Snow Modeling Capabilities within GSSHA

Why Do We Care About Snow?

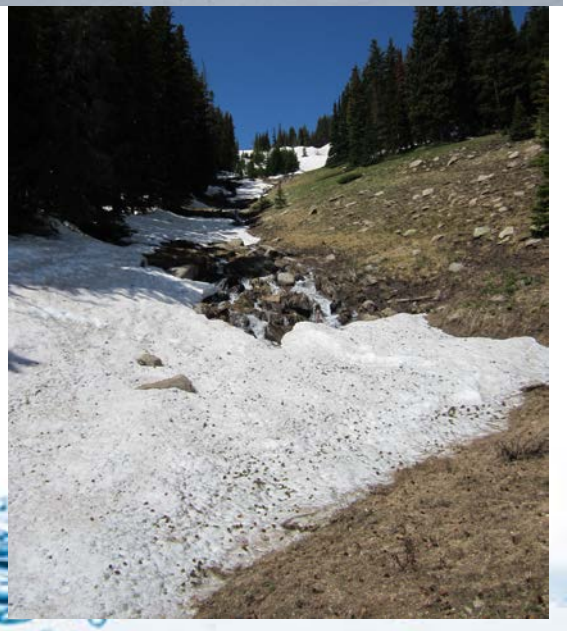
- Water Supply in the Western United States
  - Meltwater from the snowpack in the headwaters can provide 50-80% of the annual downstream water supply (Wahl, 1992).
  - Headwater catchments compose less than 25% of the total land area, but snowmelt from these areas provide roughly 70% of the annual runoff (Barros & Lettenmaier, 1993).
- Flooding

Overview

- Modeling of Snow Water Equivalent (SWE)
  - Four Snow Accumulation / Melt Methods
    - Energy Balance Method
    - Temperature-Index Method
    - Hybrid Energy Balance Method
    - Radiation-derived Temperature-Index Method
  - Accounting for the Snow Pack Dynamics within the Snow Pack

- Adjustments to HMET Forcing Data

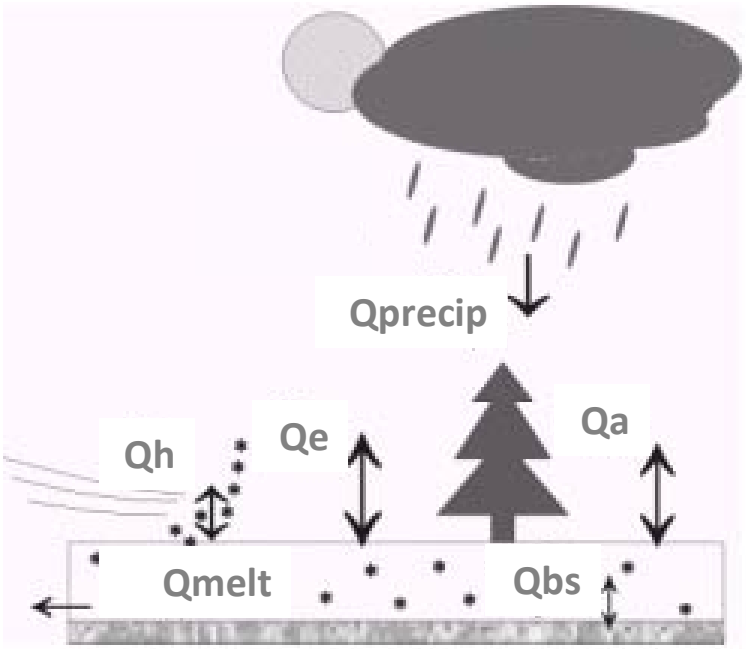
- Melt Water Transport
  - Vertical Flow through Snow Pack
  - Lateral Flow through Snow Pack
  - Frozen Ground to Impede Infiltration



- Examples

Four Snow Methods in GSSHA

- Energy Balance Method (EB) – accounts for the energy fluxes between the snow pack, ground layer, and atmosphere. If enough energy is input into the pack then melting occurs.
- Temperature-Index Method (TI) – The amount of melt within the snow pack is based on the temperature, precipitation, and calibrated parameters. Based on SNOW-17.
- Hybrid Energy Balance Method (HY, Default) – modification of the Energy Balance model that accounts for snow pack temperature dynamics (heat deficits).
- Radiation-Derived Temperature-Index Method (RTI) – Also based on SNOW-17, but uses a radiation-derived proxy temperature instead of air temperature in the melt equations.



Picture Adapted from: Tarboton 1996

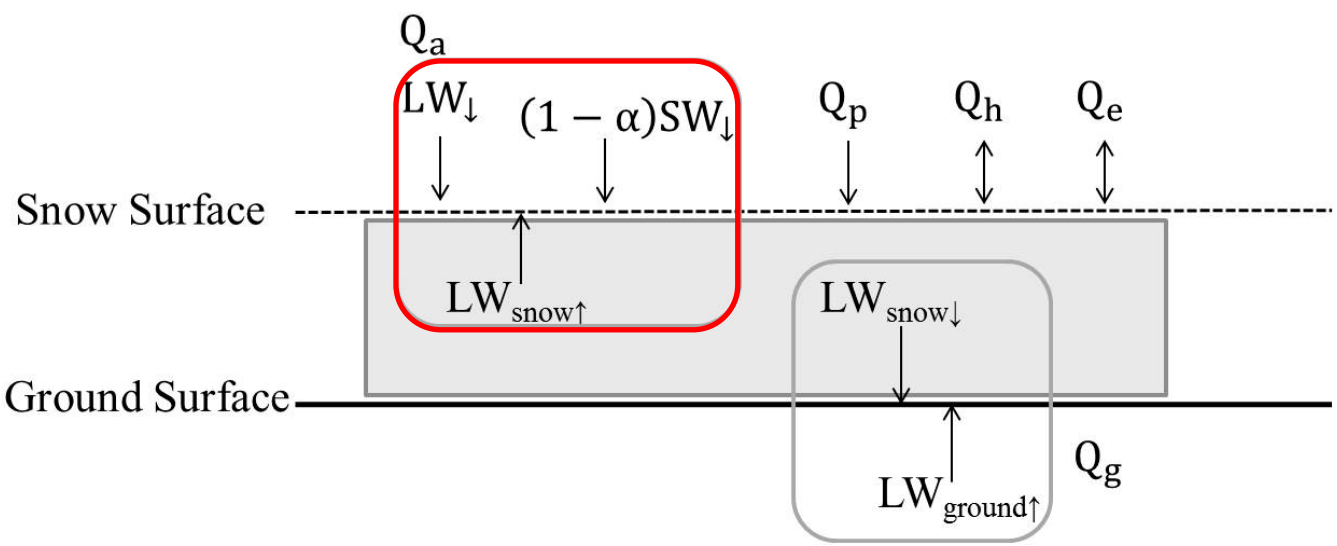
Simulating SWE – EB vs TI (In General)

Temperature Index (TI)

$$Melt = M_f \, T_a \, dt$$

Snow Energy Balance (EB)

$$Melt = \frac{\sum Q}{L_f} dt$$



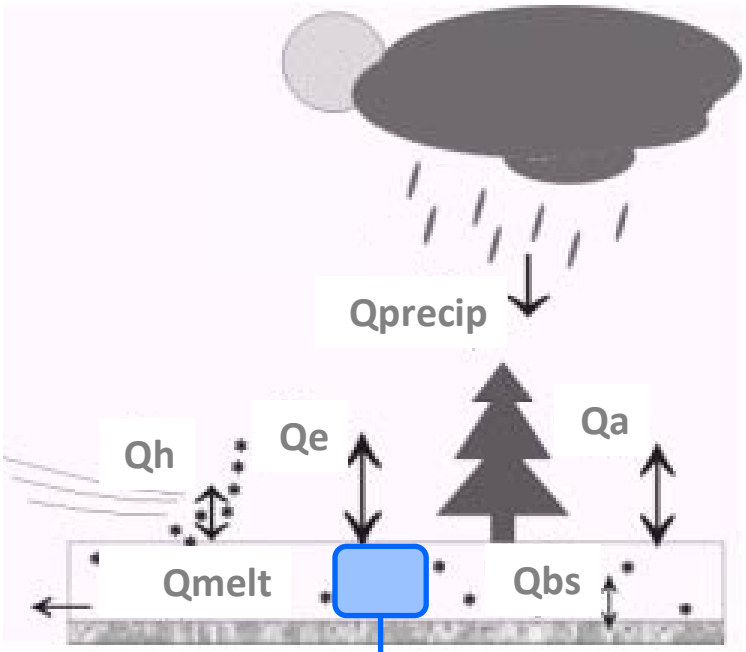
Q_a – Net Radiation
Q_p – Precipitation Heat Flux
Q_h – Sensible Heat Flux
Q_e – Latent Heat Flux
Q_g – Ground Heat Flux
σ – Stefan Boltzmann Constant
ε – Emissivity (0-1)
α – Albedo
L_f – Latent Heat of Fusion

Simulating SWE – EB & HY Methods

$$Qmelt = Qa - Qbs + Qe + Qh + Qprecip$$

- Qmelt — total energy available to melt snow
- Qe — energy due to evaporation and sublimation f(temperature, humidity, wind)
- Qh — sensible heat transfer due to turbulence f(temperature, pressure, wind)
- Qa — energy due to longwave radiation f(temperature)
- Qbs — energy due to longwave emission by soil considered constant (27 cal cm^{-2} hr^{-1})
- Qprecip — energy due to precipitation f(precipitation, temperature)

Assumes 1 cc of snow will melt for every 336 Joules which = 80 cal per gram of water



Picture Adapted from: Tarboton 1996

HY Method accounts for cold content (heat deficit) within the snowpack.

Simulating SWE – TI Method

Based on SNOW-17 (Anderson 1968; 1973; and 2006)

- Melt occurs once heat deficit is overcome
- Melt rates (M) based on Air Temperature and calibrated Melt Factors

$$M = \left[M_f \cdot (T_a - MBASE) + 0.0125 \cdot P \cdot f_r \cdot T_r\right]$$ Melt under normal circumstances

$$M = \sigma \cdot dt \cdot \left[(T_a + 273)^4 - 273^4\right] + 0.0125 \cdot P \cdot f_r \cdot T_r + 8.5 \cdot f_u \cdot (dt/6) \cdot \left[(rh \cdot e_{sat} - 6.11) + 0.00057 \cdot P_a \cdot T_a\right]$$ Melt during rain events.

where:

M_f = melt factor, varies daily between a calibrated minimum and maximum value
P = precipitation
f_r = fraction of precipitation in form of rain
f_u = wind function
$MBASE$ = temperature at which snow begins to melt

Simulating SWE – TI to RTI Method

Temperature Index (TI)

$$Melt = M_f \, T_a \, dt$$

$$T_a \approx \left(\frac{LW_{\downarrow}}{\sigma \, \varepsilon_{air}} \right)^{1/4}$$

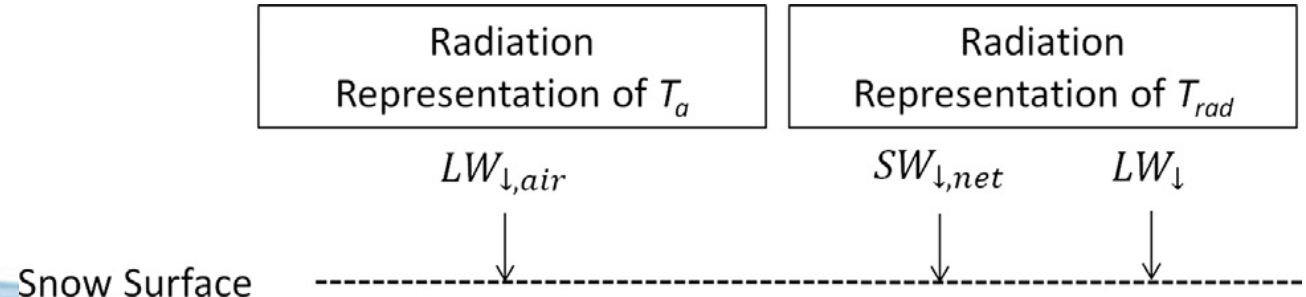
Requires:
- Temperature
- Precipitation

Radiation-Derived Temperature Index (RTI)

$$Melt = M_f \, T_{rad} \, dt$$

$$T_{rad} \approx \left(\frac{LW_{\downarrow} + SW_{\downarrow net}}{\sigma \, \varepsilon_{snow}} \right)^{1/4}$$

Requires:
- Temperature
- Precipitation
- Cloud Cover



Simulating SWE – RTI Method

How to get T_{rad}

- Account for SW radiation and related reductions

  $SW_{\downarrow} = S_0\ K_r\ K_v\ K_c\ K_{atm}\ K_s\ K_t$

  S_0=Solar Constant

  K_r=ratio of actual earth-sun distance to mean earth-sun distance (fraction)

  K_v=vegetation

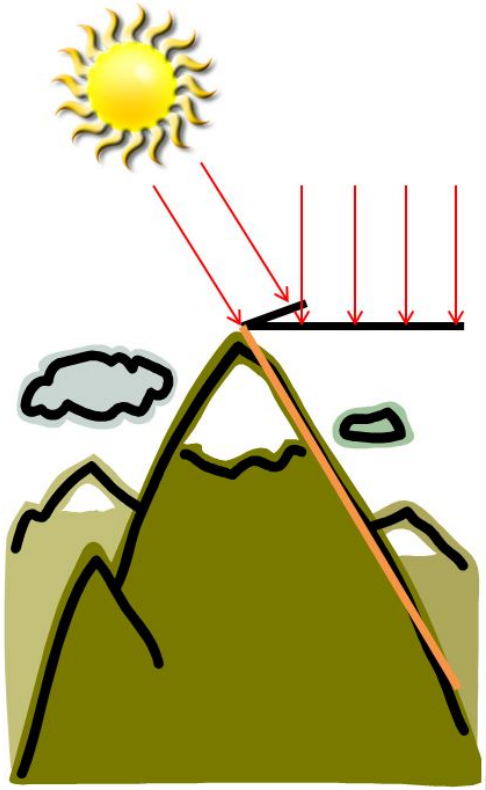
  K_c=clouds

  K_{atm}=atmospheric absorption and scattering

  K_t=topographic shading

  K_s=aspect angle

- Include snow albedo model (Henneman & Stefan, 1999)
- Account for LW radiation from clouds and canopy ($LW_{\downarrow}$)
  - LW clear sky, including emissivity of air (Bras, 1990)
  - Increase of LW due to clouds (TVA, 1972)
  - Adjustment of LW due to vegetation (Liston & Elder, 2006).



For more details see Follum et al. (2015)

Simulating SWE - Overview

- Energy Balance Method
  - Uses Energy Balance Algorithms to determine melt and accumulation, but does not include Heat Deficit.
  - Typically underestimates SWE when topography not accounted for in the model.

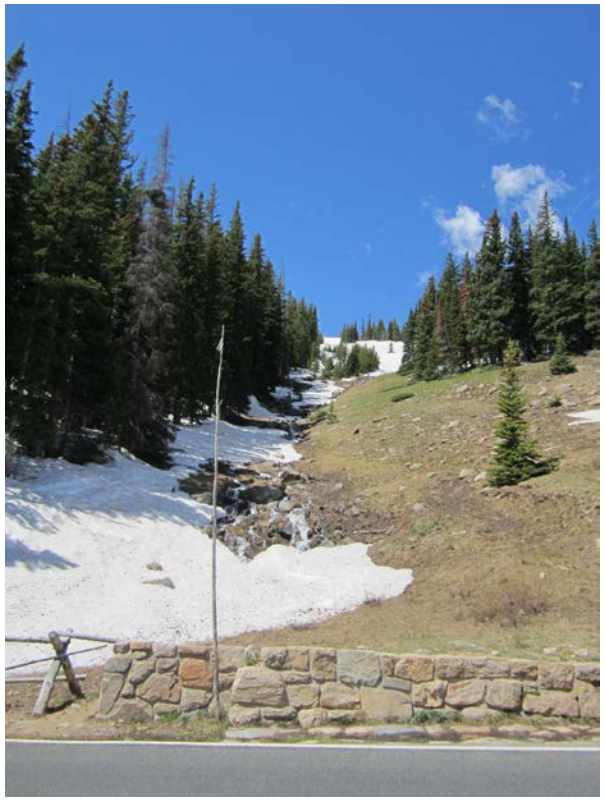
- Temperature-Index Method
  - Uses temperature, precipitation, and calibrated parameters to simulate snow accumulation and melt.
  - Incorporates the Heat Deficit / Snow Pack Dynamics
  - Requires Calibration (9 Parameters)

- Hybrid Energy Balance (Default in GSSHA)
  - Incorporates the Energy Balance Melting Algorithms
  - Incorporates the Heat Deficit / Snow Pack Dynamics (4 Parameters)

- Radiation-Derived Temperature-Index Method
  - Same as TI Method, but accounts for spatial heterogeneity in energy, and therefore produces a more accurate spatial representation of the snowpack.
  - Requires Calibration (8+ Parameters)

Adjustments to HMET Forcing Data

- Three methods for adjusting HMET with Elevation
  - **SIMPLE:** Define a constant temperature lapse rate, then GSSHA adjusts temperature. Based on change in temperature, relative humidity and pressure can also be adjusted.
  - **COMPLEX:** Let GSSHA automatically adjust temperature, pressure, and relative humidity based on elevation using MALR.
  - **PUNT:** Input raster-based forcing data from an atmospheric model, such as MicroMet (Liston & Elder, 2006)



Typically, I use a simple Lapse Rate

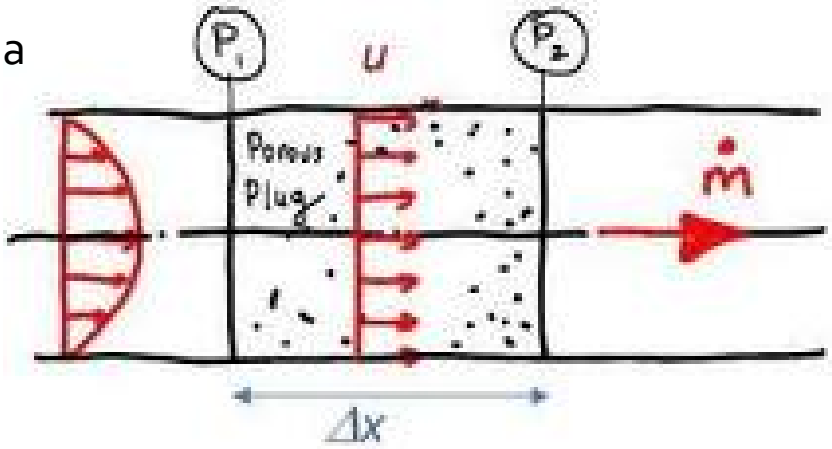
Melt Water Transport

- Once snow melts the water is transported through the system in several ways:
  - Vertically through the Snowpack
  - Laterally through the Snowpack
  - Infiltration into Groundwater
  - Overland Flow
  - Channel Flow, Etc.

- GSSHA simulates the vertical and lateral flow through the Snowpack

- Accurate groundwater simulations is also very important for capturing the timing of flows. A frozen ground simulation determines when the ground is frozen - inhibiting infiltration into groundwater.

Melt Water Transport – Basics



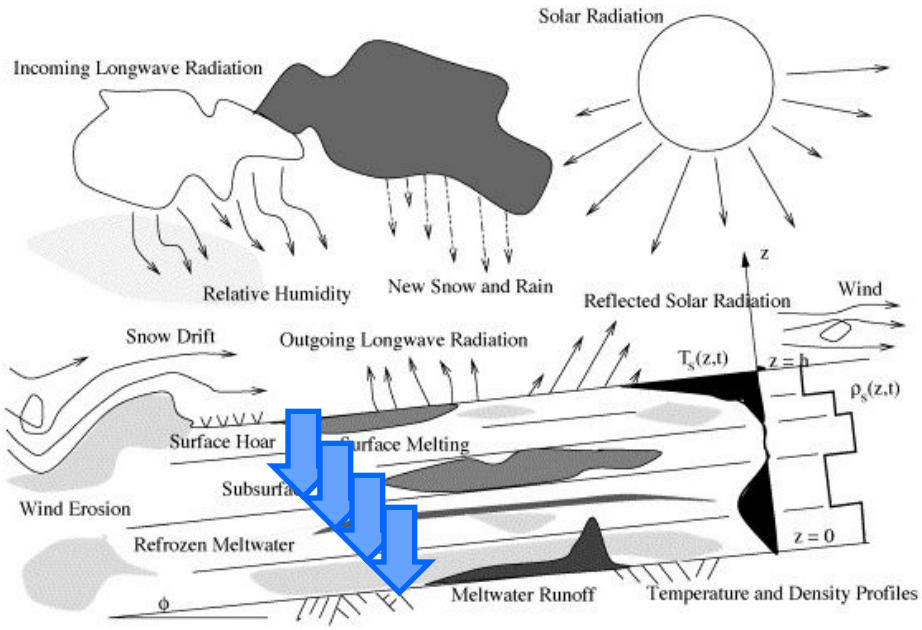
- Flow through Snow is the same as a flow through a porous medium.
- A form of Darcy's Equation is typically used to determine flux rates through the snow pack, both vertically and laterally.
- Vertical Flow is typically considered Unsaturated Flow.
- Lateral Flow at the bottom of the snow pack is typically considered Saturated Flow.
- GSSHA uses the SNAP model (Albert 1998) to determine the saturation, saturated / unsaturated hydraulic conductivity, and effective porosity of the snow pack in each cell.

Melt Water Transport – Vertical Flow

- Vertical Flow is considered unsaturated flow, but the hydraulic conductivity and effective porosity change with the degree of Saturation.

$$k_w = kS^n$$

- Flow is simulated through a single snow layer, but can have multiple wave fronts through the pack – based on both Albert (1998) and Bengtsson (1981).



From: Bartelt (2002)

Melt Water Transport – Lateral Flow

- Once the melt water reaches the ground it is considered Saturated Darcian Flow and uses methods developed by Colbeck (1974) to determine the flux volumes between each cell.

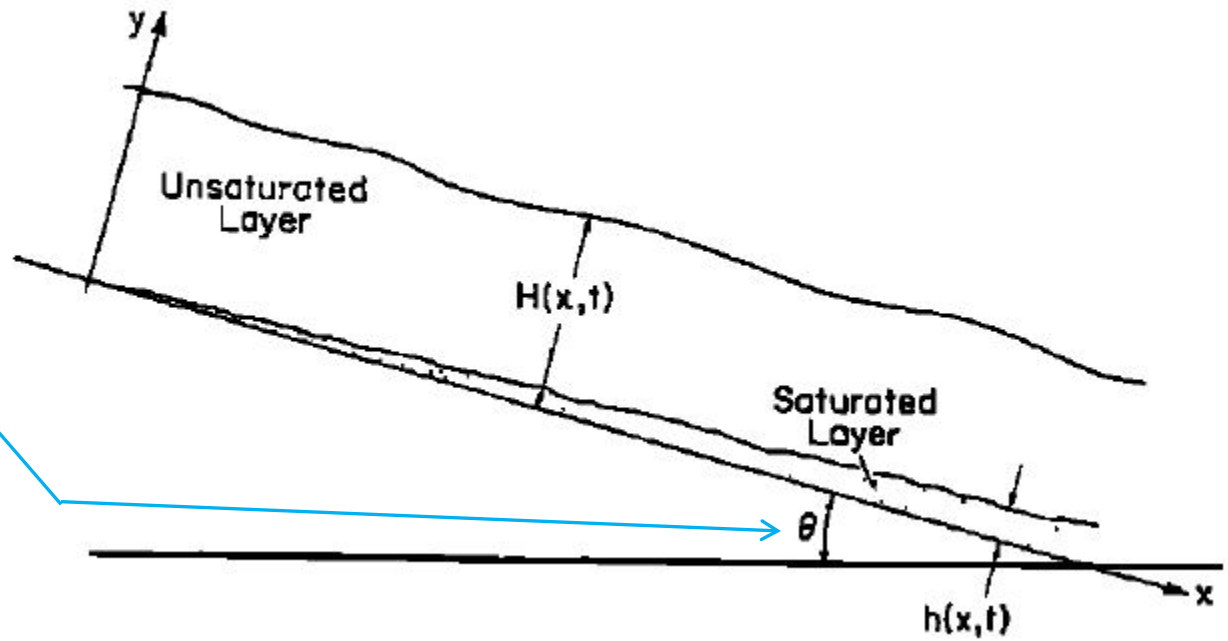
Hydraulic Properties of Water Constant

Hydraulic Conductivity

Effective Porosity

$$c = \theta \alpha k_s / \phi$$

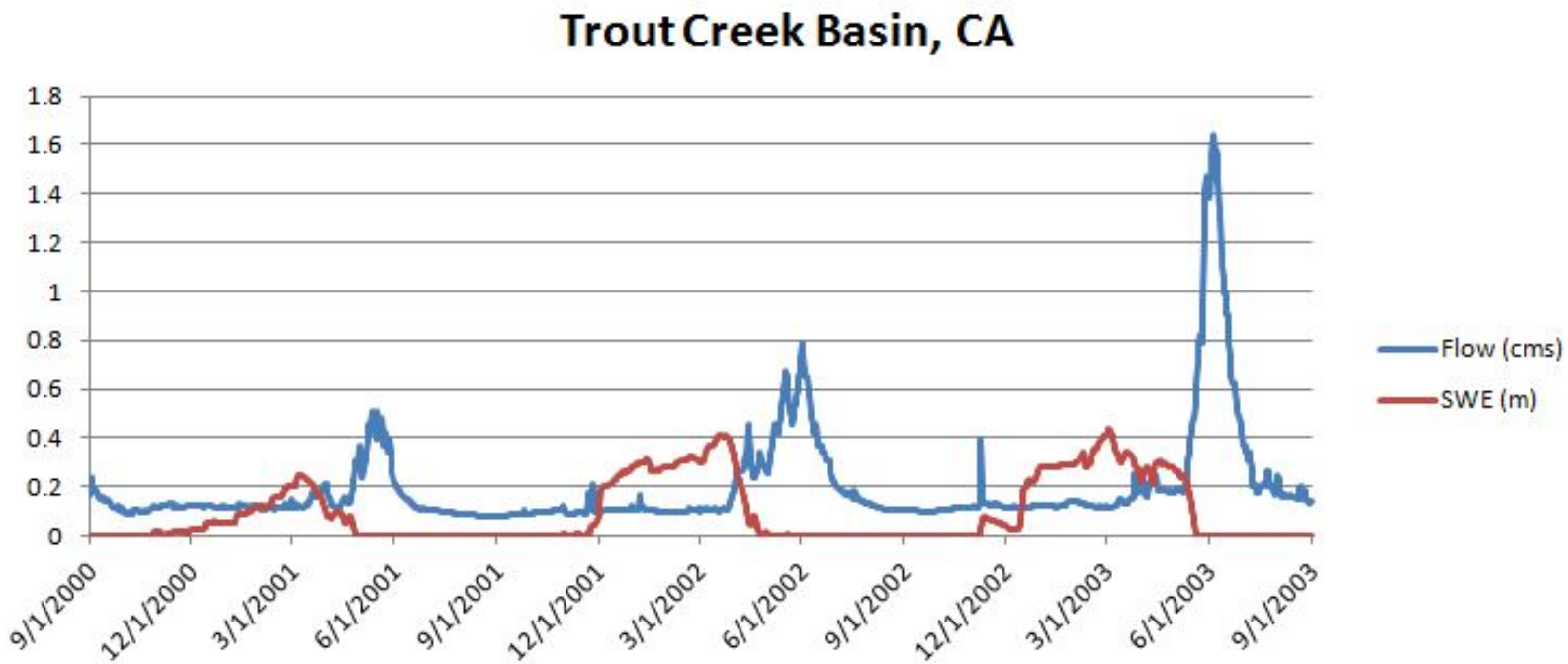
Flux Rate



From: Colbeck (1974)

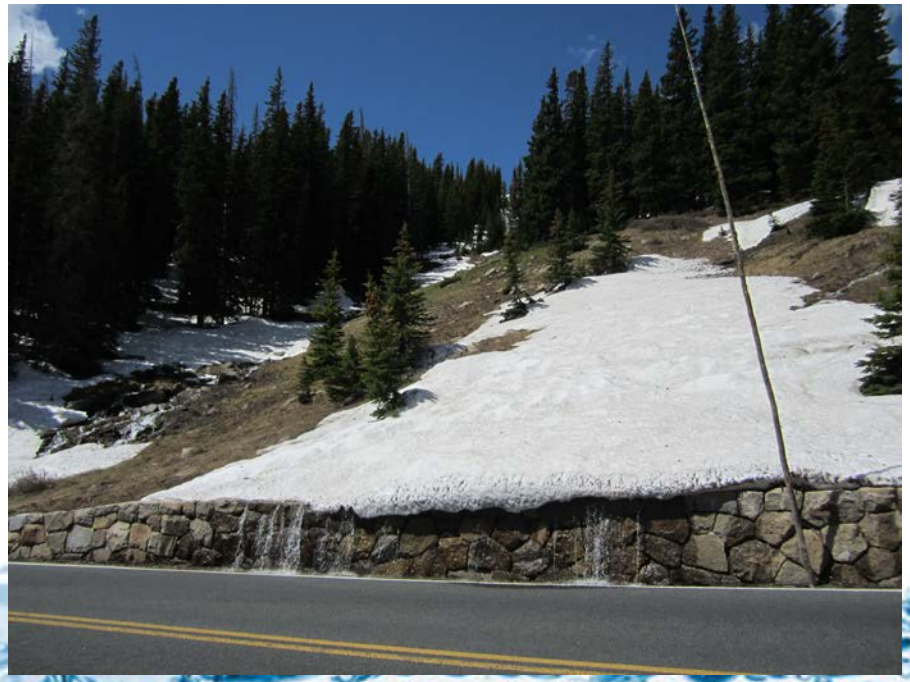
Melt Water Transport – Frozen Ground

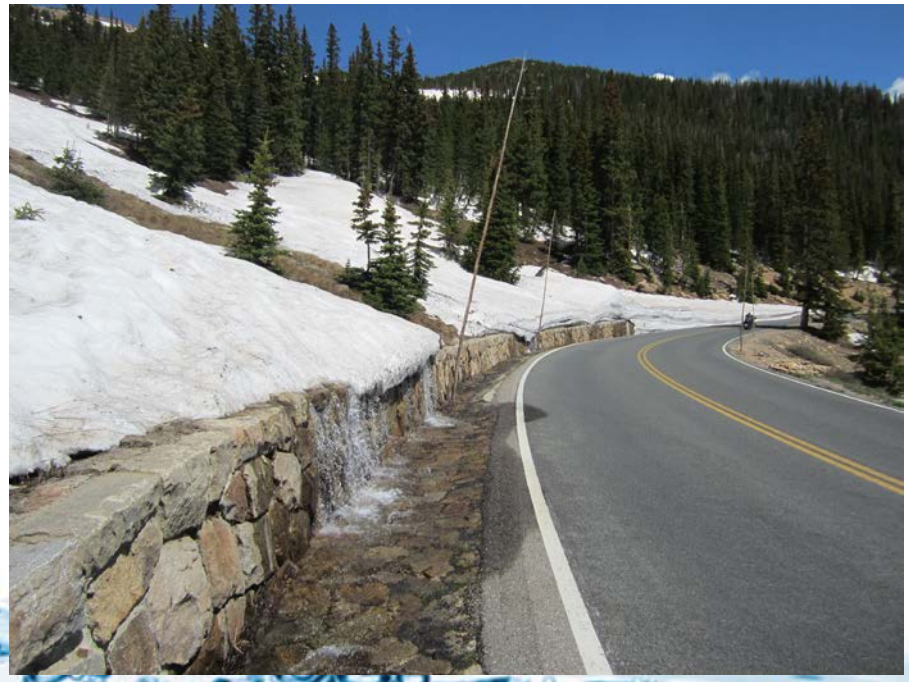
- GSSHA uses a temperature-index method (CFGI model; Molnau & Bissel, 1983) to determine when the ground beneath a snow pack is frozen, thus preventing infiltration.
  - See for more info: http://www.gsshawiki.com/Frozen_Soil:Frozen_Soil
- The Handbook of Snow (Gray and Male, 1981) states that for long-term sustained water yields the groundwater flow component may be most important aspect considered.



Melt Water Transport - Overview

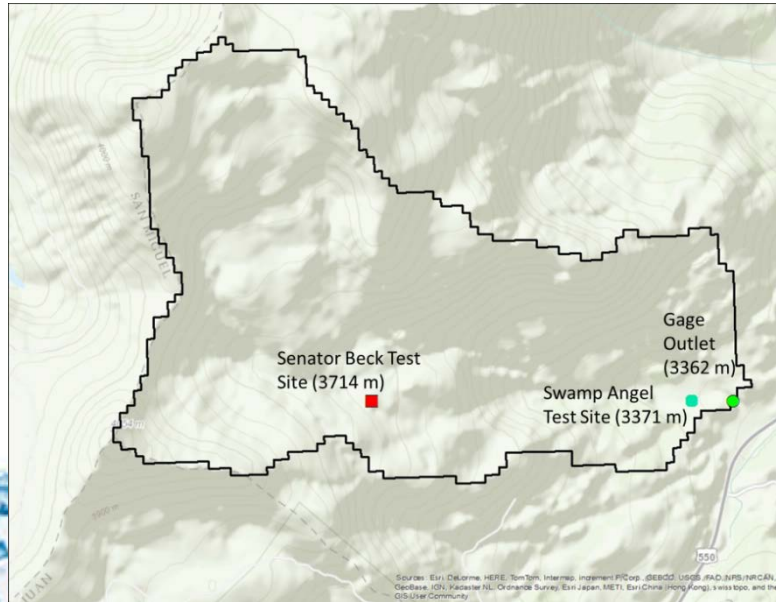
- Vertical Flow through Snow Pack
- Lateral Flow through Snow Pack
- Frozen Ground Simulation
- Existing routing mechanisms already in GSSHA



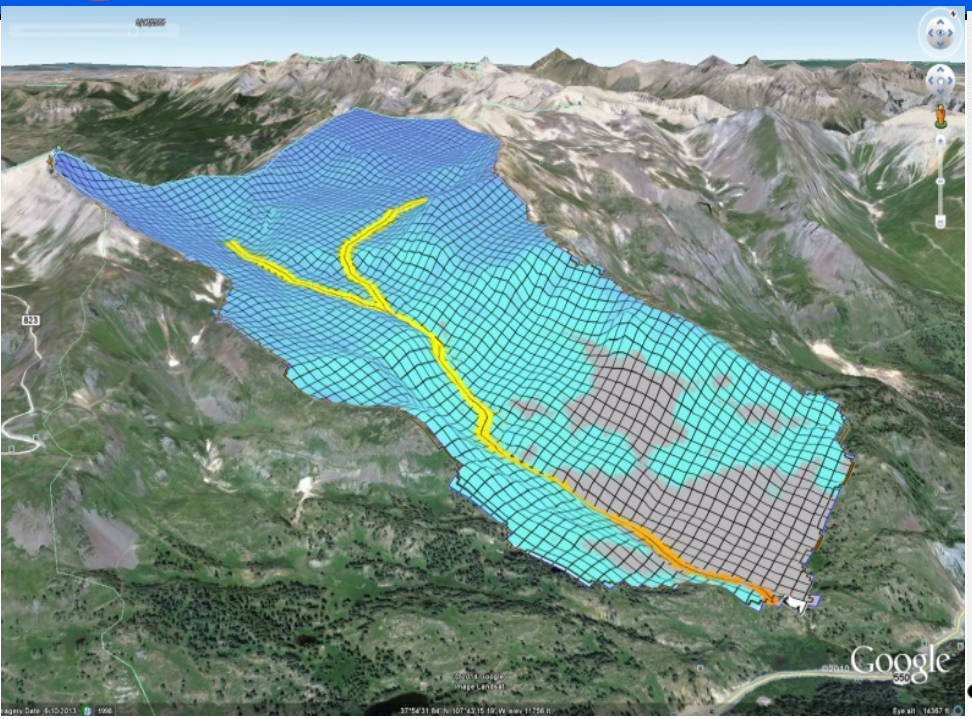


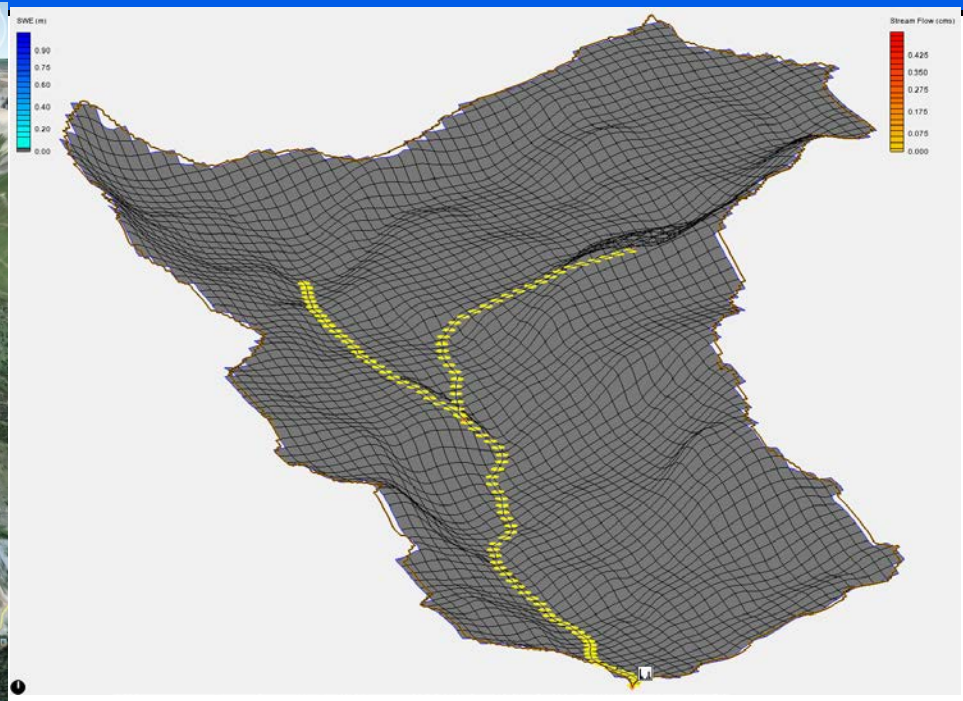
Test Basin: Senator Beck Basin, CO (SBB)

- Test Basin: Senator Beck Basin, CO
  - Drainage Area: 2.91 km^2 , Elev: 3362 – 4118 m
  - Alpine terrain with primarily bare rock and tundra, with some forest below 3600-m
- Point Data Sources
  - Hydrometeorology at 3 sites from WY 2003 through current (Landry et al., 2014)
    - Temperature, precipitation, relative humidity, pressure, and wind speed
    - SWE, soil moisture, and shortwave (SW) radiation
  - Cloud cover data from Telluride Regional Airport (~16 km to northwest)
  - Streamflow data at outlet (Landry et al., 2014)
- Spatial Data Sources
  - SCA estimates from LandSat Imagery (31 images)
    - Spectral signatures processed using ERDAS Imagine
    - Assigned classifications: snow, no snow, and snow fringe
  - Elevation -> 1/3 Arc Second NED (Gesch et al., 2002)
    - projected to 30 m grid
  - Land Cover -> 2006 NLCD (Fry et al., 2011)
  - Soils Data -> SSURGO dataset (Soil Survey Staff, 2014)



Test Basin: Senator Beck Basin, CO (SBB)



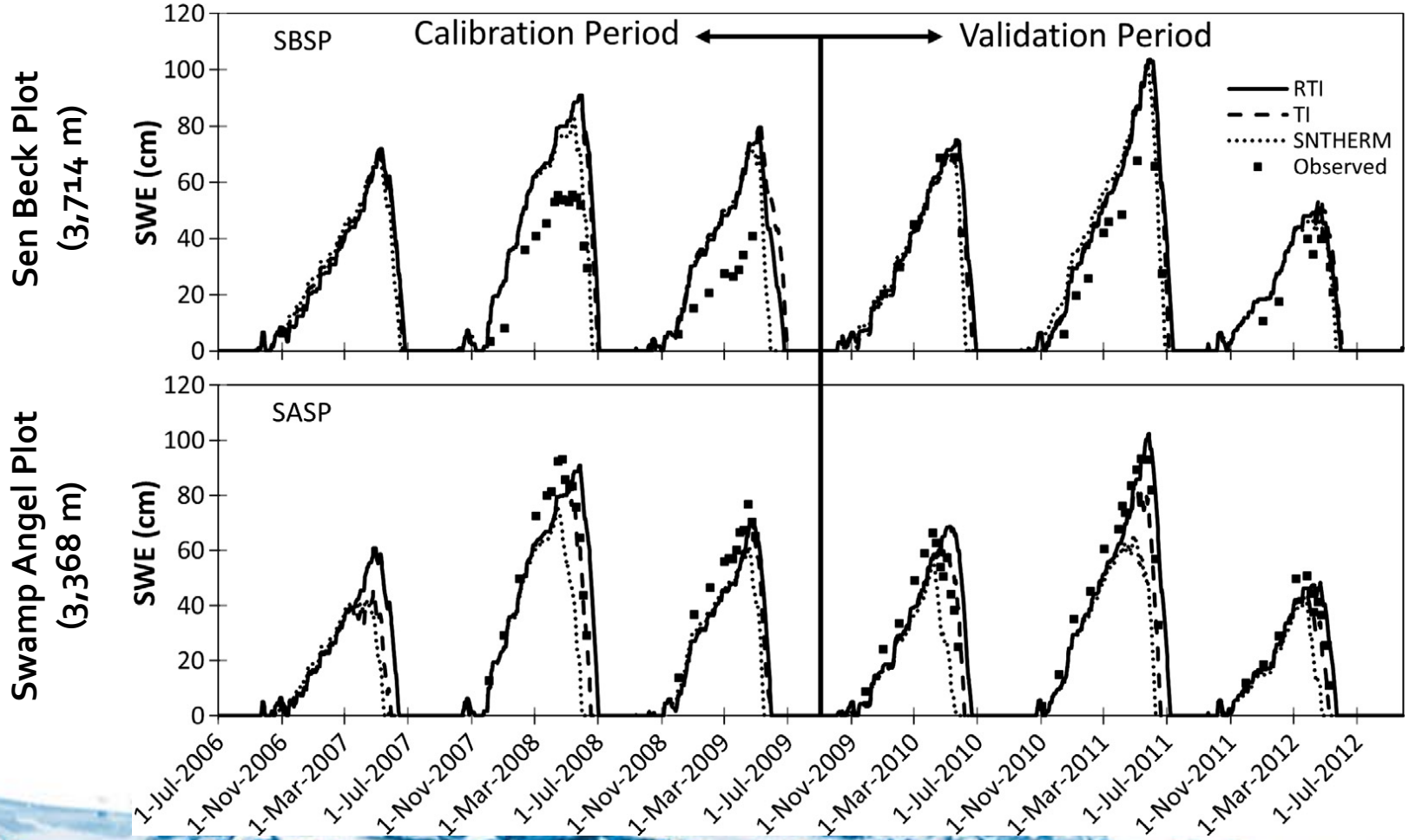


Highlights:

- Showed accurate snow simulation in an Alpine terrain (Follum et al., 2015)
- RTI model more accurate than TI and EB models

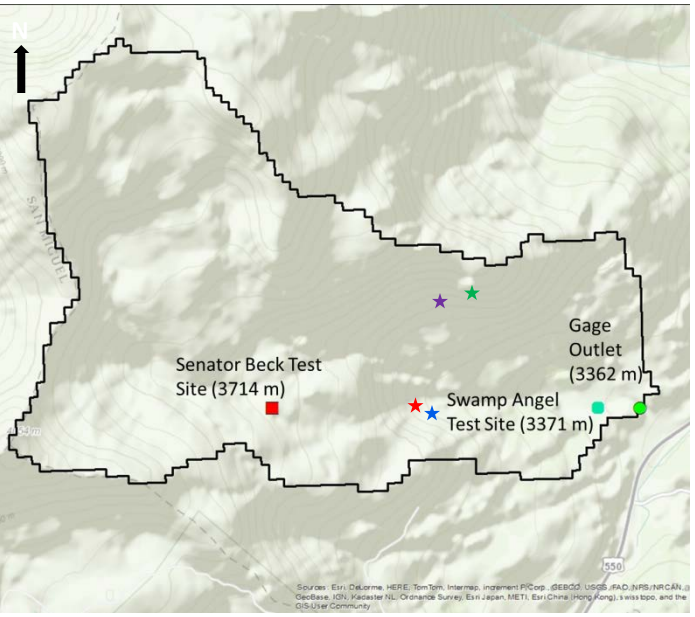
SBB using TI and RTI Model

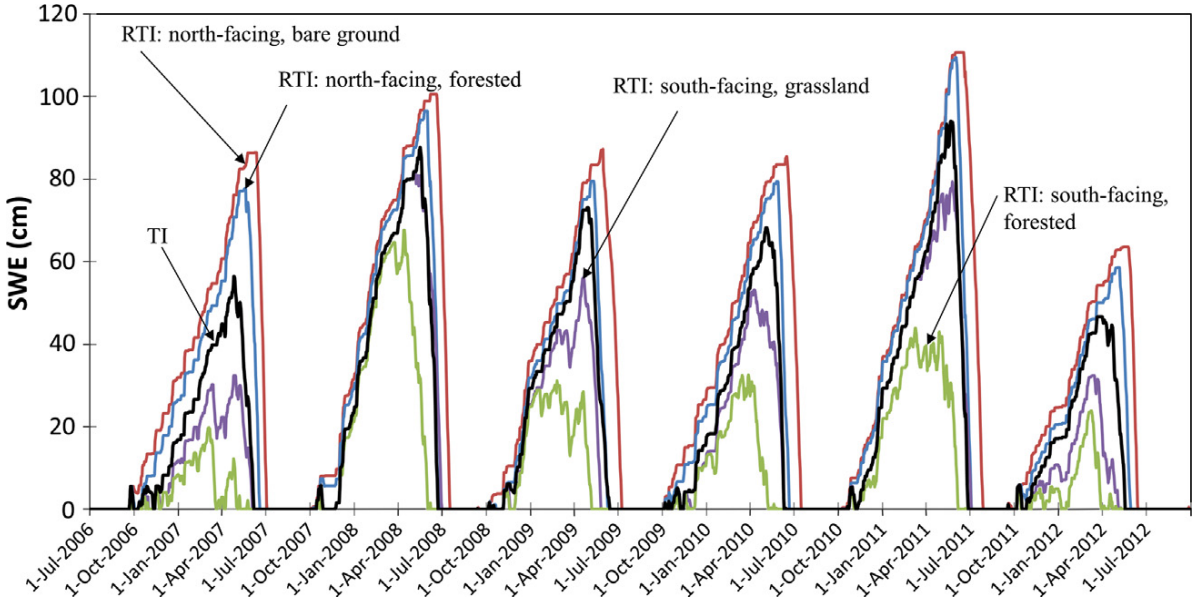
- **Modest improvement in SWE at two gage sites**



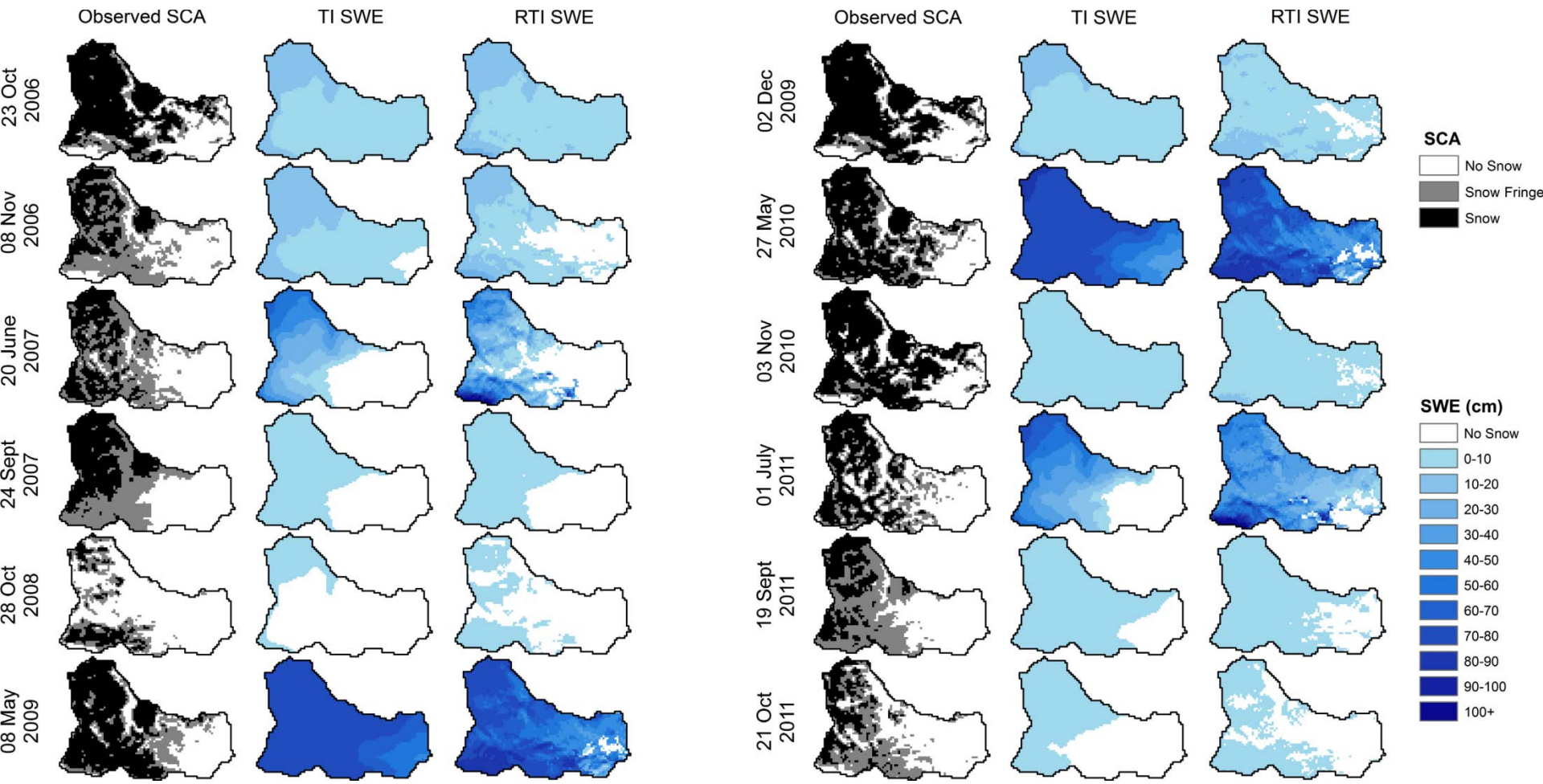
SBB using TI and RTI Model

- **Variability in SWE due to topography and vegetation**

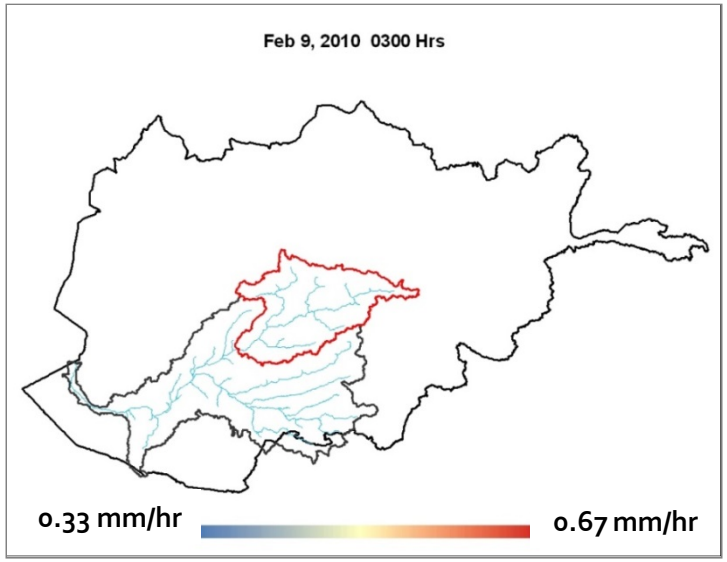




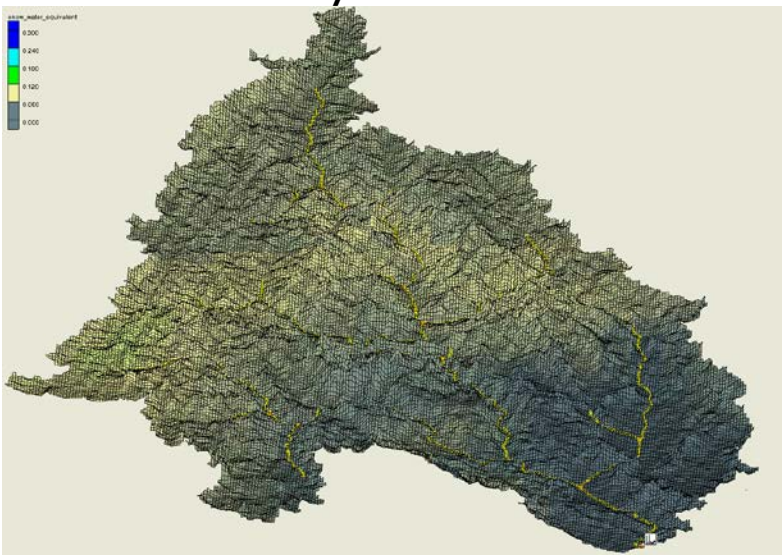
SBB using TI and RTI Model



Helmand River Basin, Afghanistan



Upper Helmand Basin Simulation: January – June 2010



- **Watershed-based**
- **Manual setup**
- **Limited forecasting window**

Data Sources

- NRCS / USDA - http://www.wcc.nrcs.usda.gov/
  - SNOTEL, SCAN, Snowcoarses
- National Snow & Ice Data Center - http://nsidc.org/
- Remotely Sensed
  - Landsat, MODIS, AVHRR
- CZO's - http://criticalzone.org/national/
- Test Watersheds:
  - Senator Beck Basin, CO
  - Niwot Ridge, CO
  - Fraser Experimental Forest, CO
  - Loch-Vail, CO
  - Reynolds Experimental Watershed, ID
  - Sleepers River, VT
  - Hubbard Brook, NH
  - HJ Andrews, OR
  - Marmot Creek, Canada Rockies

Questions?

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