

1.3 Approach

Details of the theoretical background on coupling and linking of the GIPL model and GSSHA are described in Pradhan et al. (2013). Pradhan et al. (2019) shows the details of the implementation of the coupled model in the headwaters of the subcatchment, 0.2 km^2, of the Caribou Poker Creek Research Watershed, located 48 km north of Fairbanks 65°10′ N, 147°30′ W Alaska. To present a guideline on hydrological dynamics in seasonal freezing and thawing cycles, numerical considerations in the use of the linked models will be discussed, the model inputs in detail will be described, and example problems from the above-mentioned publications will be provided (Pradhan et al. 2013; Pradhan et. al. 2020).

The GIPL model is a stand-alone permafrost model that computes a 1D (vertical) soil temperature profile over time using static values of soil moisture at daily intervals. As implemented in GSSHA, GIPL is a subroutine that computes 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, several tasks were performed:

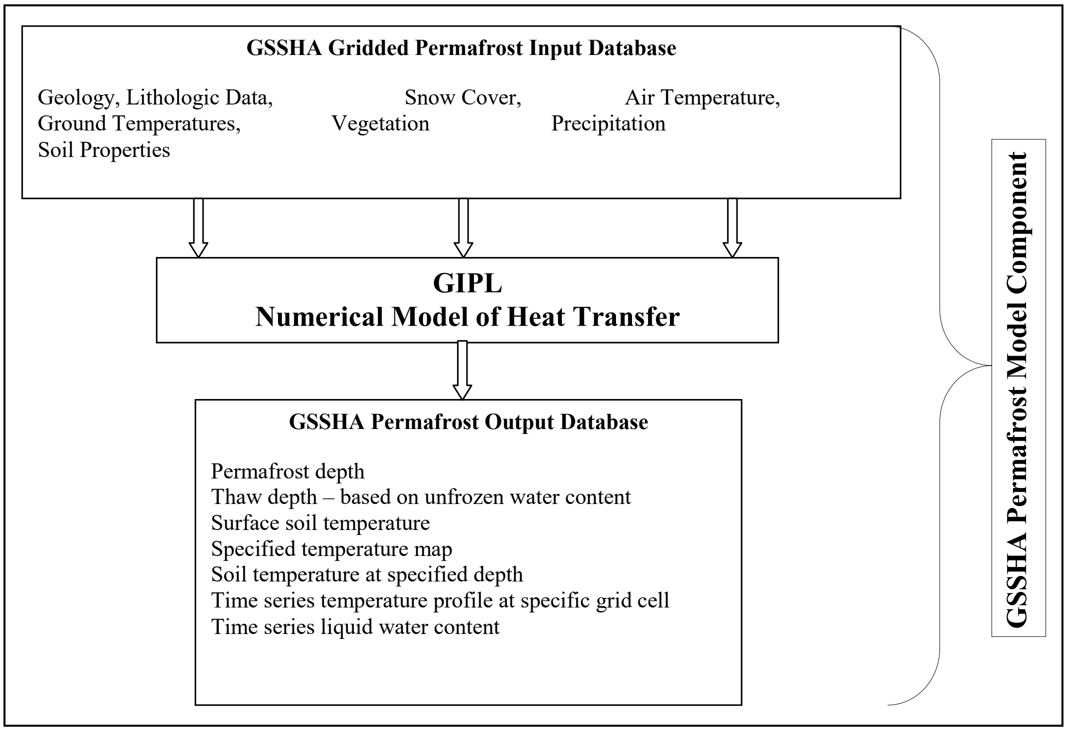
1. The original GIPL permafrost model was converted from FORTRAN to C and C++ source code.
2. Originally, GIPL parameters were 1D in the soil's vertical profile but are lumped into the horizontal spatial extent of application. Significant effort was expended to make all the GIPL state variables and parameters horizontally distributed as grid based or permafrost soil type based before merging the C and C++ version of GIPL into GSSHA. Thus, the 1D limitations of GIPL are enhanced into multidimensional distributed applicability in the GSSHA distributed modeling framework.
3. Originally, the GIPL numerical model of heat transport used daily or larger time-steps. As implemented in GSSHA, GIPL can have any time-step, as specified by the user. The default time-step is the infiltration time-step, which is now on the order of seconds or minutes.

Several thermohydrodynamic 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 the saturated and unsaturated permafrost layer. Details on linking GIPL and GSSHA in the coupled framework are in Pradhan et. al. (2013). The following links between GIPL and GSSHA thermohydrodynamic formulations are implemented to exchange the information between GIPL and GSSHA:

- Linking GIPL and GSSHA computational nodes
- Linking GIPL soil thermodynamics with GSSHA soil moisture hydrodynamics
- Linking GIPL soil temperature and GSSHA hydraulic conductivity
- Linking soil heat transfer effect on effective groundwater transmissivity

The spatial variability of land-surface and hydrodynamic parameters, including subsurface soil moisture state, are 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 are provided in Pradhan et al. (2013) and Pradhan et. al. (2020).

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



2 Use Guidelines for Permafrost Modeling in Gridded Surface Subsurface Hydrologic Analysis (GSSHA)

General use guidelines of GSSHA are in the GSSHA wiki: http://gsshawiki.com/gssha/Main_Page. The use guidelines in this document pertain to GSSHA watershed hydrologic modeling that includes a soil thermodynamics process component.

Along with the typical files associated with the GSSHA project, there are two additional files needed to run a GIPL-coupled simulation (Table 1).

Table 1. Permafrost-related files needed for a GIPL-coupled simulation.

File	Value	Specified in the …	Description
Permafrost Mask	Filename–*.pbd	GSSHA Project File (*.prj)	File containing permafrost mask map information.
Permafrost Parameter Index Map	Filename–*.idx	Mapping Table File (*.cmt)	File containing index values related to the thermodynamics parameters.

The use of these files is described in the following sections.

2.1 Project File

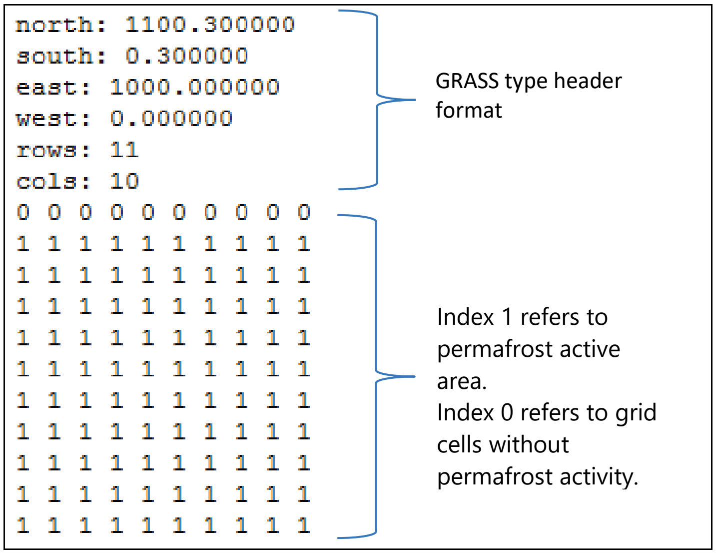
In GSSHA, the model simulation is controlled by a card-based file called the project file (extension .prj). Model instruction cards and some parametric values are contained in the project file. The card PERMAFROST_GIPL (Table 2) is required in the project file for any GIPL-coupled simulation.

Table 2. Card required in the project file for specifying a GIPL simulation.

Card	Value	Description
PERMAFROST_GIPL	Filename–*.pbd	File containing permafrost mask map information.
MULTI_LAYER_INFIL_GIPL	—	Flag for the multilayer thermodynamics option. No value is required.

The permafrost mask file, with the suggested filename extension .pbd, defines the boundary of the permafrost active zone. More than one zone can be defined within the mask file. In the mask file, cells intended to be part of the permafrost thermodynamic numerical calculation active zone(s) are assigned the value 1, and cells outside the zone(s) are assigned 0, as shown in Figure 2. Any heat-transfer numerical solution is limited to within the active zone.

Figure 2. Permafrost mask index map.



```
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 permafrost active area.
Index 0 refers to grid cells without permafrost activity.

If it is desired that the thermodynamic numerical calculations are multilayer, the project file must also contain the MULTI_LAYER_INFIL_GIPL card. This card (Table 2) specifies the use of multilayered thermal dynamic (Alexiades and Solomon 1993; Verdi 1994) and hydrodynamic simulation (Downer and Ogden 2004; Richards 1931) in the soil profile. This user guideline is based on the tests and verifications of the coupled numerical model of phase change and the Richards numerical soil moisture model (Pradhan 2013; Pradhan 2019).

Table 3 shows additional cards that can be used to provide optional functionality for the GIPL routine.

Table 3. Optional cards.

Card	Value	Description
GIPL_TIMESTEP	Numerical value	GSSHA permafrost model user-defined numerical heat transfer time-step in seconds. If the card GIPL_TIMESTEP is not used, the GSSHA model time-step is used as default for numerical heat transfer calculation.
OUT_GIPL_TEMP	Filename–*.tgi	Name of the file to which to write the output time series of soil temperature—at location xyz.

The card GIPL_TIMESTEP can be used to specify a unique time-step for use with the GIPL routines. If the card GIPL_TIMESTEP is not used, the GSSHA model time-step is used as default for numerical heat transfer calculation.

2.2 Mapping Table File

Most parametric values for a GSSHA model are specified in the mapping table file (extension .cmt). If the project file contains the PERMAFROST_GIPL card, the mapping table file must contain the following:

- In the GSSHA_INDEX_MAP_TABLES section, a reference to a permafrost index map file, along with a corresponding index map label is included.
- In the parameter mapping section, the permafrost zone parameters are specified as declared by the card shown in Table 4.

Table 4. Card required for GIPL grid-based parameter input in the mapping table.

Card	Value	Description
PERMAFROST_LAYER_SOIL	The label associated with the permafrost index map.	This card uses the label that was assigned to the permafrost index map in the GSSHA_INDEX_MAP_TABLES section.

In the following example from the GSSHA mapping table file, *perma* is a label that is used to refer to the index map file permafrost.idx via the PERMAFROST_LAYER_SOIL card.

```
INDEX_MAP    “permafrost.idx” “perma”
```

The PERMAFROST_LAYER_SOIL card in the mapping table file appears below the index maps section and creates the parameter-mapping section that contains the thermodynamic parameter values:

```
PERMAFROST_LAYER_SOIL "perma"
```

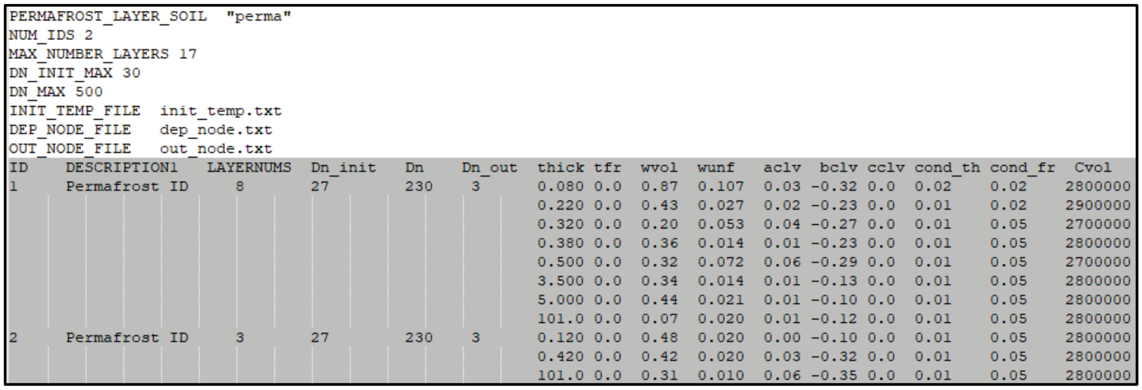
Following the PERMAFROST_LAYER_SOIL card in the mapping table file is a series of other cards that assign the thermodynamics parameters, as shown in Table 5.

Table 5. Permafrost mapping table inputs referencing thermodynamic data following the PERMAFROST_LAYER_SOIL card.

Card	Value	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
INIT_TEMP_FILE	Filename–*.txt	Model Input: Initial temperature of soil profile. Format: Each soil ID number followed by the depth and temperature for that soil ID.
DEP_NODE_FILE	Filename–*.txt	Model Input: Computational node depth file. Format: Each soil ID number followed by the computational node depth for that soil ID.
OUT_NODE_FILE	Filename–*.txt	Model Output: Time series state variable node depth. Format: Each row and column followed by the computational node depth(s) for that grid.

Table 5 provides details on parametric value input. An example of the format for the multilayer parameters is shown in the text with gray background in Figure 3. The text without the gray background in Figure 3 is the input format for the content described in Table 4 and Table 5.

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
```

A description of items in Figure 3 is in Table 6.

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}

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 (W m^{-1} k^{-1})
Clay	0.5−3.1
Silt	0.8−2.4
Peat	0.05−0.9
Sandstone	0.5−4.2

Table 7 (cont.). Thermal conductivity parametric value range.

Soil Type	Thermal Conductivity Range (W m^{-1} k^{-1})
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

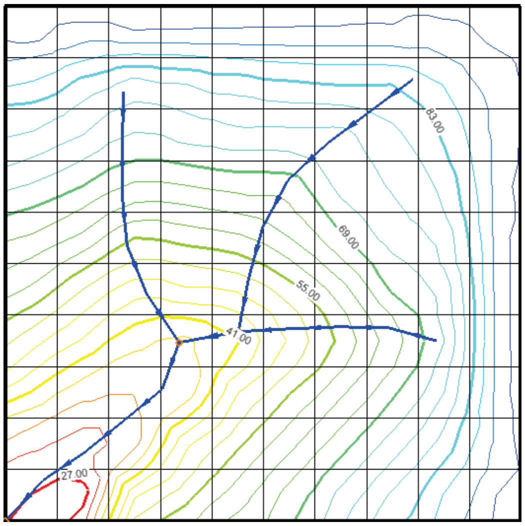
2.3 Illustration of Permafrost Modeling in GSSHA

The example in this section illustrates modeling 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 and subsurface runoff where infiltration and groundwater components are turned on. The soil moisture and soil physical state are defined by the Richards Equation.

2.3.1 Test Model

Figure 4 shows the test case example model having 10 × 10 grid of cells within the watershed.

Figure 4. Test case 10 × 10 example project of coupled GSSHA and GIPL where the permafrost parametric values represent woodland and tundra ecosystem sites in permafrost active Alaskan regions.



2.3.2 Cards and Index Maps

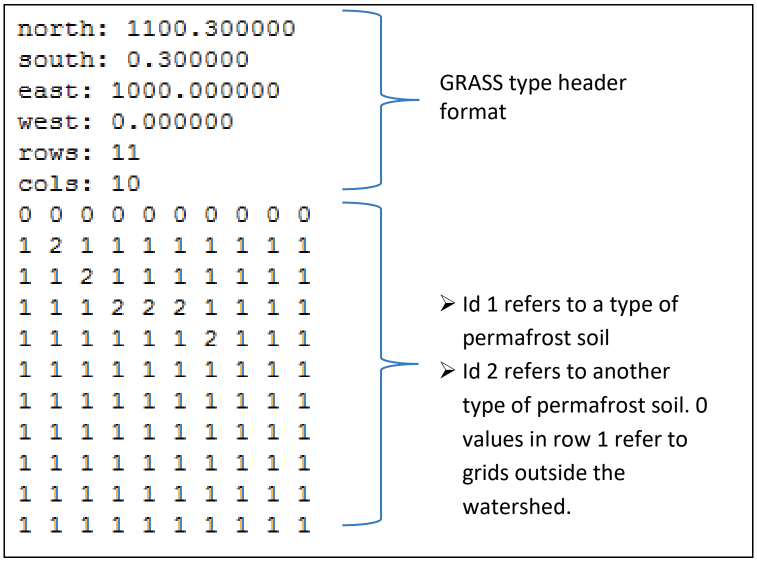
The following cards are included in the GSSHA project file:

```
PERMAFROST.          "permabound.pbd"
GIPL_TIMESTEP.       900.
OUT_GIPL_TEMP.       temp_out.gip
```

Figure 2 is an example of the permabound.pbd file where index 1 refers to the active permafrost portion of the grid. The time-step is 900 sec.

Figure 5 is an example of a permafrost soil index map indicated in the GSSHA mapping table file as defined in Table 4. In this permafrost soil index map, index greater than 0 refers to a soil type with a set of physical properties as defined in Figure 3 and Table 6.

Figure 5. Permafrost soil index map.



```
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
```

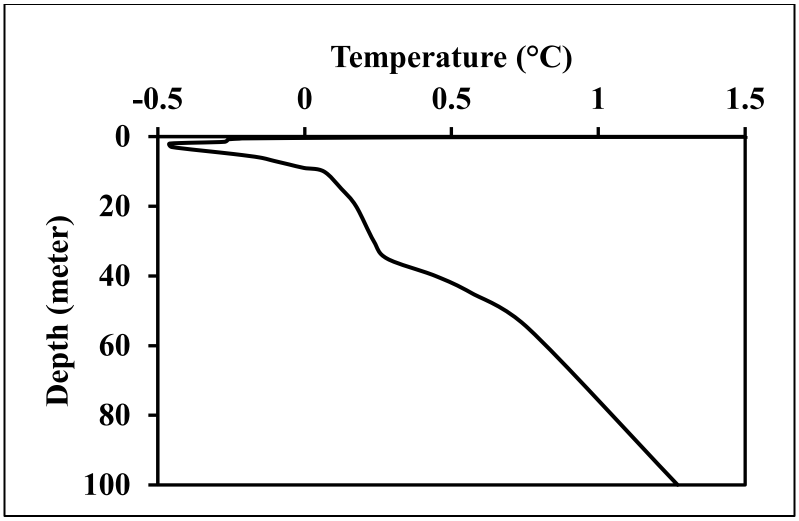
GRASS type header format

- Id 1 refers to a type of permafrost soil
- Id 2 refers to another type of permafrost soil. 0 values in row 1 refer to grids outside the watershed.

2.3.3 Initial Condition

The numerical solution of the soil thermal state using quasilinear heat conductive equation (Sergueev et al. 2003; Pradhan et al. 2019) requires an initial condition. Figure 6 shows the initial temperature condition which is from an Alaskan permafrost site consisting of woodland and tundra. The initial condition data are in the file *.txt as indicated by the card INIT_TEMP_FILE in Table 5.

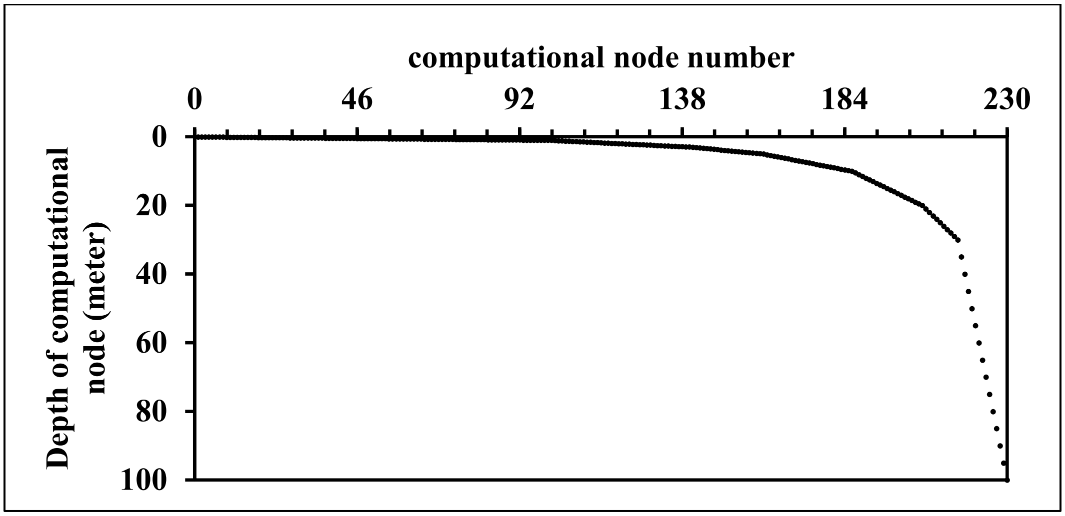
Figure 6. Soil temperature profile as an initial condition for the thermodynamics numerical simulation.



2.3.4 Soil Temperature and Soil Water Computational Nodes

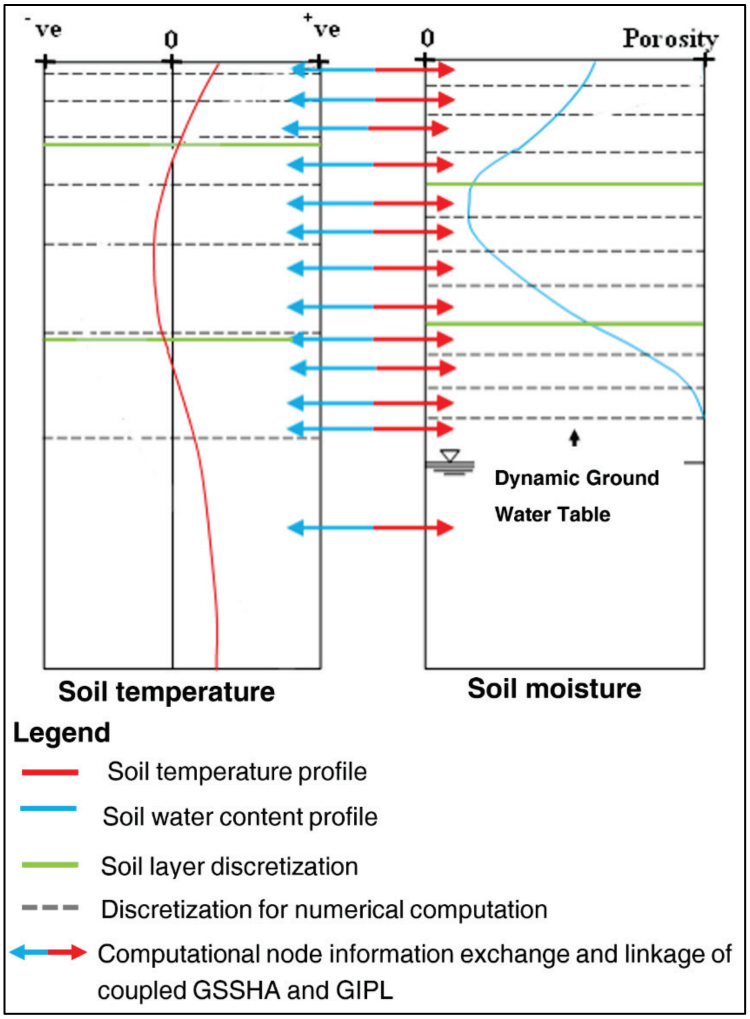
The computational node depth data of Figure 7 is in the file "*.txt" indicated by the card DEP_NODE_FILE as specified in Table 5 and is an input requirement. This figure shows the depths (location address in the vertical soil profile) for the computation nodal points.

Figure 7. Depth information of the computational nodal number.



The numerical model of phase change is used to compute a vertical soil temperature profile using the soil moisture information from the Richards equation solver; the soil moisture numerical model, in turn, uses this temperature and phase information to update hydraulic conductivities in the vertical soil moisture profile. The computational nodal points are the locations where this information is exchanged and is shown by the *blue* and *red arrows* in Figure 8.

Figure 8. Thermodynamics coupling into the hydrodynamics.



The solution domain of the GIPL soil temperature model overlaps in a somewhat complex manner with both the saturated and unsaturated soil water movement domains in GSSHA. If there is a no-flux lower GIPL boundary condition, constant geothermal heat at the lower boundary, the GIPL domain must extend very deep into the soil, as much as 1000 m, or more.

In GSSHA, only the surficial aquifer is simulated, so the saturated groundwater domain is down to the first confining layer in the subsurface. This is typically on the order of a few meters to hundreds of meters deep. The unsaturated zone domain is any soil above the saturated zone. The unsaturated domain is dynamic in both space and time and can vary from no domain (groundwater table is at or above the soil surface) to the depth of the surficial aquifer, depending on groundwater conditions. The unsaturated zone is further divided into soil horizons, as well as the deeper groundwater media as shown in Figure 8. A soil horizon is a layer having different physical, chemical, or biological characteristics from the layers above and beneath. In Figure 8, soil horizons for thermodynamic and hydrodynamic process may be the same or different as per the significance of the physical, chemical, and biological characteristics for individual process.

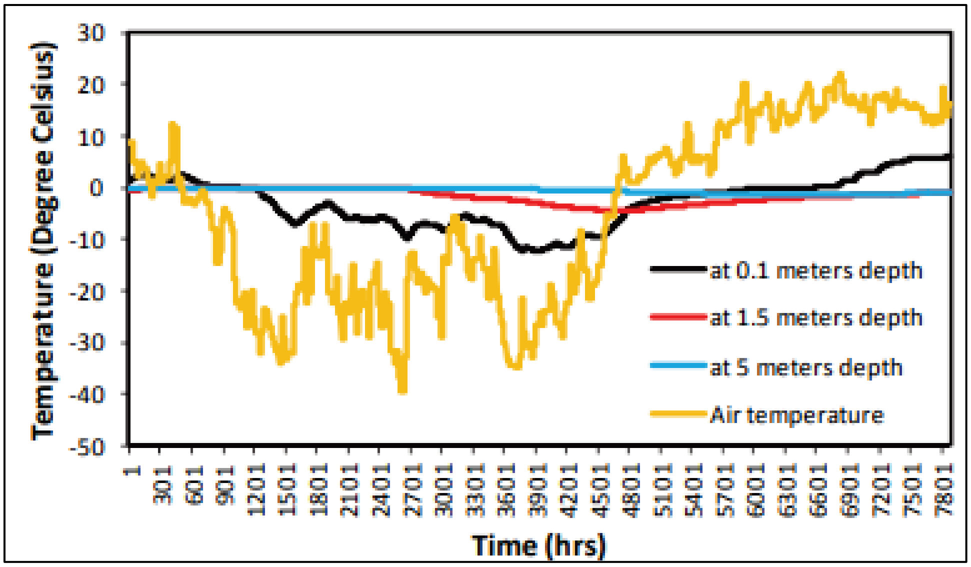
Because of the differences in domains, and requirements for solution, in the coupled framework, the GIPL domain and discretization are independent of the saturated and unsaturated soil water domains and discretizations. The linkage of computational nodal discretized information from GIPL to GSSHA and vice versa is shown in Figure 8.

2.3.5 Results

Once the long-term GSSHA simulation run in continuous long-term mode (Section 2.3.6) is complete, the time series of soil profile temperature output is found in the file defined next to the card OUT_GIPL_TEMP, as specified in Table 3. Locations at depths of the temperature output is defined in the file defined next to the card OUT_NODE_FILE specified in Table 5.

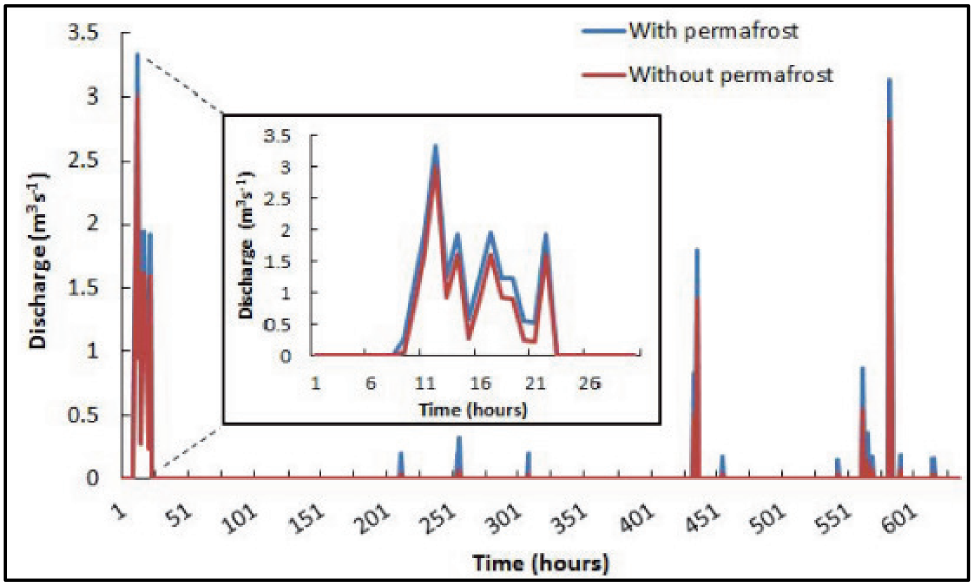
Figure 9 shows the soil temperature at various depths and that the air temperature has the most significant influence in the near surface soil layer. As the soil layer depth increases, air temperature influence in soil thermodynamics is diminished along with the increase in the time lag. The figure also shows the soil temperature dynamics and informs about the depth of seasonal freezing and thawing.

Figure 9. Time series of temperature at various depths.



Stream response to storms differs for permafrost-free and permafrost-affected slopes. Stream flow from watersheds underlain with a large proportion of permafrost responds rapidly to precipitation, with rapid rising and falling limbs of the stream hydrographs (Quinton and Carey 2008). The hydrograph simulation result of the example hydrological model with permafrost (Figure 10) has larger peak flows than the hydrograph without permafrost. In contrast, for streams with little or no permafrost, peak flows are smaller as precipitation can percolate into soil layers resulting in enhanced connectivity between the surface and groundwater storage regimes and more soil pore water storage (Figure 10).

Figure 10. Hydrograph with and without active permafrost.



2.3.6 Discussion

The simulation of soil temperature dynamics and the depth of seasonal freezing and thawing in GSSHA model requires the simulation run in a continuous long-term mode. The long-term continuous mode requires the hydrometeorological inputs that include the air temperature along with other meteorological inputs, which are not discussed in this report. For details of this long-terms simulation in GSSHA it is recommended to go through GSSHAwiki (GSSHA, n.d.). Pradhan et al. (2019) also discuss the long-term simulation parameter inputs for the thermodynamic simulation in GSSHA.

The Richards Equation infiltration process in GSSHA is not discussed in this report. The details of the infiltration process can be found in GSSHAwiki (GSSHA, n.d.). Pradhan et al. (2019) also discuss the infiltration process and the parameter inputs requirements for the thermodynamic simulation in GSSHA.

The illustration of the permafrost modeling in GSSHA in this report is a simple and easy-to-understand modeling materials demonstration solely from the user-guideline point of view. Pradhan et al. (2019) show the details of the real-case thermal hydrodynamic simulation in the headwater subcatchment at the peak of the Caribou Poker Creek Research Watershed, representing the Alaskan permafrost active region. A review of the results from Pradhan et al. (2019) verify that freezing temperatures decrease infiltration and increase overland flow and peak discharges by increasing the soil ice content and lowering the soil hydraulic conductivity value exponentially. Figure 11 and Figure 12 are from Pradhan et al. (2019). Figure 11 shows that runoff with the active permafrost thermodynamics simulation included is significantly higher than that without it. Figure 12*b* shows the verification of the simulated versus observed soil temperature at 10 cm depth Figure 12*b* shows a significant drop in soil temperature reaching to −3.8°C during 19–20 September 2002, resulting in freezing of the soil water content. Because of the frozen soil water content and soil hydraulic conductivity dropping down by orders of magnitude, the thermohydrodynamic model simulation resulted in decreased infiltration as shown in Figure 12*c* and an increase in the runoff as shown in Figure 11. This numerical model’s increased runoff response in freezing soil conditions is the representation of the physical process that influences discharge at a basin under freezing conditions.

Figure 11. Hydrograph with and without active permafrost.

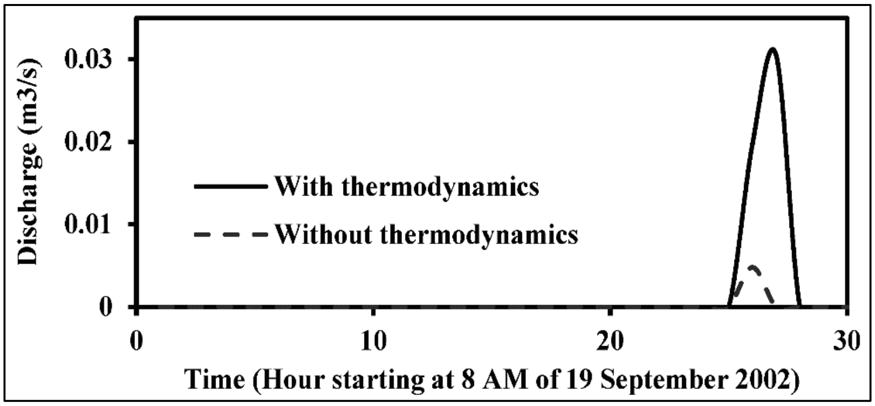
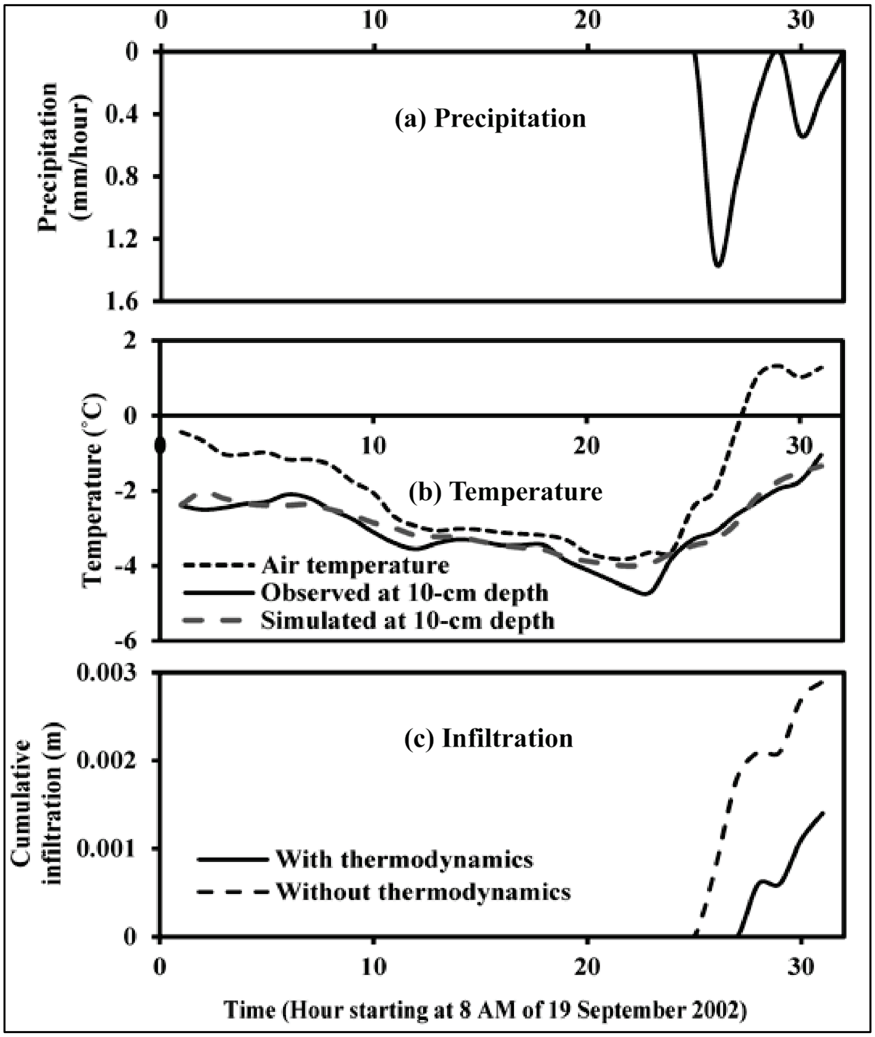


Figure 12. Thermal hydrodynamic simulation in the headwater subcatchment at the peak of the Caribou Poker Creek Research Watershed: (*a*) observed precipitation, (*b*) observed and simulated soil temperature, and (*c*) simulated infiltration with and without soil thermodynamics.



3 Conclusions and Recommendations

This report is an application guideline for implementing GSSHA hydrologic simulation in permafrost active areas. Details of the theoretical guideline of linking GIPL and GSSHA thermohydrodynamic information are provided in Pradhan et al. (2013, 2019).

3.1 Conclusions

The new permafrost heat transfer in GSSHA is computed through a scheme called GIPL that simulates soil temperature dynamics and the depth of seasonal freezing and thawing by numerically solving a 1D quasilinear heat equation with phase change. All the GIPL input parameters are made consistent with the GSSHA input format and data requirements. This report provides a guideline in setting the GIPL parameters and variables along with the GIPL-GSSHA linking variables distributed in each GSSHA simulation distributed grid. Time-series output of thermal dynamic state in a soil column is made accessible as per the requirement of a model user. For the simplicity of understanding for a user of this document, the coupled GSSHA GIPL is demonstrated on a contrived watershed. In addition, the discussion section does provide some real-world thermal hydrodynamic simulation outputs for reference. 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 include vadose zone soil moisture and ice content information feedback and its effects on hydraulic conductivity and transmissivity.

3.2 Recommendations

This document presents the detail guidelines on setting up watershed thermodynamic process parameters and initial conditions. The details of the soil moisture and infiltration hydrodynamics are not presented in this document. For details of the Richards (1931) infiltration process in GSSHA, it is recommended to view the topic on the GSSHAwiki (GSSHA, n.d.). Pradhan et al. (2019) also discuss the infiltration parameter inputs for the thermodynamic simulations in GSSHA. The simulation of soil temperature dynamics and the depth of seasonal freezing and thawing in a GSSHA model requires the simulation to be run in a continuous long-term mode. The long-term continuous mode requires the hydrometeorological inputs that include the air temperature along with other meteorological inputs, which are not discussed in this report. For details of this long-term simulation in GSSHA, it is recommended to go through GSSHAwiki (GSSHA, n.d.). Pradhan et al. (2019) also discuss the long-term simulation parameter inputs for the thermodynamic simulation in GSSHA.

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14. ABSTRACT

Climate warming is expected to degrade permafrost in many regions of the world. Degradation of permafrost has the potential to 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. Such a coupled framework was developed to explicitly simulate the soil moisture effects of soil thermal conductivity and heat capacity and its effects on hydrological response. In the coupled framework, the 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 with the GIPL scheme that simulates soil temperature dynamics and the depth of seasonal freezing and thawing by numerically solving a one-dimensional quasilinear heat equation with phase change. All the GIPL input and output parameters and the state variables are set up to be consistent with the GSSHA input-output format and grid distribution data input requirements. Test-case simulated results showed that freezing temperatures reduced soil storage capacity, thereby producing higher peak and lower base flow. The report details the functions and format of required input variables and cards, as a guideline, in GSSHA hydrothermal analysis of frozen soils in permafrost active areas.

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