Conceptualizing Peatlands in a Physically-Based Spatially Distributed Hydrologic Model

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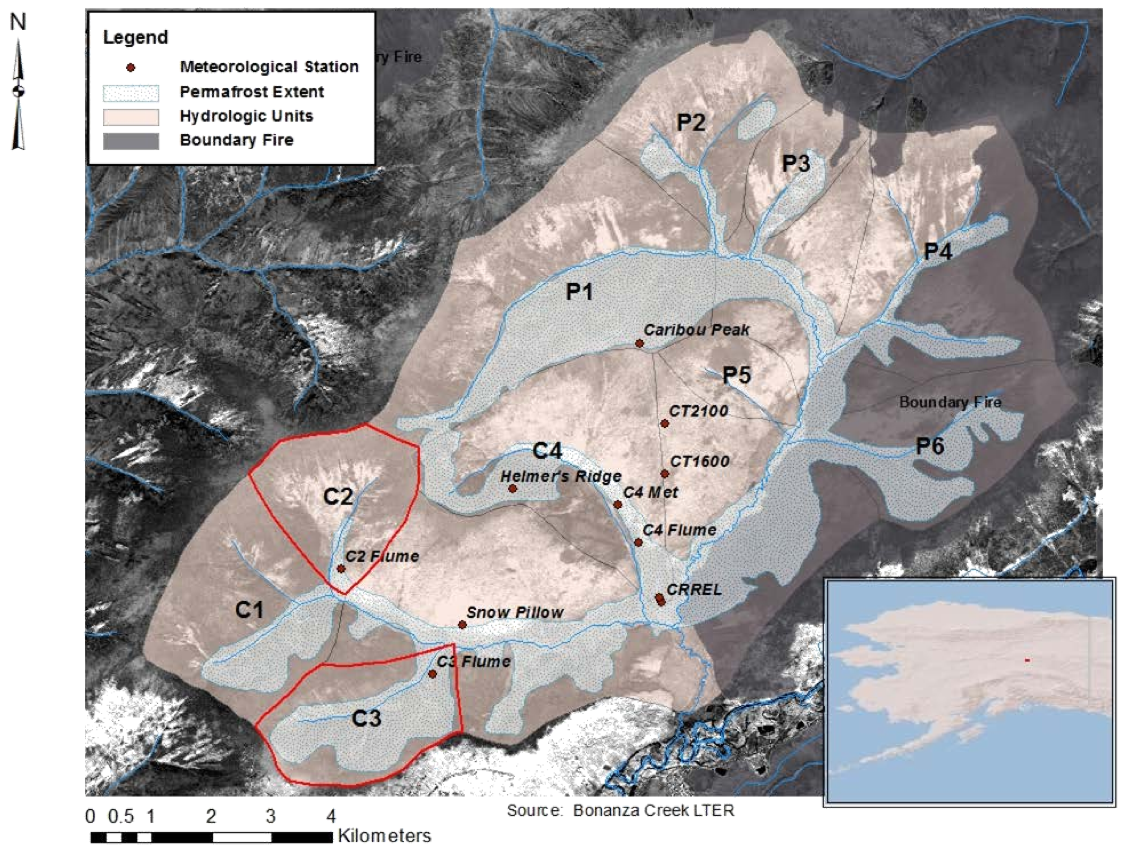
Abstract

As part of a research effort focused on climate change effects on permafrost near Fairbanks, Alaska, it became apparent that peat soils, overlain by thick sphagnum moss, had a considerable effect on the overall hydrology. Peatlands represent a confounding mixture of vegetation, soils, and water that present challenges for conceptualizing and parametrizing hydrologic models. We employed the Gridded Surface Subsurface Hydrologic Analysis Model (GSSHA) in our analysis of the Caribou Poker Creek Experimental Watershed (CPCRW). The model enables simulation of surface water and groundwater interactions, as well as soil temperature and frozen ground effects on subsurface water movement. A site visit exposed the presence of surface water flows indicating a mixed basin that would require both surface and subsurface simulation capability to properly capture the response. Soils in the watershed are predominately silt loam underlain by shallow fractured bedrock. Throughout much of the basin, a thick layer of live sphagnum moss and fine peat covers the ground surface. A restrictive layer of permafrost is found on north facing slopes. The combination of thick moss and peat soils presented a challenge in terms of conceptualizing the hydrology and identifying reasonable parameter ranges for physical properties. Various combinations of overland roughness, surface retention, and subsurface flow were used to represent the peatlands. The process resulted in some interesting results that may shed light on the dominant hydrologic processes associated with peatland, as well as what hydrologic conceptualizations, simulation tools, and approaches are applicable in modeling peatland hydrology.

Caribou/Poker Creeks Research Watershed

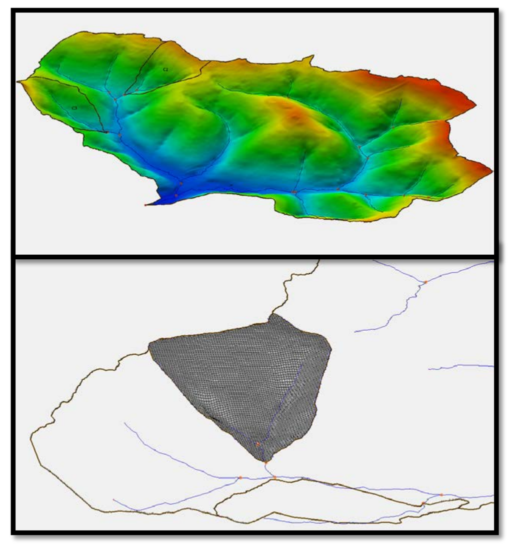


Hydrologic units of the Caribou/Poker Creeks Research Watershed (CPCRW) with locations of hydrometeorological stations and permafrost extents indicated (Chapin and Hollingsworth 2010a; b). Models of the C2 and C3 sub-watersheds compare the hydrologic effects from disparate expanses of permafrost.

Caribou/Poker Creek Research Watershed

- Located in the Yukon-Tanana Uplands of the Northern Plateaus Physiographic Province near Fairbanks Alaska. (Lat/Lon: 65˚10' N 147˚30' W)
- Area: 104 km²
- Characterized by rounded hilltops with gentle slopes and alluvium-floored valleys having minimal relief (Wahrhaftig 1965) underlaid by a mica shist of the Birch Creek formation (Rieger et al. 1972).
- Cold continental climate characterized by short warm summers and long cold winters.

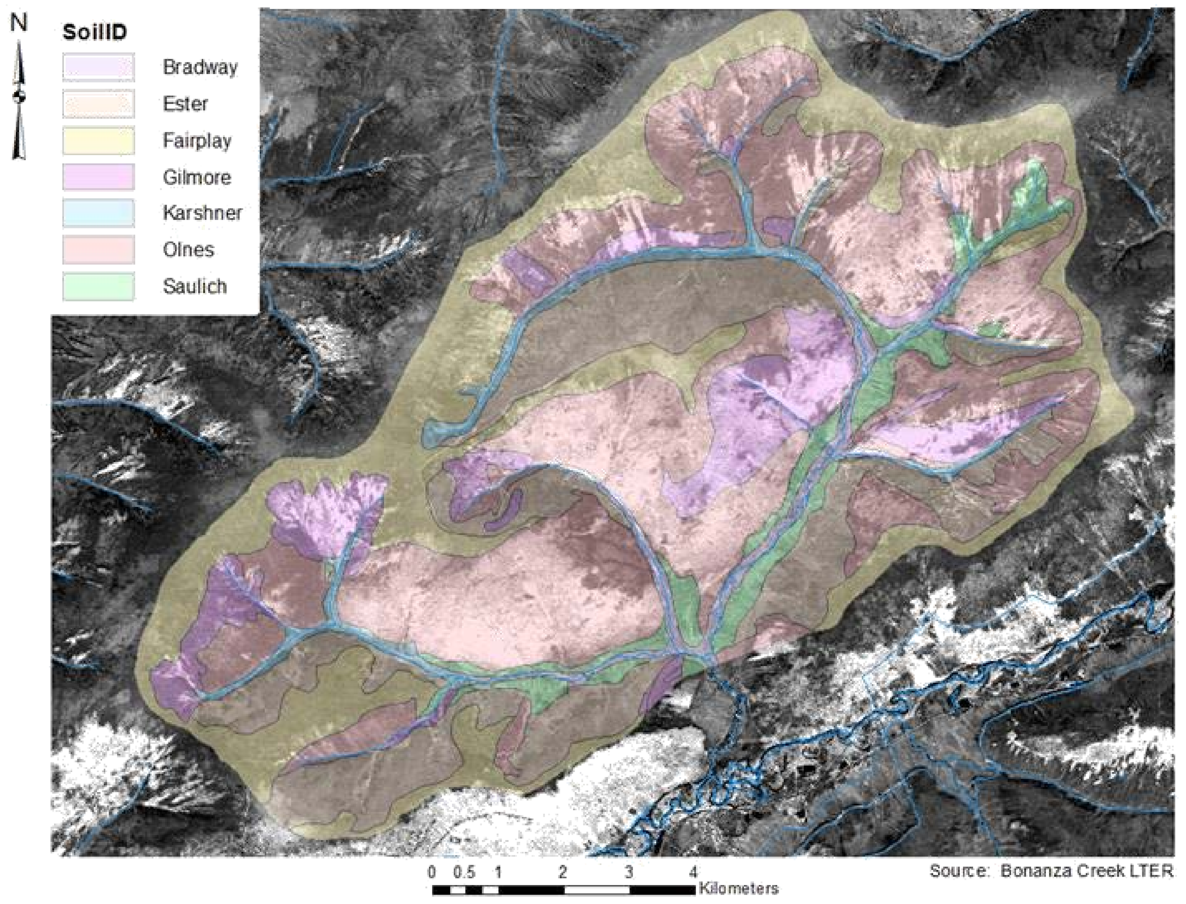
Modeling Approach



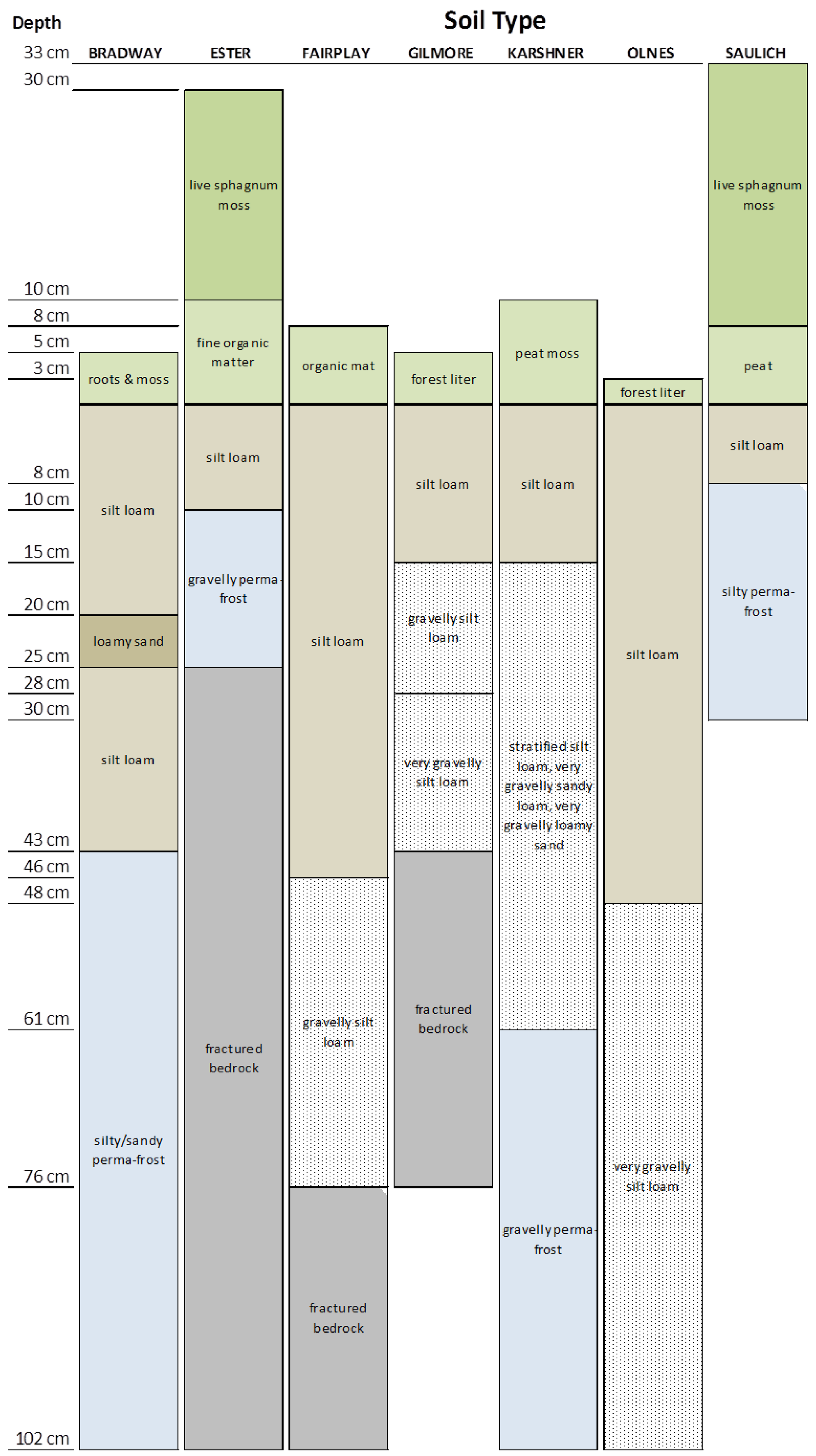
- Coupled Gridded Surface Subsurface Hydrologic Analysis (GSSHA) model and soil thermal regime model (Marchenko et al. 2008) from the Geophysical Institute Permafrost Lab (GIPL).
- Subdivided the basin into sub-watersheds for their disparate expanses of permafrost to better understand the effects of frozen soils.
- C2 basin – 5 km² basin nearly free of permafrost
- C3 basin – 5.4 km² with a large expanse of permafrost.

The GSSHA model is a physically-based spatially distributed numerical model used to simulate important stream flow processes (Downer and Ogden 2004a). GSSHA is used to evaluate flood inundation (Sharif et al. 2010) soil moisture (Downer and Ogden 2003), constituent fate and transport (Downer 2009), and snow accumulation (Follum and Downer 2013). (Hollingsworth 2007)

Soils at Caribou/Poker Creeks Research Watershed

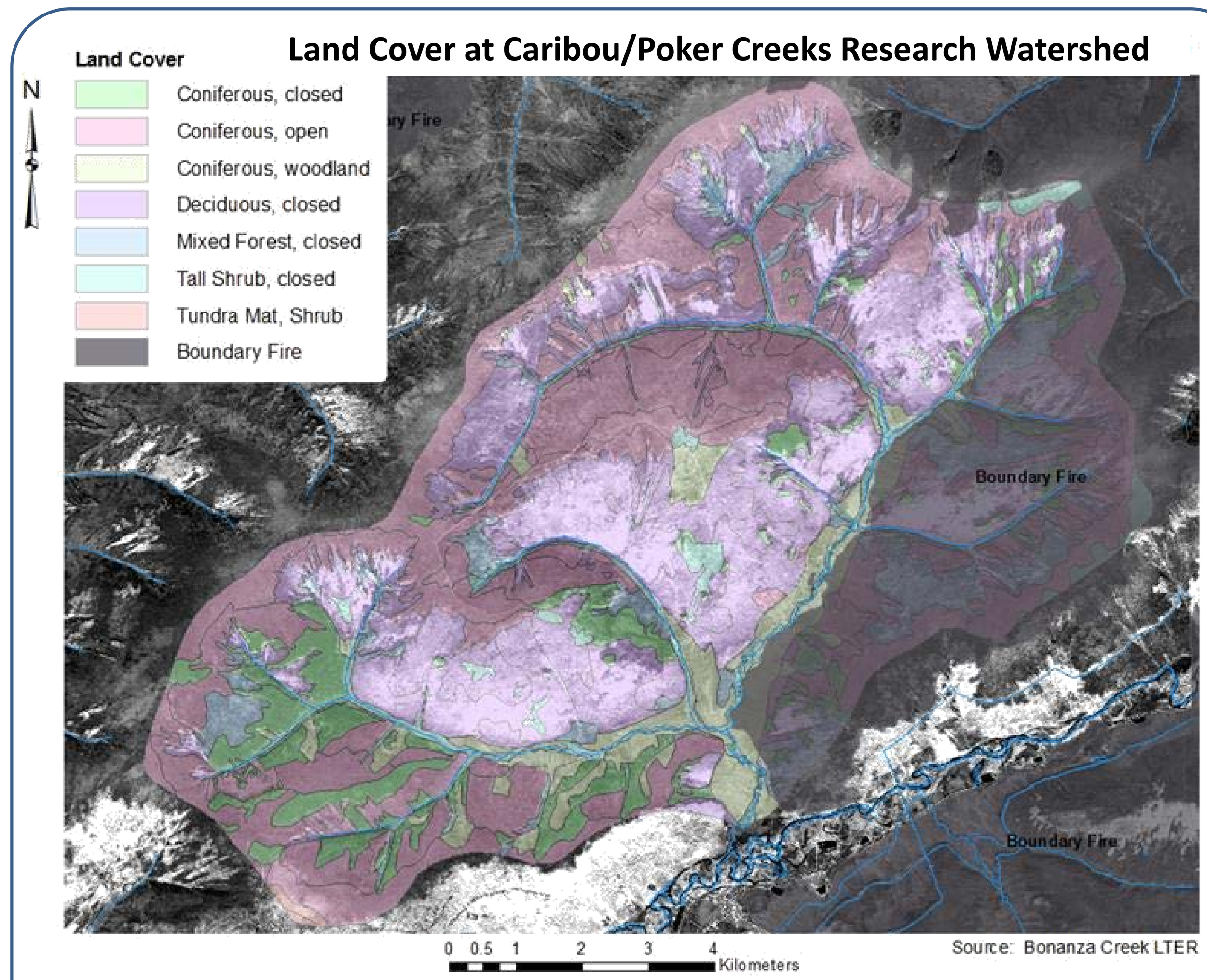


Soil map based on Reiger (1972) at the Caribou/Poker Creek Research Watershed



Profiles of the seven soil types found in the Caribou-Poker Creek Research Watershed. Perma-frost and peat/moss dominate the hydrologic regime.

Land Cover at Caribou/Poker Creeks Research Watershed



Land cover map at the Caribou/Poker Creek Research Watershed including extents of the 2004 Boundary Fire. Open and closed designations refer to canopy density. An open canopy permits a view of the sky through it.

Hydrologic Simulation

Overland Flow

- Alternating direction explicit (ADE) method.
- Overland roughness values assigned according to land cover within the range suggested by Senarath and Ogden 2000.
- Retention storage accounted for in soils with heavy forest litter.
- Overland flow routed through snowpack using Darcy's law.

Channel Routing

- A one-dimensional diffusive wave channel routing scheme is used to simulate stream flow.
- Idealized trapezoidal channel cross-sections are assumed.

Infiltration

- Richards Equation.
- 1D iterative finite-difference solution to describe the movement of water through an unsaturated soil (Downer and Ogden 2006).
- Vertical discretization is a critical factor to the accuracy of the solution (Downer and Ogden 2004b).
- A convergence study identified appropriate sizes of vertical cells for each soil layer. Generally the upper most soil layer had a vertical cells less than 1 cm while cell sizes for the subsequent layers increased from 1-3 cm in most cases.

Groundwater Interactions

- 2D simulation of lateral saturated groundwater flow is included in the model.
- Sub-surface stream losses and gains governed by a river flux boundary condition.

Evapotranspiration

- Penman Monteith method specified within GSSHA to calculate ET.
- Model parameters assigned according to the vegetation map above.
- Surface albedo values are based on recommended values from the GSSHA user manual (Downer and Ogden 2006).
- Canopy transmission coefficients assigned according to light interception studies for deciduous (Hutchison and Matt 1977) and coniferous (Gholz and Vogel 1991) forests.
- Canopy stomatal resistance based on two published studies (Eliáš 1979; Verma and Baldocchi 1986).
- Penman Monteith method is sensitive to stomatal resistance (Lemeur and Zhang 1990) so consideration was given to stomatal resistance during calibration.

Conceptualization of Peat/Moss Layers

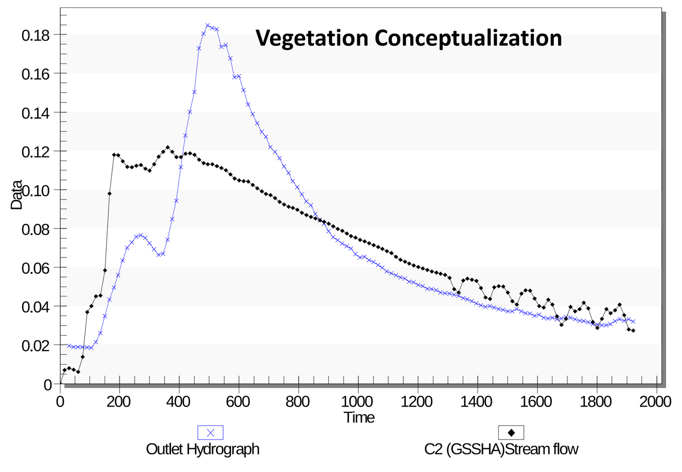
The combination of a thick mat of sphagnum moss and peat soils presented a challenge in terms of conceptualizing the hydrology and identifying reasonable parameter ranges for physical properties. Various combinations of overland roughness, surface retention, and subsurface flow were used to represent the peatlands. We attempted to simulate the fluxes through the peat using three different representations.

- Free-surface overland flow
- Peat represented as an additional unsaturated soil layer
- Peat specified as a special GSSHA wetland cell

Wetland cells in GSSHA consider three zones of lateral fluxes: free surface flow over the vegetation, mixed mode flow (Darcian and Manning's) through vegetation, and Darcian fluxes through the peat layer.

Moss/Peat as Vegetative Roughness

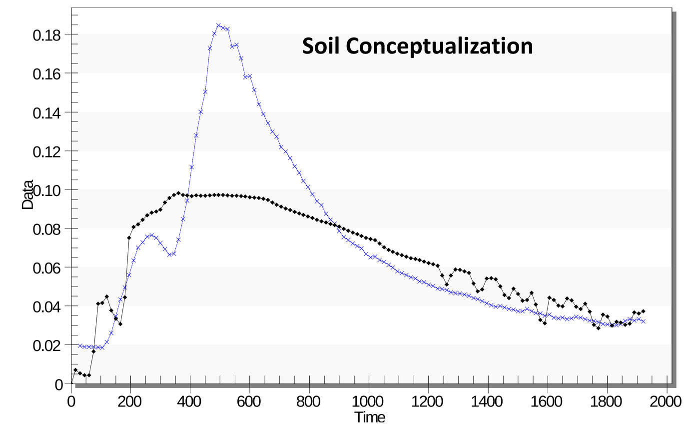
- Increased the overland roughness values of the peat and sphagnum well beyond the range associated with the forested landuse.
- Failed to match the timing of the peak and overall shape of the observed hydrograph.
- Overland flow equations with increased roughness poorly represent the lateral fluxes through the peat.



Simulation result for calibration period with Moss/Peat conceptualized as a vegetation.

Moss/Peat as Soil Layer

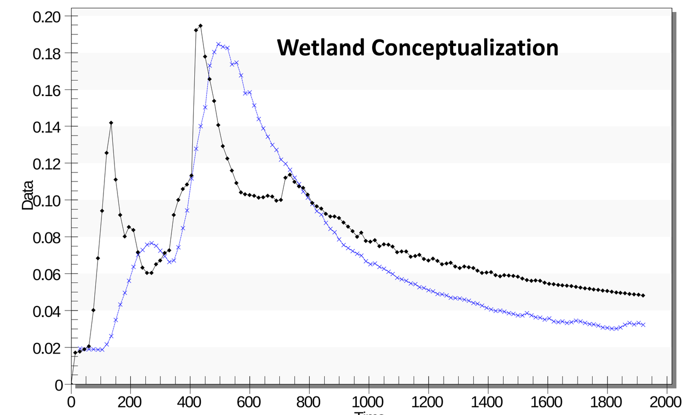
- Peat is treated as an additional soil layer in Richards Equation
- Surface roughness were consistent with normal ranges for each landuse type.
- Failed to match the timing of the peak and overall shape of the observed hydrograph.
- Simulating the peat/moss as part of the unsaturated zone minimizes the lateral fluxes through the peat.



Simulation result for calibration period with Moss/Peat conceptualized as a soil layer.

Moss/Peat as Wetland

- Fluxes through the peat are simulated using the three lateral zones in the GSSHA wetland cells.
- The resulting hydrograph better matches the peak and overall shape of the observed hydrograph.
- While this simulation can be improved, the results indicate that all flow domains are critical in representing the peat hydrology.
- Ignoring any of the processes (i.e. free surface overland flow, mixed flux through the vegetation, and Darcian flux through the peat) produces poor results and unrealistic parameter values.



Simulation result for calibration period with Moss/Peat conceptualized as a wetland.

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