Thermal Algorithms in the Water Balance Simulation Model

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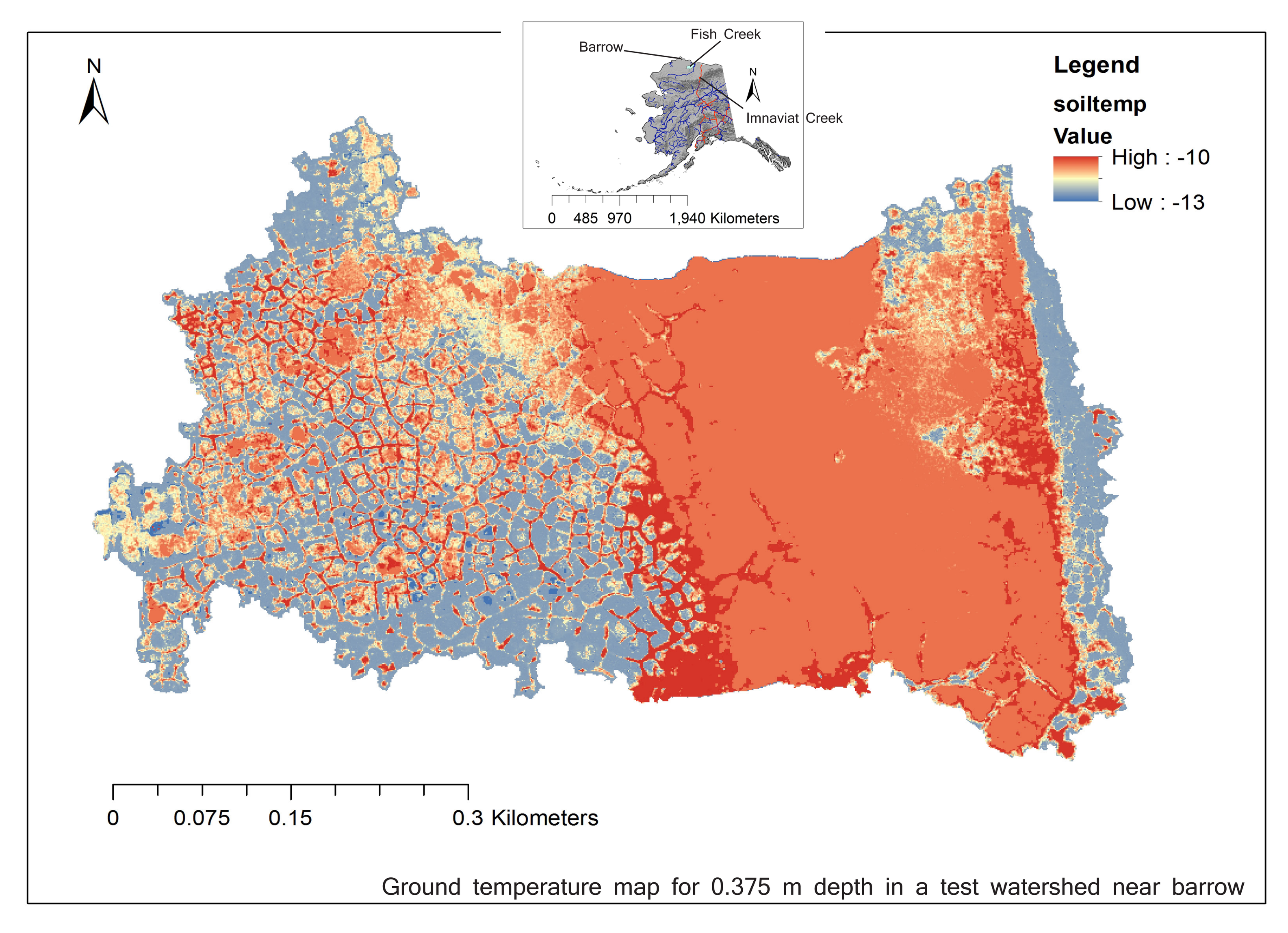
Introduction:

The water balance simulation model (WaSiM) is a well-known hydrological model that has been applied successfully to many catchments. In 2013 in collaboration with the University of Alaska Fairbanks a new heat transfer module was included in the model. This module enables WaSiM to simulate water movement in a dynamic active layer environment, important in Arctic watersheds. In this poster we summarize the details of the thermal model and show preliminary results of simulations across Alaska. Other relevant modules currently included in WaSiM are a dynamic glacier module, an advanced snow accumulation module and various snowmelt routines that are flexible to data availability. WaSiM has strong and efficient hydrological simulation capabilities due to direct coupling in 2-½ D of groundwater and vadose zone water movement by solving the Richard's equation and now it also simulates the ground thermal regime.

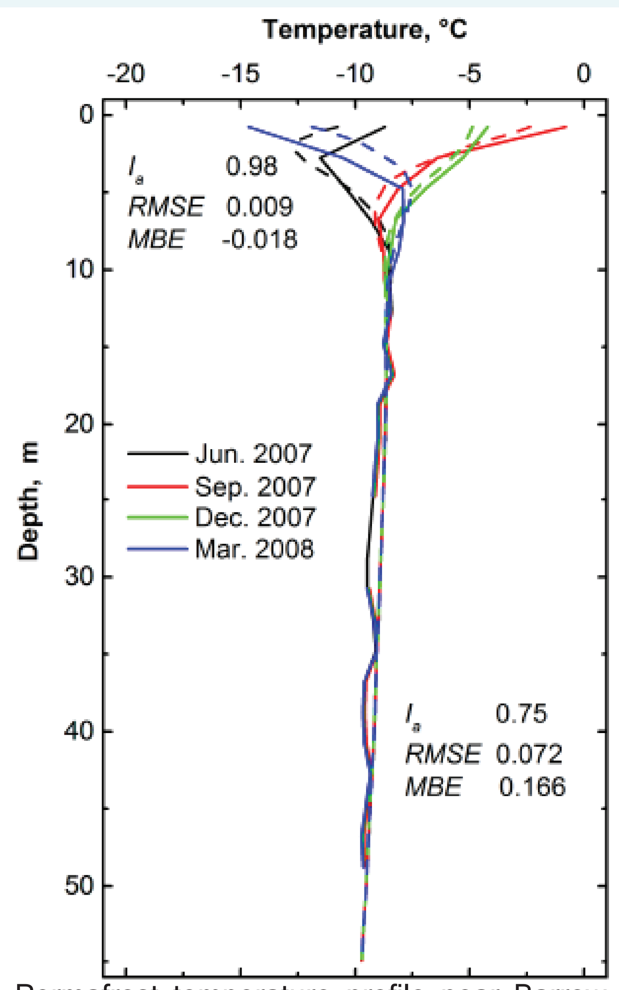
Barrow Simulations:

This study focused on the effects of small scale topography on evapotranspiration from a permafrost watershed (Liljedahl et.al, 2016).

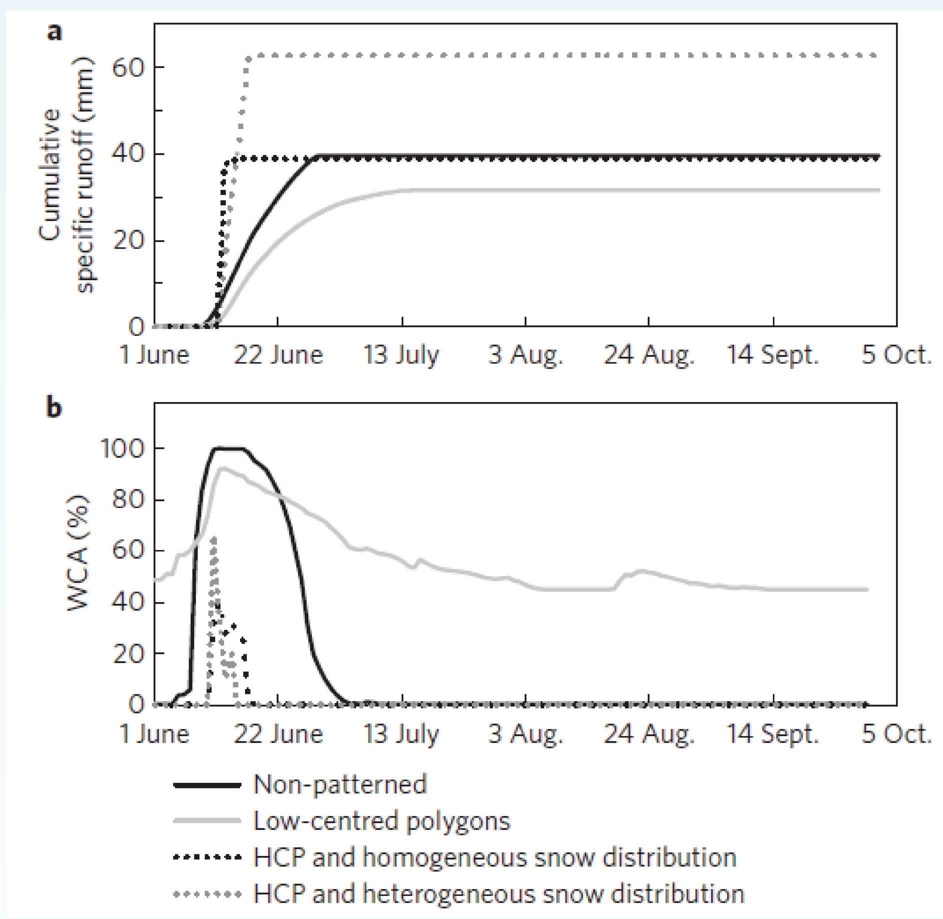
We show here that the model is capable of simulating soil temperature variability based on variable soil water content; results shown are for April 30, 2000. Only two soil types and surface vegetation types were used in this simulation.



Ground temperature map for 0.375 m depth in a test watershed near barrow



Permafrost temperature profile near Barrow



Hydrological response of low versus high centered polygons using and artificially created watershed.

Thermal Algorithms:

The heat transfer module solves Fourier's Law for heat conduction with convection. Heat capacity and thermal diffusion are calculated based on typical soil properties in the unfrozen and frozen states. Phase change is accounted for by calculating the change in liquid water content with the change in temperature. We use the unsaturated water characteristic curve, the freezing temperature and the Clapeyron equation to calculate the unfrozen water characteristic. In WaSiM this curve is based on Mualem's equation described by Van Genuchten (Schulla, 2015).

$$S_E = \left(\frac{1}{1+\left(\alpha\cdot|f\cdot T_{eff}|\right)^n}\right)^m \quad \text{for } T\le 0\,°C$$
$$S_E = 1 \quad \text{for } T>0\,°C \qquad (1)$$
$$\text{with } T_{eff} = \left(T+\min\left(\frac{h(\Theta)}{f},|T|\right)\right)$$

In theory f is 122 m/C°, however we leave it up to the user to decide if this value fits observations; new research suggests this value is soil dependent (Darrow, Pers. Comm.). We recommend users maintain the Van Genuchten parameters $alpha, n$ and m. from the soil moisture characteristic curve.

The apparent heat capacity for the soil is corrected for the latent heat of fusion by:

$$\frac{\partial E}{\partial T} = L_f\cdot\rho_l\cdot(\Theta_{act}-\Theta_r)\cdot m\cdot n\cdot\alpha\cdot f\cdot\left(-\alpha\cdot f\cdot T_{eff}\right)^{(n-1)}\cdot\left(1+\left(-\alpha\cdot f\cdot T_{eff}\right)^n\right)^{(-m-1)} \qquad (2)$$

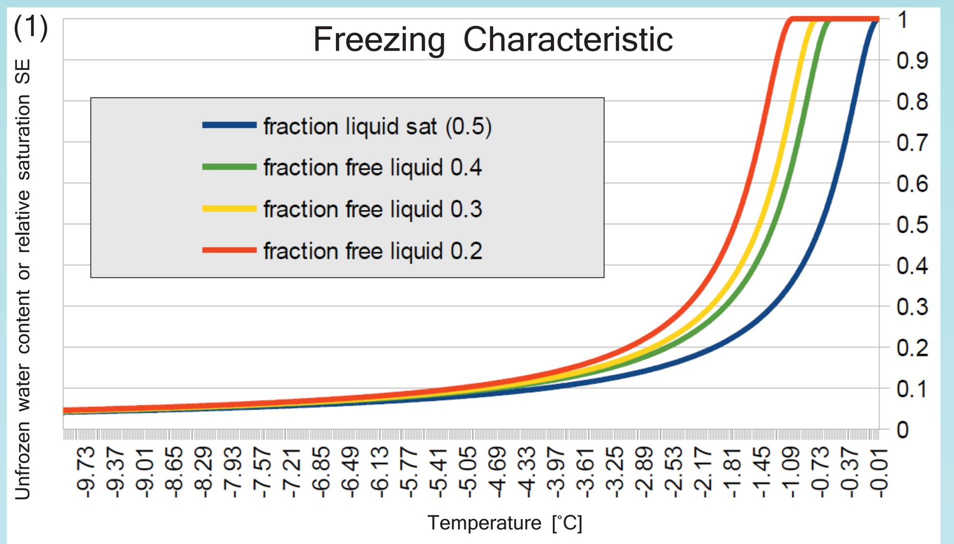
Thermal conductivity is calculated based on the amount of water and ice present in dry soil.

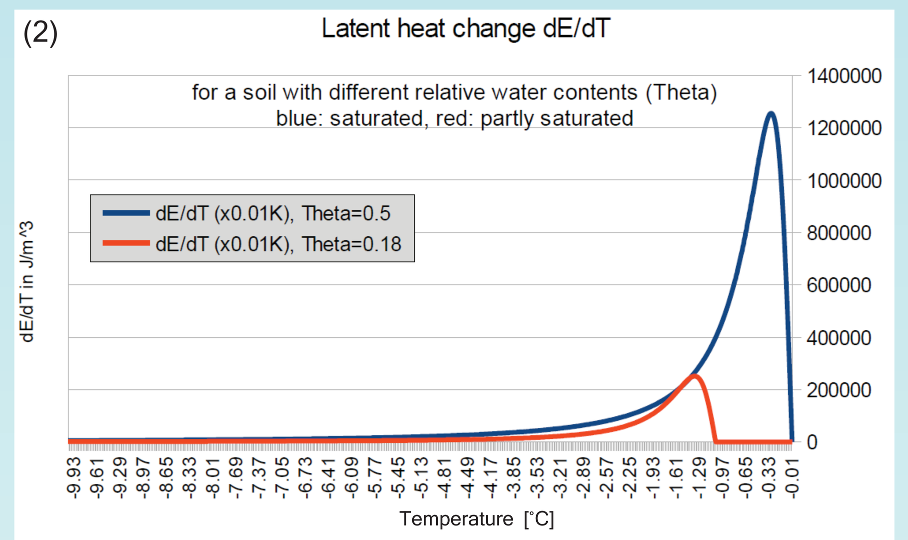
$$\lambda_{eff} = (\varphi-\Theta)\cdot\lambda_a + (\Theta+\theta_{ds})\cdot\lambda_{ds}^{\theta_{ds}/(\Theta+\theta_{ds})}\cdot\lambda_l^{\theta_l/(\Theta+\theta_{ds})}\cdot\lambda_{ice}^{\theta_{ice}/(\Theta+\theta_{ds})} \qquad (3)$$

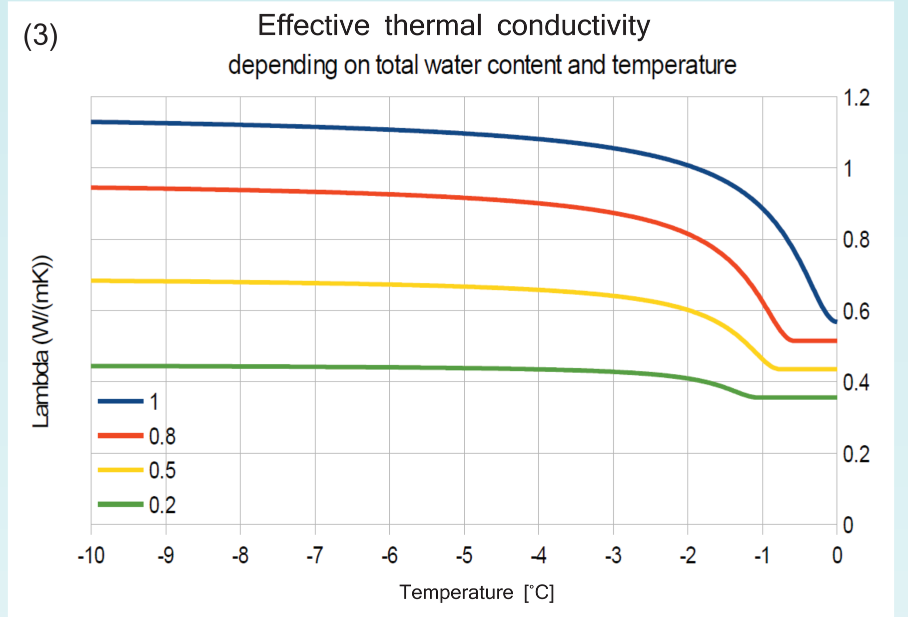
where λ_{eff} is the effective thermal conductivity in J/(m·s·K); φ is the porosity, Θ is the total water content (ice and water), λ_a, ds, l, ice is the thermal conductivity of air, dry soil, liquid water and ice, θ ds, l, ice is the dry soil, liquid water and ice content as relative volume fractions. (the default value of λa is set to 0.0262 J/(m·s·K), λ_{ds} = 0.58 J/(m·s·K), λ_l = 0.5562 J/(m·s·K) and λ_{ice} = 2.33 J/(m·s·K).) θ_l is expressed by SE·Θ (liquid fraction on water content or unfrozen soil water) and θ_{ice} = (1-SE)·Θ.

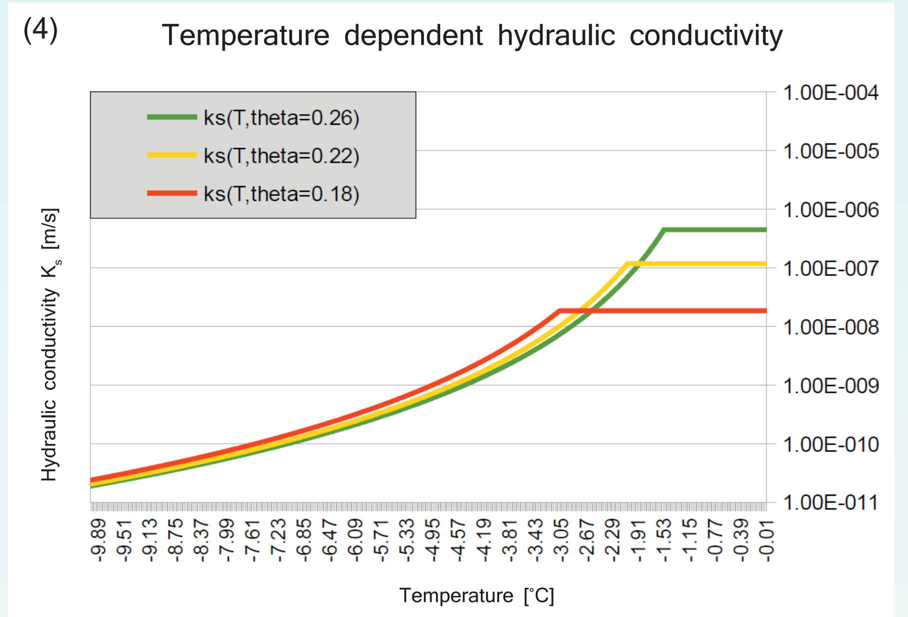
The hydraulic conductivity is the same as the unsaturated hydraulic conductivity which is automatically corrected for the amount of ice blocking the pores. The saturation for the Richards equation is the total water saturation, in contrast to the saturation based on the freezing temperature, which is based on only the liquid water portion.

$$k(T,S_{min}) = k_{sat}\cdot k_{rel}(T,S_{min})$$
$$k_{rel}(T,S_{min}) = S_{min}^{0.5}\cdot\left(1-\left(1-S_{min}^{1/m}\right)^m\right)^2 \qquad (4)$$
$$\text{with } S_{min} = \min(S_E,S_R) \quad \text{and} \quad S_R = (\Theta_{sat}-\Theta_{res})/(\Theta_{act}-\Theta_{res})$$





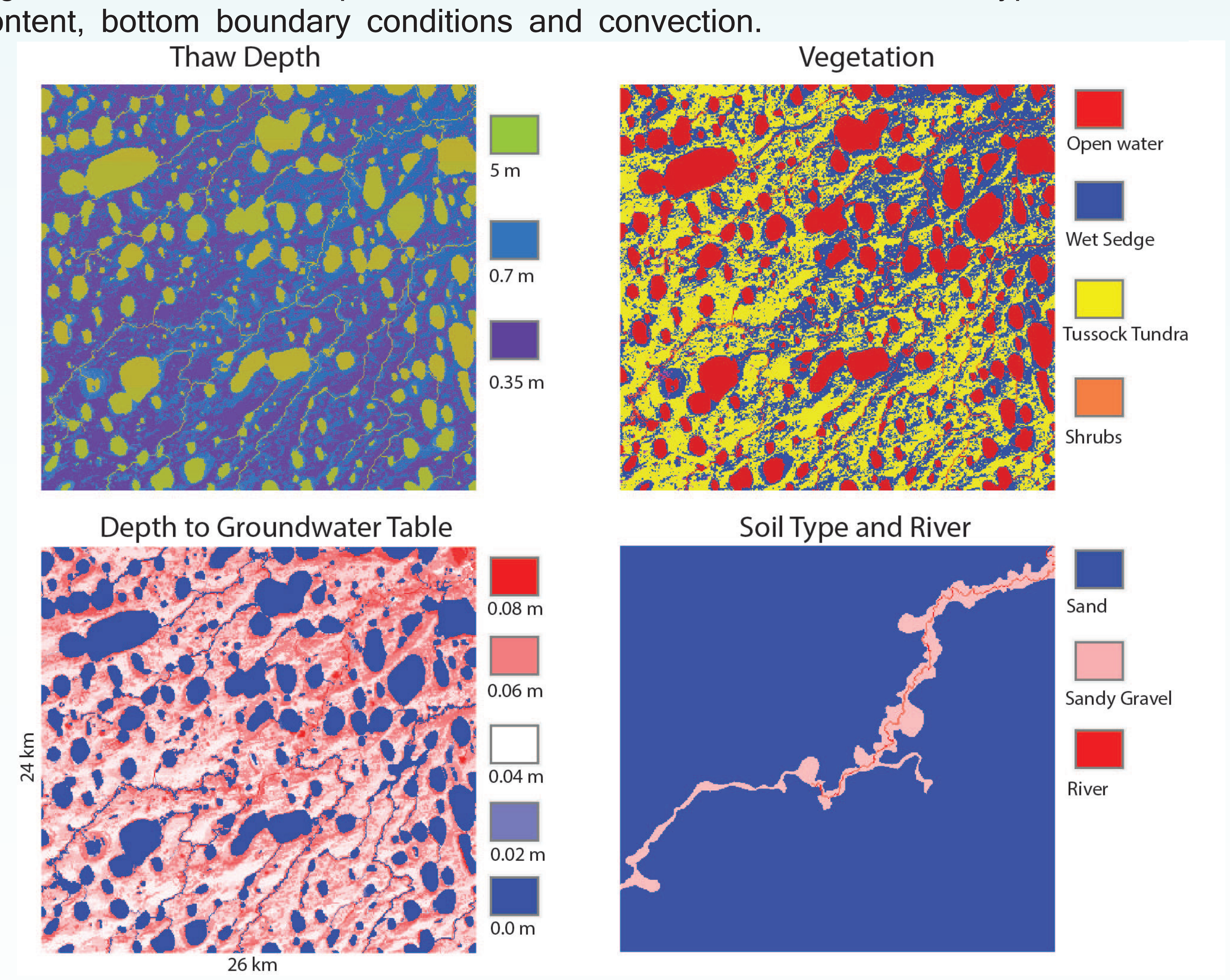




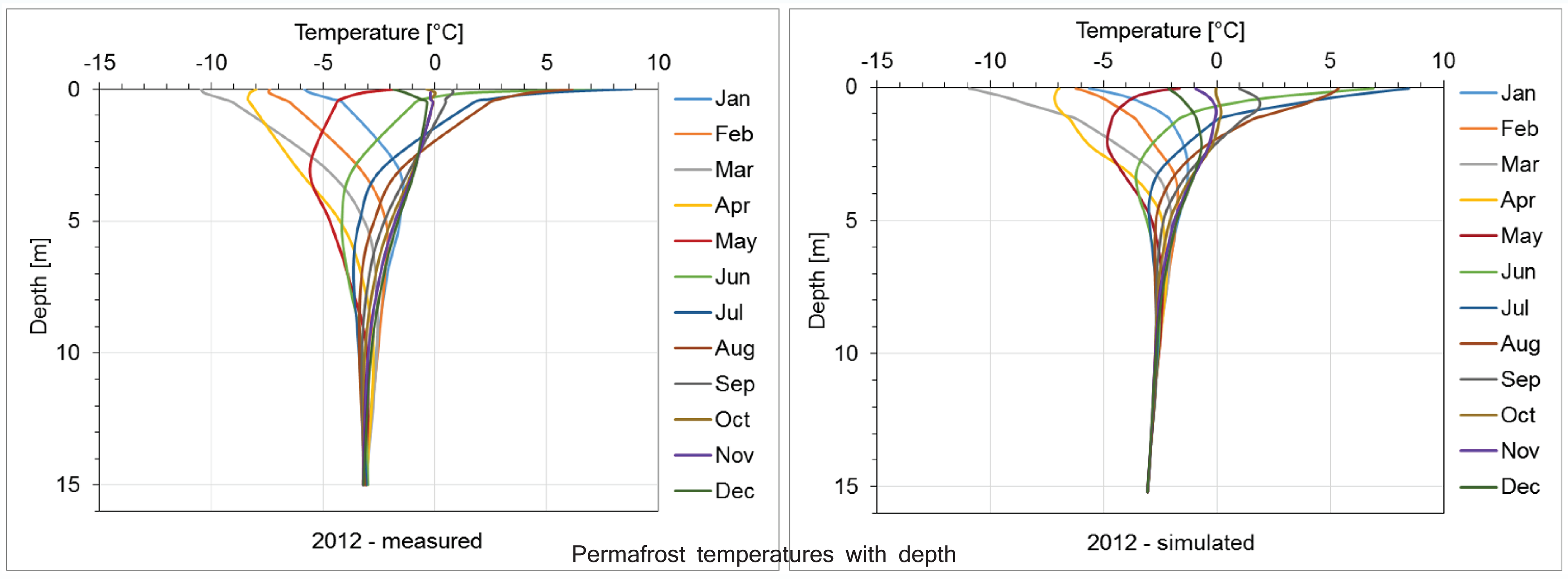
The initial deep temperature profile can be calculated based on a variety of methods. Here we applied a linear initial condition with a 10-year spin-up. To ensure faster spinup times the thermal spin-up only calculates energy equations and only for cells with unique parameters or Hydrological Response Units, HRUs.

Fish Creek Watershed Results:

WaSiM calculates the thermal regime based on atmospheric conditions, surface conditions, soil type, soil water content, bottom boundary conditions and convection.



Imnaviat Basin Permafrost Simulation



Permafrost temperatures with depth

Future Developments:

WaSiM is currently in development to expand its capabilities to include more of the physically based processes that are important for simulating complex interactions between climate, cryosphere and hydrology. The next module will focus on the surface energy balance, including radiative, sensible and latent heat fluxes. We will include snowpack processes that affect thermal and hydrological fluxes. We are currently working on a project that includes deep groundwater fluxes through taliks. We are interested in modifying the soil domain to include the effects of massive ice and soil surface degradation.

References:

Liljedahl, A. K., J. Boike, R. P. Daanen, A. N. Fedorov, G. V. Frost, G. Grosse, L. D. Hinzman, Y. Iijma, J. C. Jorgenson, and N. Matveyeva (2016), Pan-Arctic ice-wedge degradation in warming permafrost and its influence on tundra hydrology, Nat. Geosci., 9, 312-318, doi:10.1038/ngeo2674.

Schulla, J. (2015) Model description WaSiM Hydrology Software Consulting, http://www.wasim.ch/en/ or scan the QR-code on the right.

Acknowledgments:

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