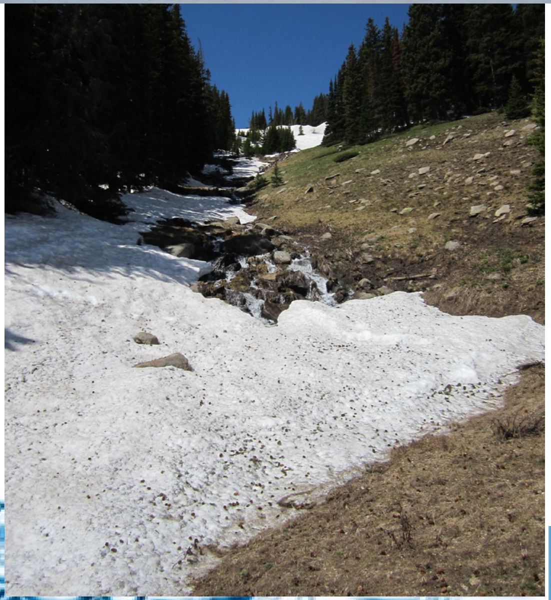
GSSHA Snow Modeling Capabilities

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).
- Hydrograph Timing
  - Snow has the effect of changing the timing of annual streamflow
  - Instead of the rapid rainfall runoff response in non-snow dominated regions, water is stored in the snowpack until the spring/summer thaw period
- Flooding
  - In the upper midwestern United States US rainfall on snow events produce the largest, and most damaging, flooding events

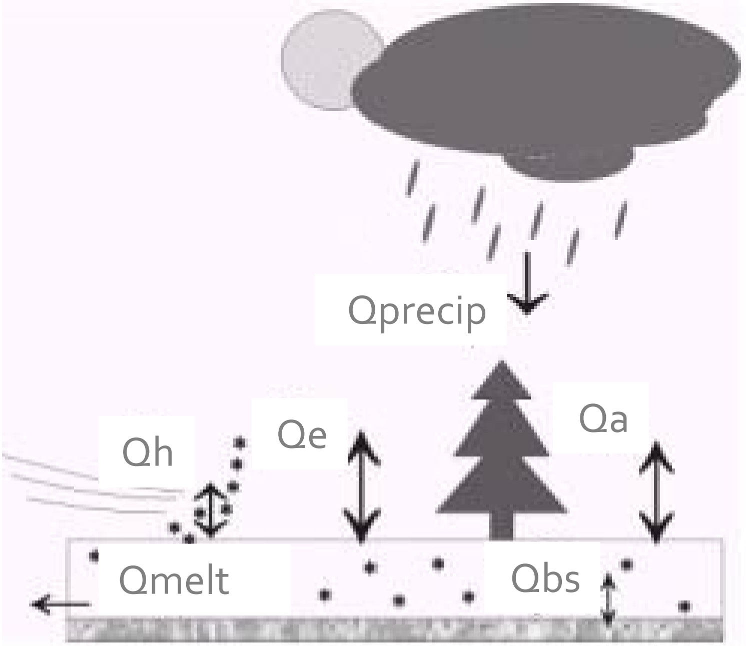
Overview

- Modeling of Snow Water Equivalent (SWE)
  - Four snow-pack melt models
    - Energy Balance
    - Temperature-Index
    - Hybrid Energy Balance
    - Radiation-derived Temperature-Index
  - Accounting for snow-pack dynamics
- Adjustments to Hydro-meteorological Forcing (HMET) Data
- Melt Water Transport
  - Vertical flow through snow-pack
  - Lateral flow through snow-pack
  - Frozen soil impedes infiltration



Four Snow Melt Models in GSSHA

- Energy Balance (EB) – accounts for the energy fluxes between the snow-pack, ground, atmosphere, and precipitation. If enough energy is input into the snow-pack then melting occurs.
- Temperature-Index (TI) – The amount of melt within the snow-pack is based on the temperature, precipitation, and calibrated parameters. Based on SNOW-17 model.
- Hybrid Energy Balance (HY - **Default**) – modification of the Energy Balance model that accounts for snow-pack temperature dynamics (heat deficits).
- Radiation-Derived Temperature-Index (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

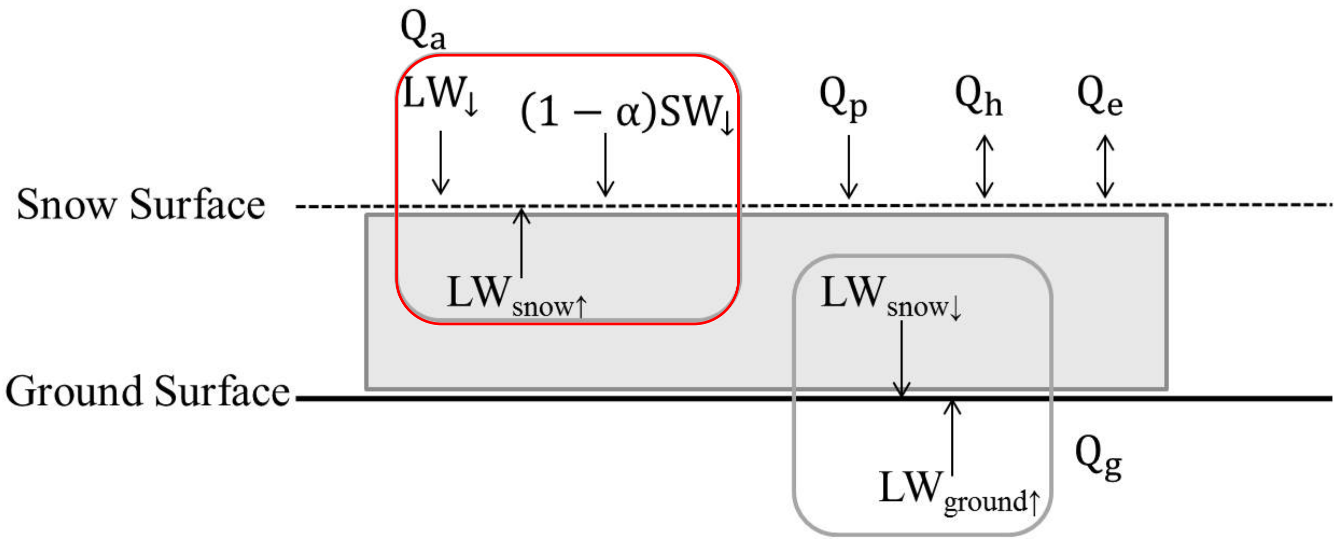
Simulating SWE – EB vs TI (In General)

Snow Energy Balance (EB)

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

Temperature Index (TI)

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



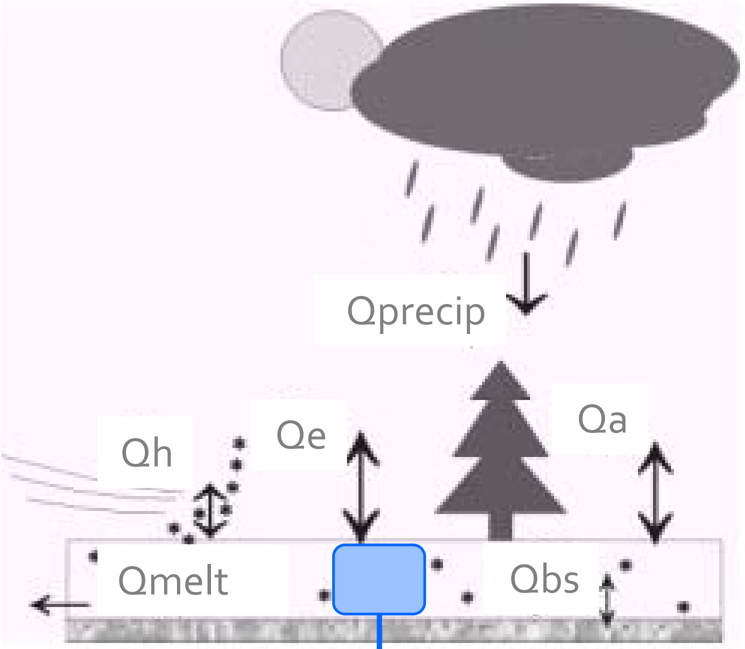
Q_a – Net Radiation
Q_p – Precipitation Heat Flux
Q_h – Sensible Heat Flux
Q_e – Latent Heat Flux
Q_g – Ground Heat Flux
σ – Stefan Boltzmann Constant
ε – Emissivity (0-1)
α – Albedo
L_f – Latent Heat of Fusion

Simulating SWE – EB & HY Methods

$Q_{melt} = Q_a - Q_{bs} + Q_e + Q_h + Q_{precip}$

- Q_{melt} total energy available to melt snow
- Q_a longwave radiation
  f(temperature)
- Q_{bs} longwave emission by soil
  considered constant (27 cal cm^{-2} hr^{1})
- Q_e evaporation and sublimation
  f(temperature, humidity, wind)
- Q_h sensible heat transfer due to turbulence
  f(temperature, pressure, wind)
- Q_{precip} precipitation
  f(precipitation, temperature)

Assumes 1 cc of snow will melt for every 336 Joules
(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
  - Melt under normal circumstances:

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

  - Melt during rain events:

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

- 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

$f_{\boldsymbol{u}}$ = 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

Radiation Representation of T_a	Radiation Representation of T_{rad}
$LW_{\downarrow,air}$	$SW_{\downarrow,net}$ $LW_{\downarrow}$

Snow Surface

Simulating SWE – RTI Method

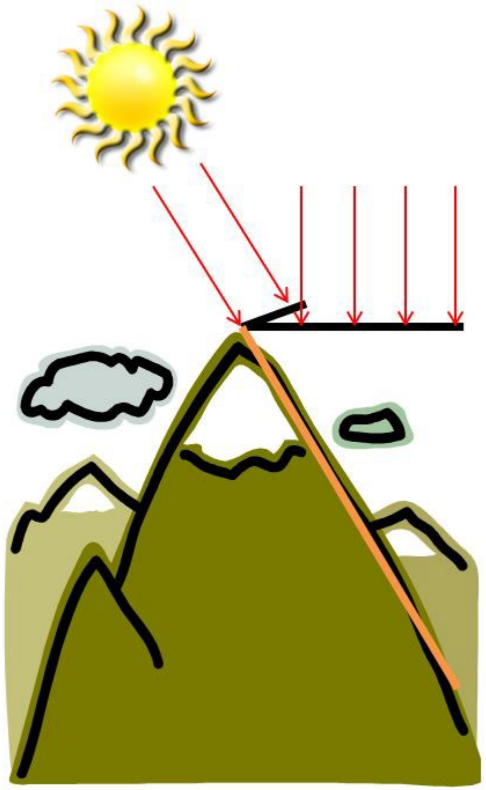
How to get T_{rad}

- 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)

Methods of Simulating SWE - Review

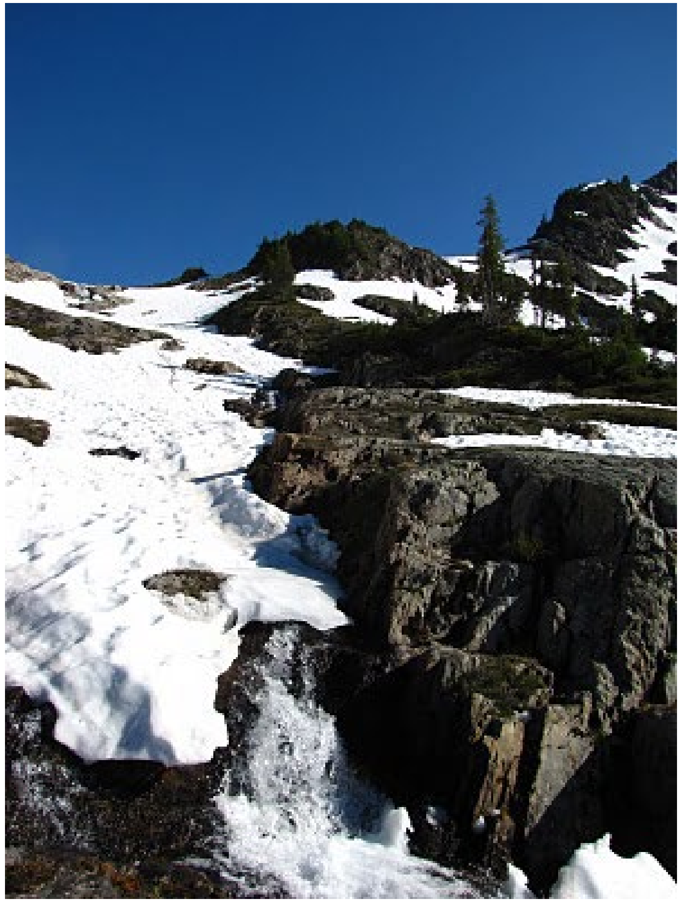
- Energy Balance
  - Uses energy balance algorithms to determine melt, but does not include Heat Deficit.
  - Typically underestimates SWE when topography not accounted for in the model.
- Temperature-Index
  - Uses temperature, precipitation, and calibrated parameters to simulate snow melt.
  - Incorporates 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
  - <u>SIMPLE:</u> Define a constant temperature lapse rate, then GSSHA adjusts temperature. Relative humidity and pressure can also be adjusted. Typically used.
  - <u>COMPLEX:</u> Let GSSHA automatically adjust temperature, pressure, and relative humidity based on elevation using mean adiabatic lapse rate (MALR).
  - <u>PUNT:</u> Input raster-based forcing data from an atmospheric model, such as GFS (US) or ECMWF (European)

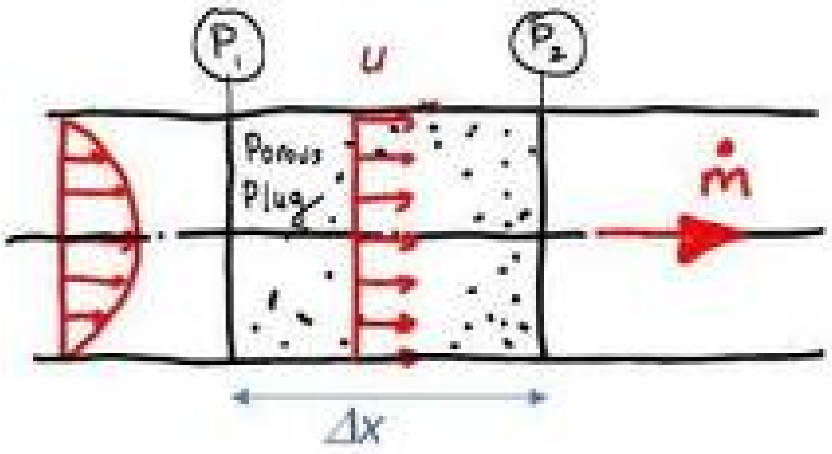
Melt Water Transport

- Snow melt water is transported through the system in several ways:
  - Vertically through the snow-pack
  - Laterally through the snow-pack
  - Infiltration into soil (frozen/unfrozen)
  - Overland flow
  - Groundwater flow
  - Channel flow



Melt Water Transport – Basics

- Flow through the Snow-pack is simulated Porous Media Flow.
  - A form of Darcy's Equation is typically used to determine flux through the snow-pack, both vertically and laterally.
  - Vertical flow is typically considered unsaturated flow.
  - Lateral flow through the the snow-pack is typically considered saturated Flow.
- GSSHA uses the SNAP Model (Albert 1998) to Determine Snow-pack Properties in each Computational Cell:
  - Saturation
  - Saturated / unsaturated hydraulic conductivity
  - Effective porosity

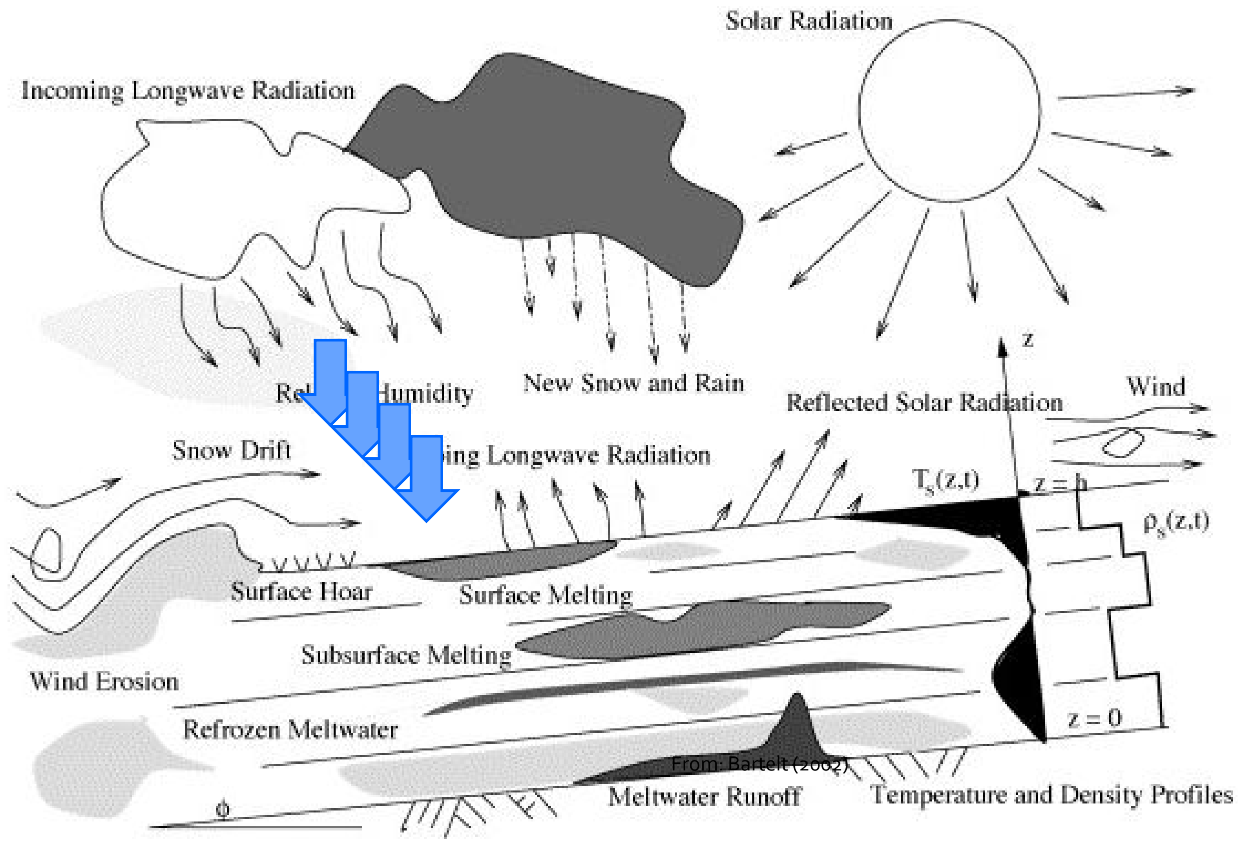


Melt Water Transport – Vertical Flow

- Vertical Flow is considered unsaturated flow
  - Effective hydraulic conductivity (k_w) changes with the degree of saturation (S).

$$k_w = kS^n$$

  - Effective porosity also changes with the degree of saturation.
- While flow is simulated through a single snow layer, multiple wetting fronts through the pack can occur – based on both Albert (1998) and Bengtsson (1981).



Melt Water Transport – Lateral Flow

- Once the melt water reaches the ground it is transported as saturated Darcian flow according to methods developed by Colbeck (1974) to determine the flux between each cells.

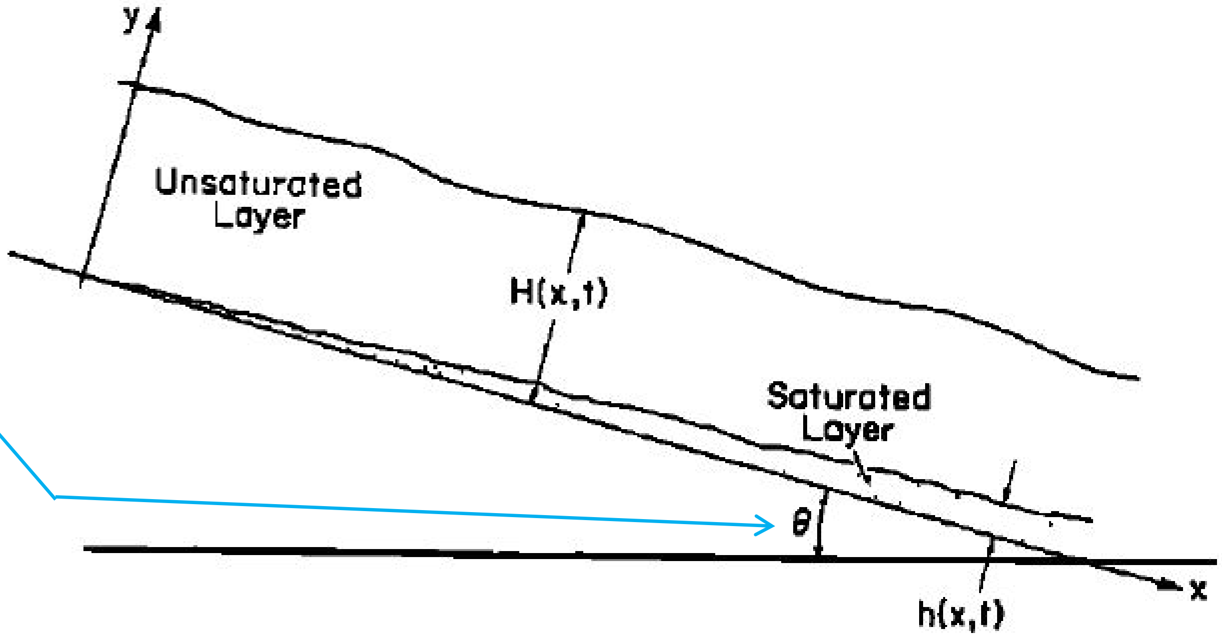
Hydraulic Properties of Water Constant

Hydraulic Conductivity

Effective Porosity

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

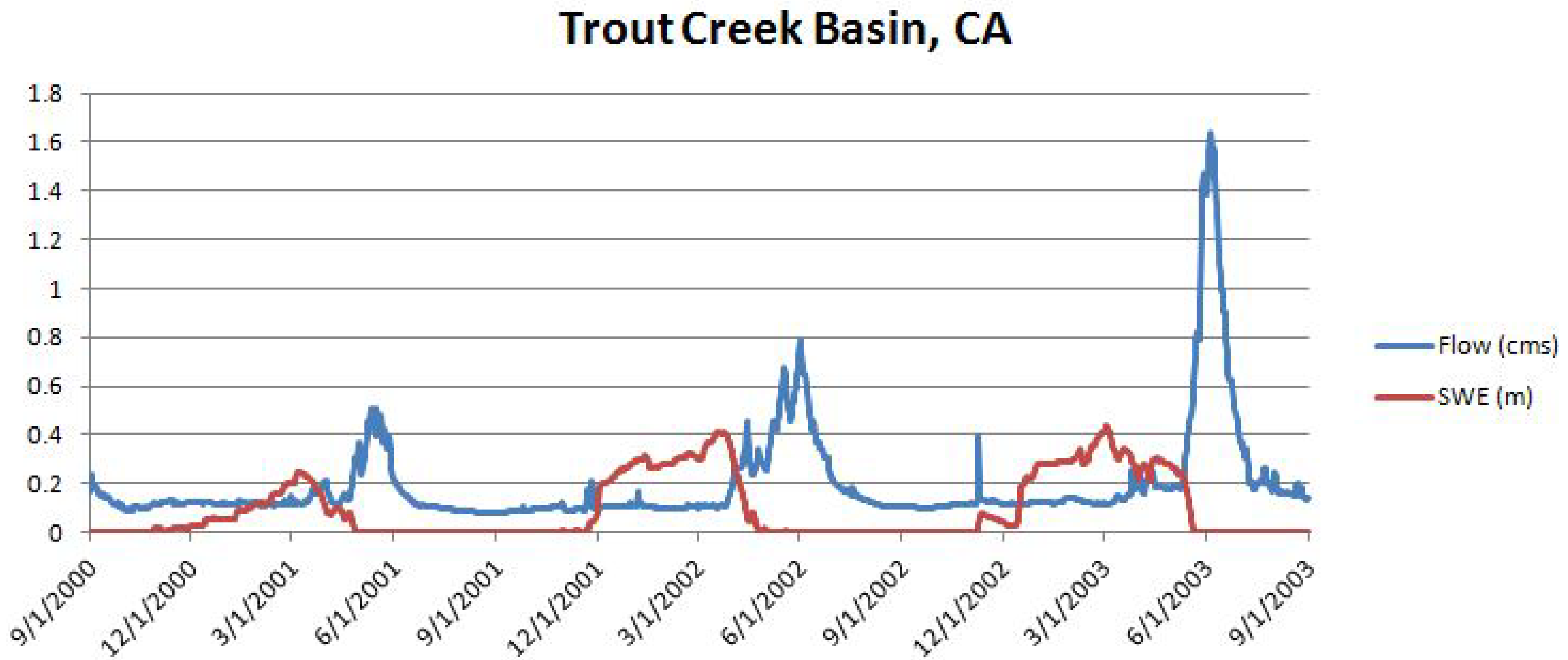
Lateral Flux



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.



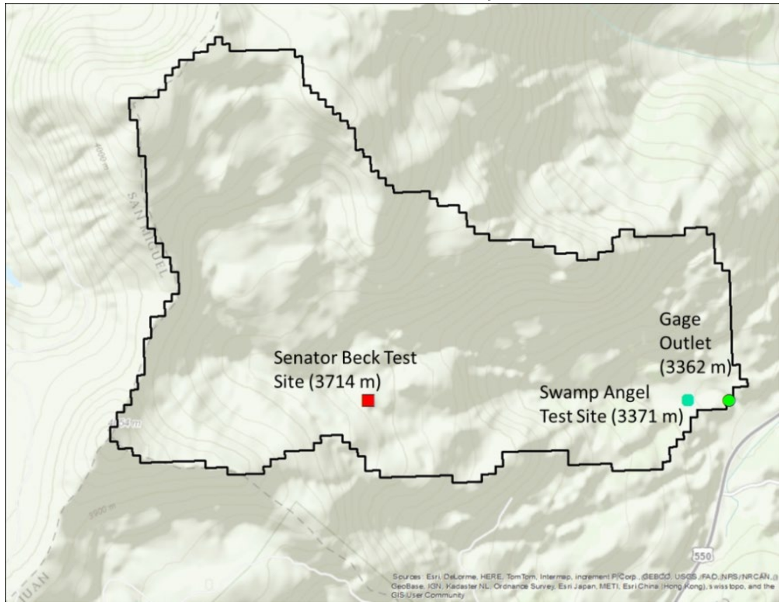
Melt Water Transport - Review

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

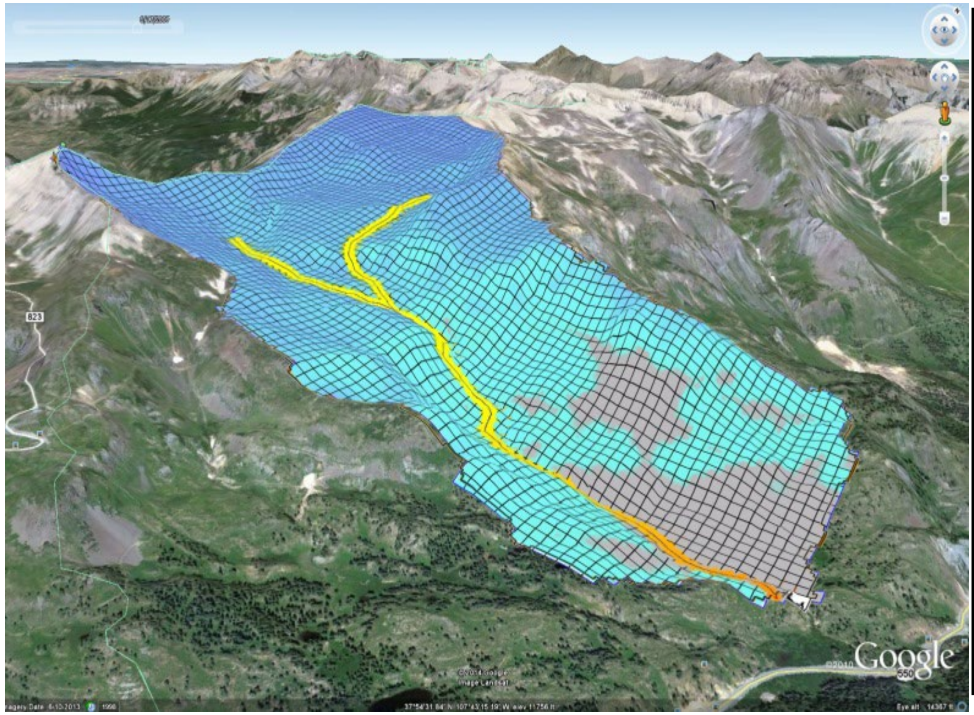
Test Basin: Senator Beck Basin, CO (SBB)

- 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)

Senator Beck Basin, CO



Test Basin: Senator Beck Basin, CO (SBB)

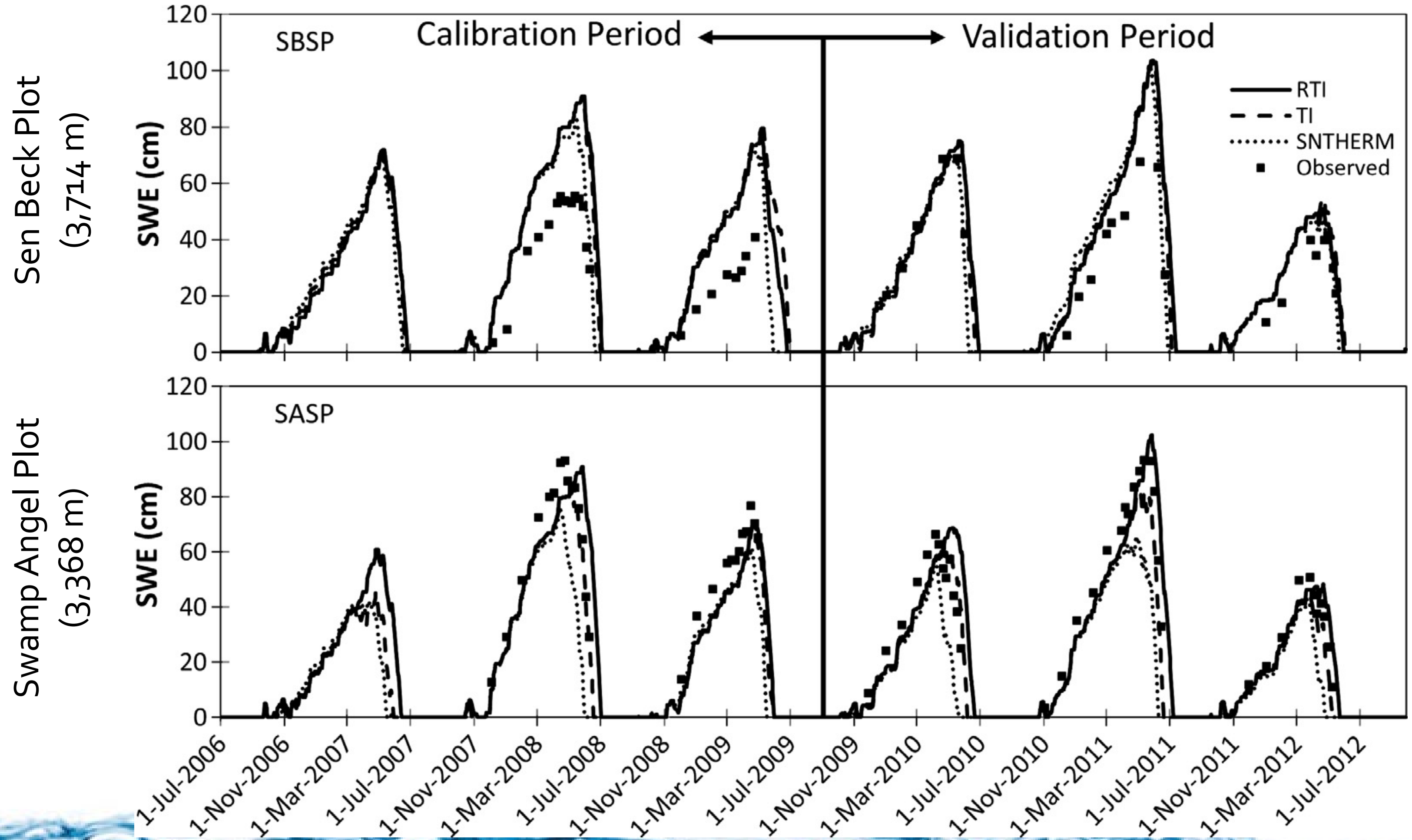


Highlights:

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

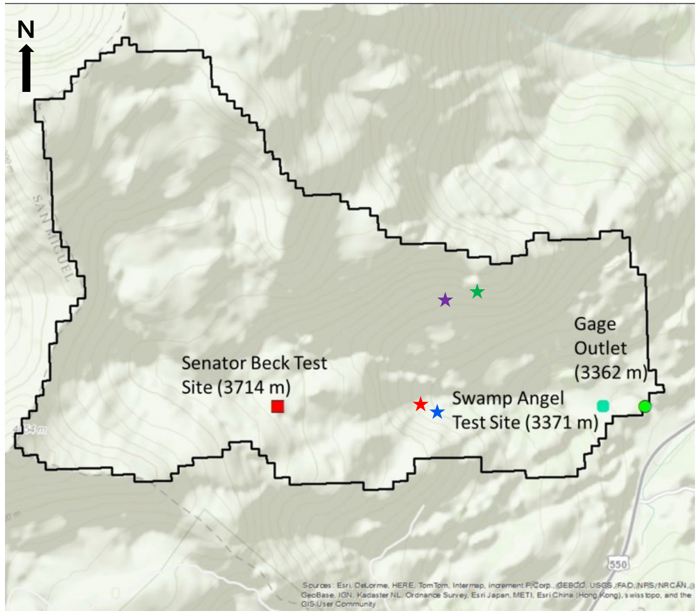
SWE using TI and RTI Model

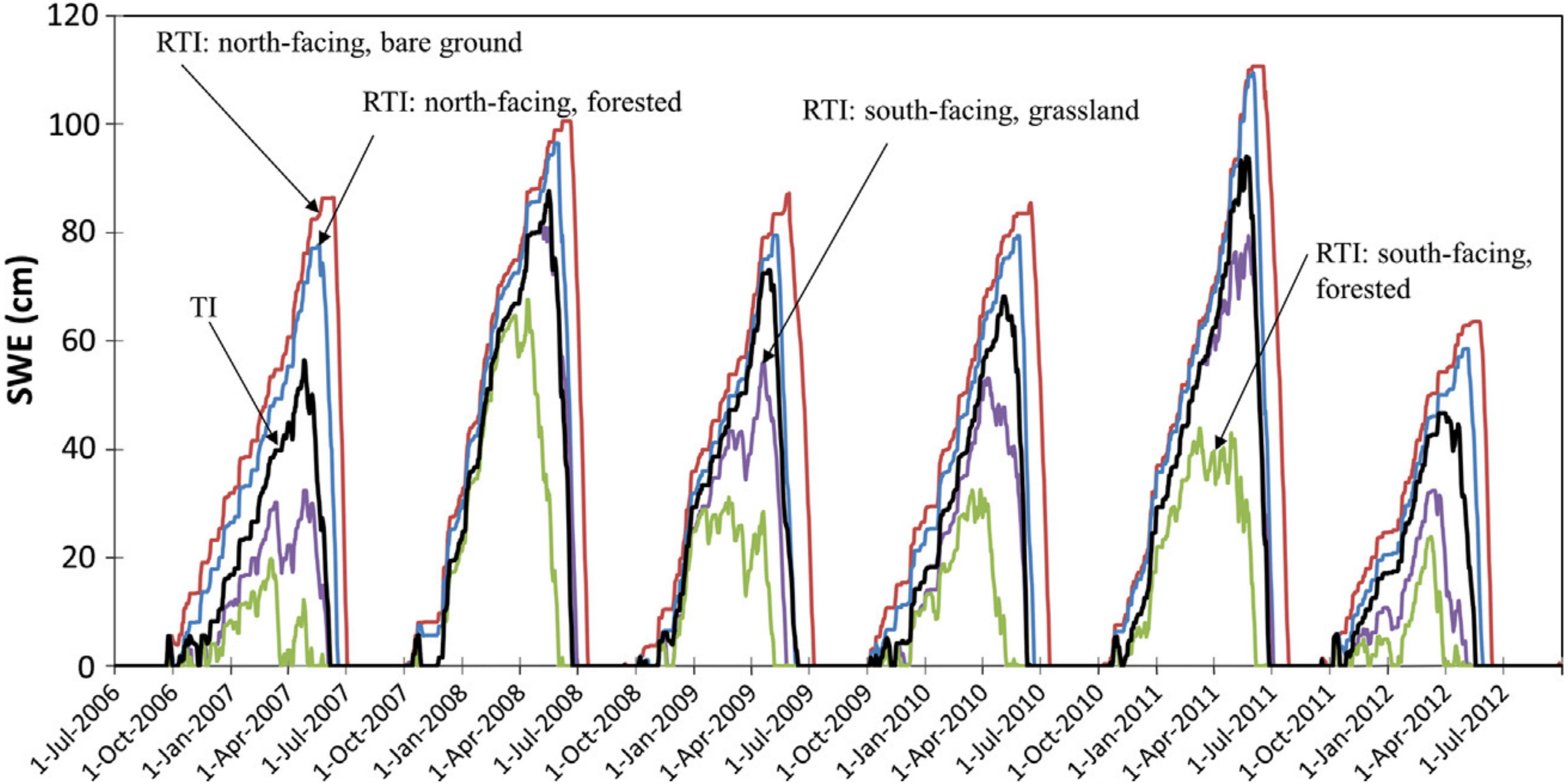
- Modest improvement in SWE at two gage sites



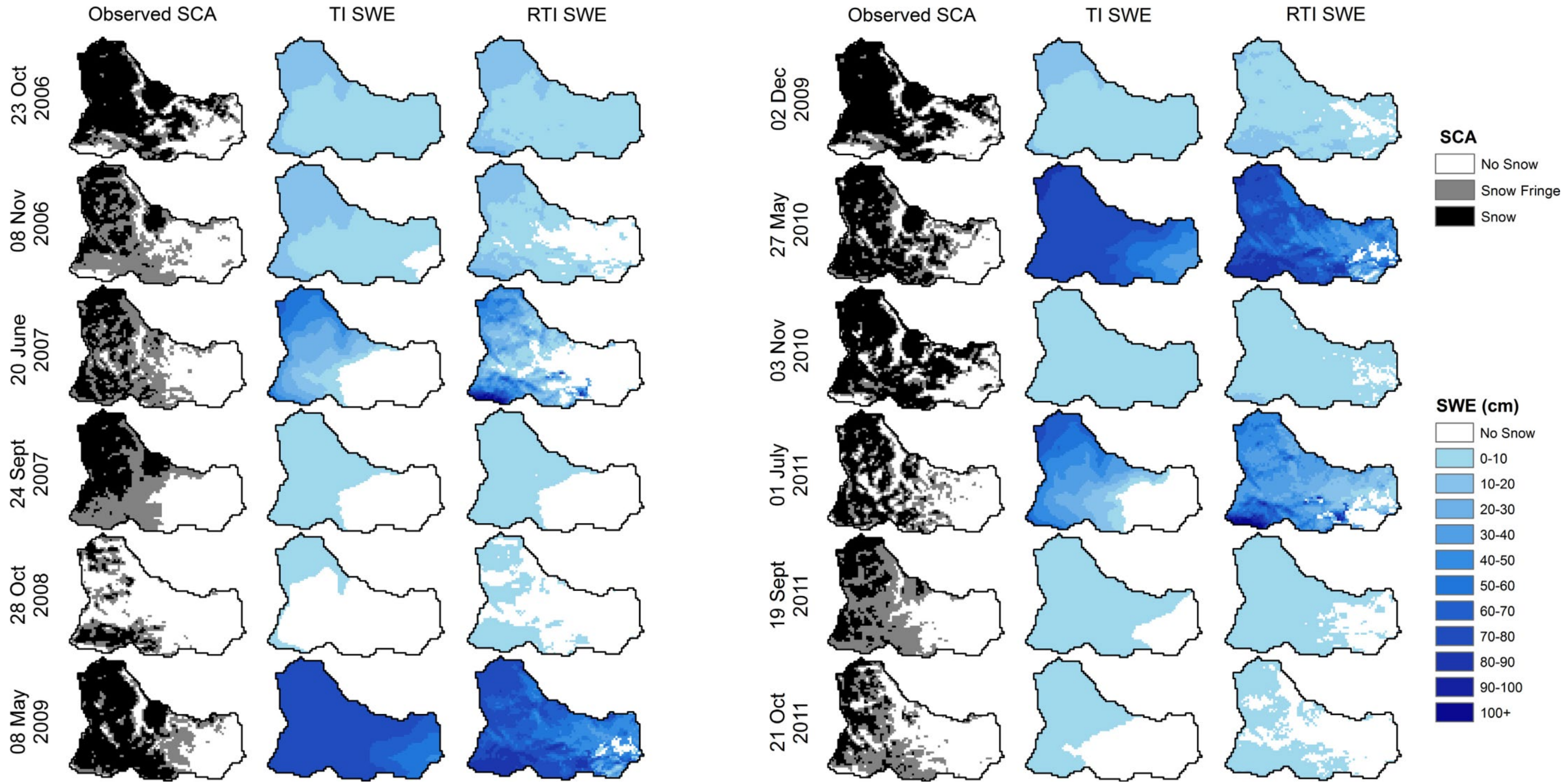
SBB using TI and RTI Model

- Variability in SWE due to topography and vegetation

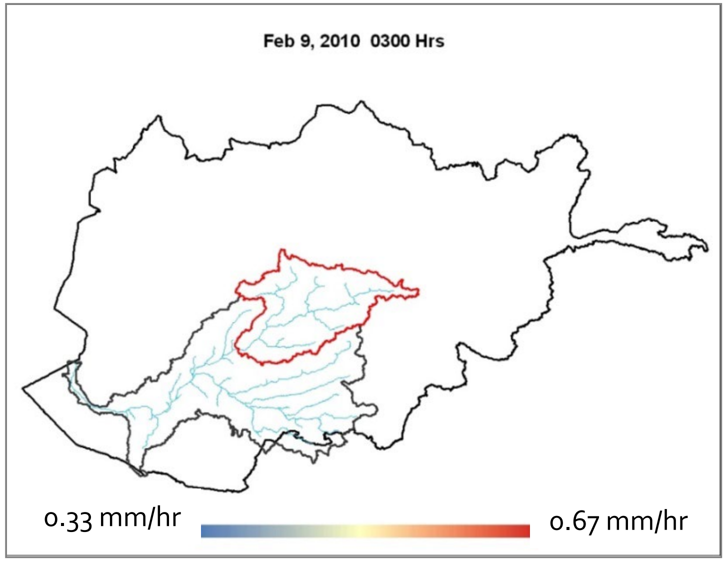




SCA using TI and RTI Model



Helmand River Basin, Afghanistan

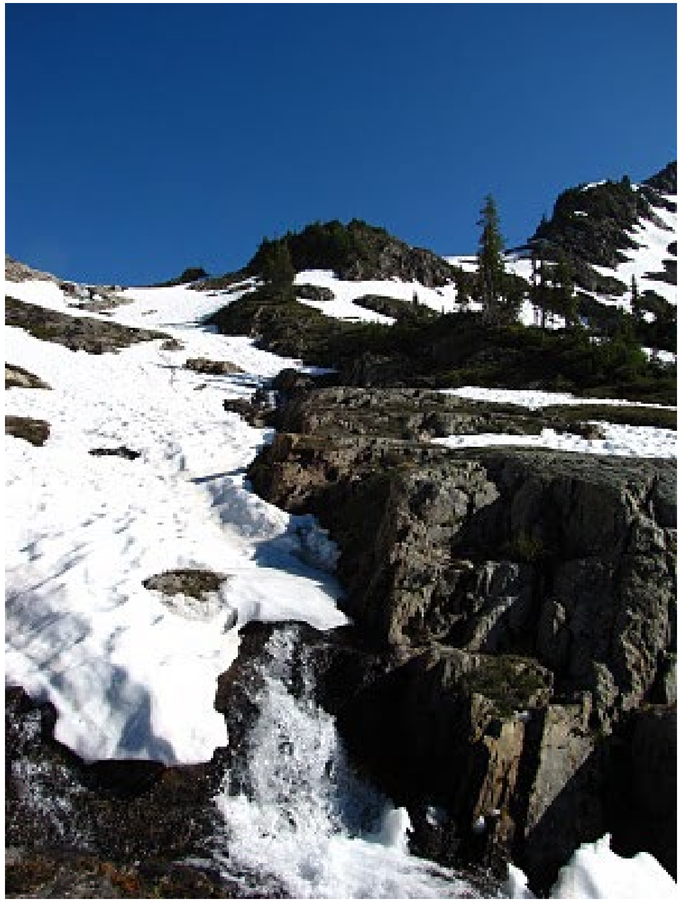


- **Watershed-based**
- **Manual setup**
- **Limited forecasting window**

Upper Helmand Basin Simulation: January – June 2010

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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