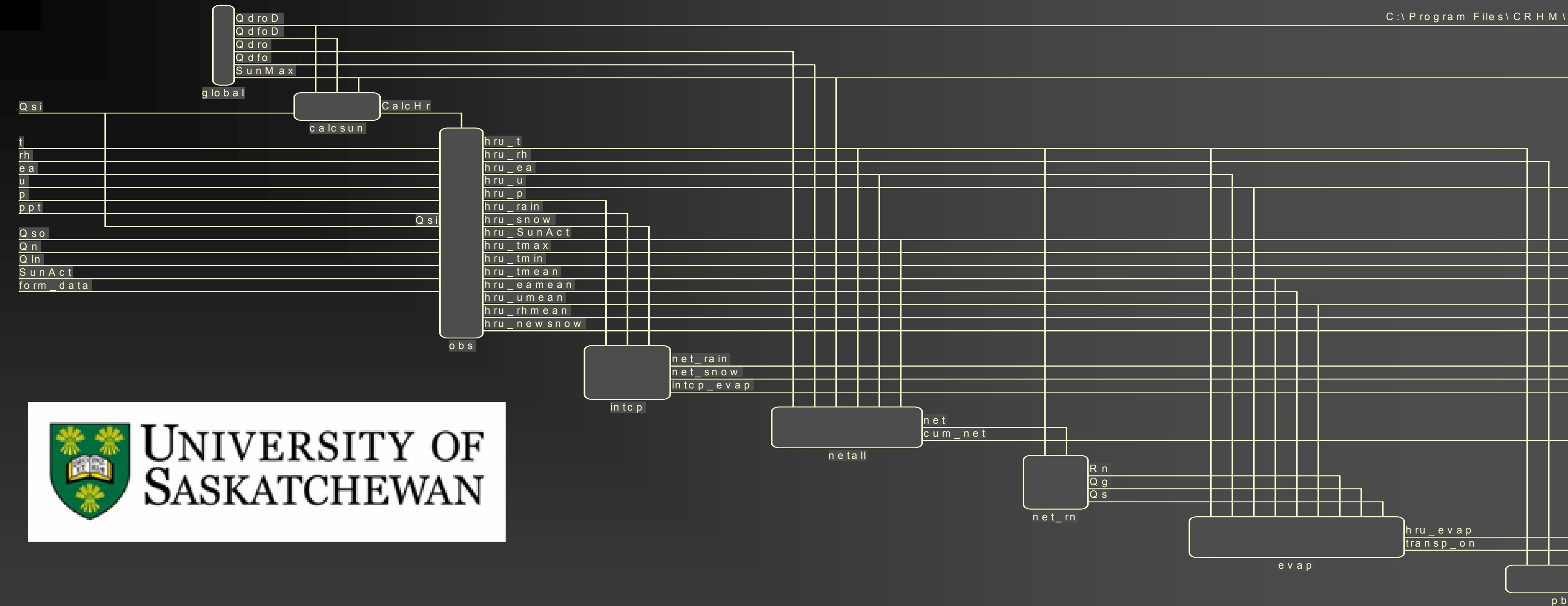

Cold Regions Hydrological Model Platform, CRHM: The Course

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Objectives of Course

- Familiarisation with basic hydrological principles necessary for modelling
- Introduction to CRHM platform
- Review of components and features of CRHM
- Familiarisation with examples of hydrological models using CRHM
- Ability to create a purpose built hydrological model using CRHM
- Everyone becomes a modeller

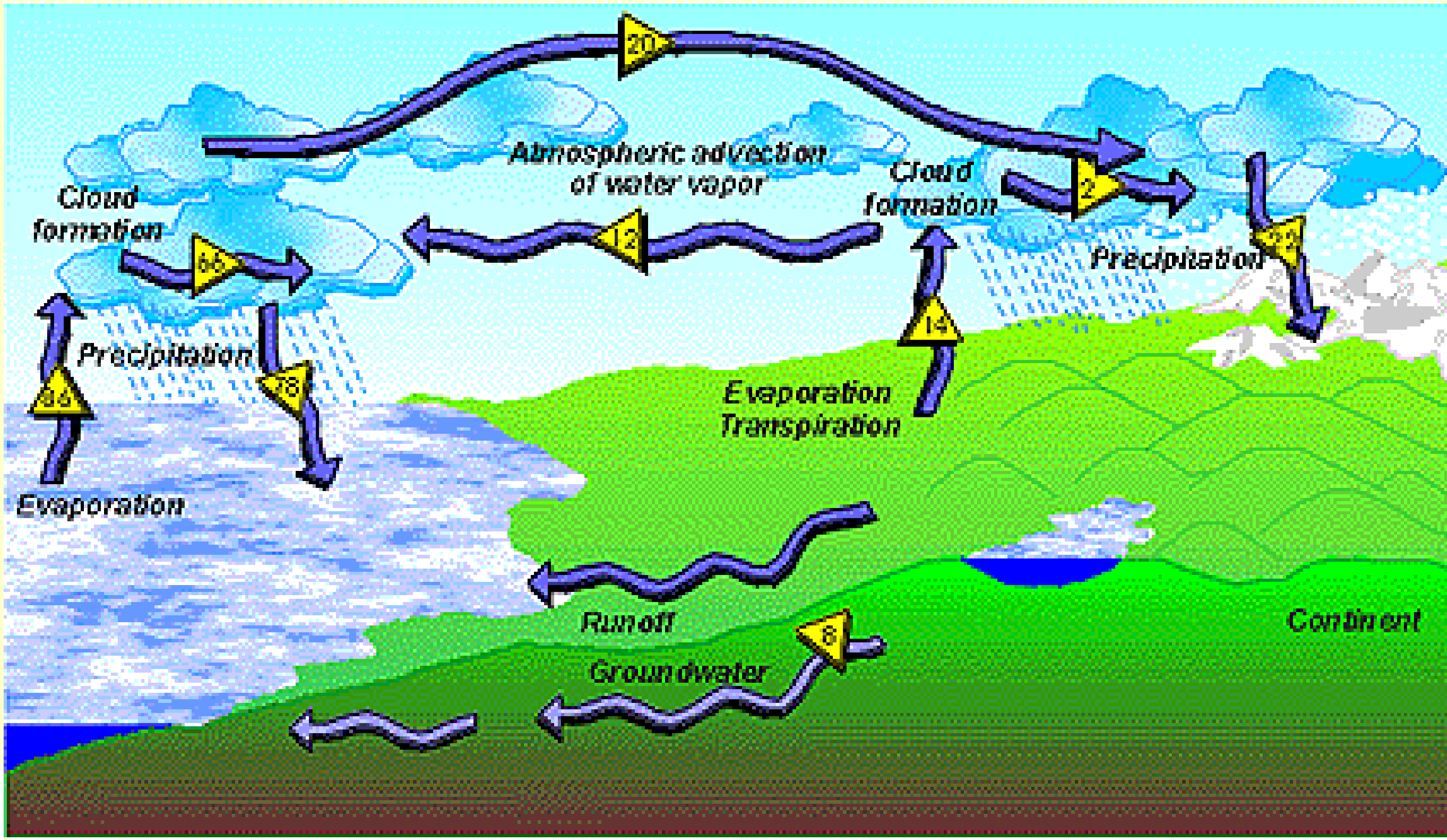
Structure of Course

- Review philosophy of modelling, model structure, processes, model components
- Review of model modules and features using Help File and model examples
- Review of example projects
- Lab – YOU make a hydrological model from scratch.

Models and Reality in Hydrology

- The Hydrological Cycle is manifested with strong regional variations around the world.
- Hydrologists have created a vast number of models (assumptions) to describe some aspects of this cycle.
- It is generally not necessary or likely that one hydrological model approach is applicable to all environments, scales or predictive interest
- Physically-based models attempt to describe reality faithfully (but do not completely succeed)
- Hydrological models predict most successfully in catchments near where they were derived
- Logical selection and design of model strategy, structure and their inherent assumptions are governed by local problems and local hydrology – **this is not just parameter selection**.

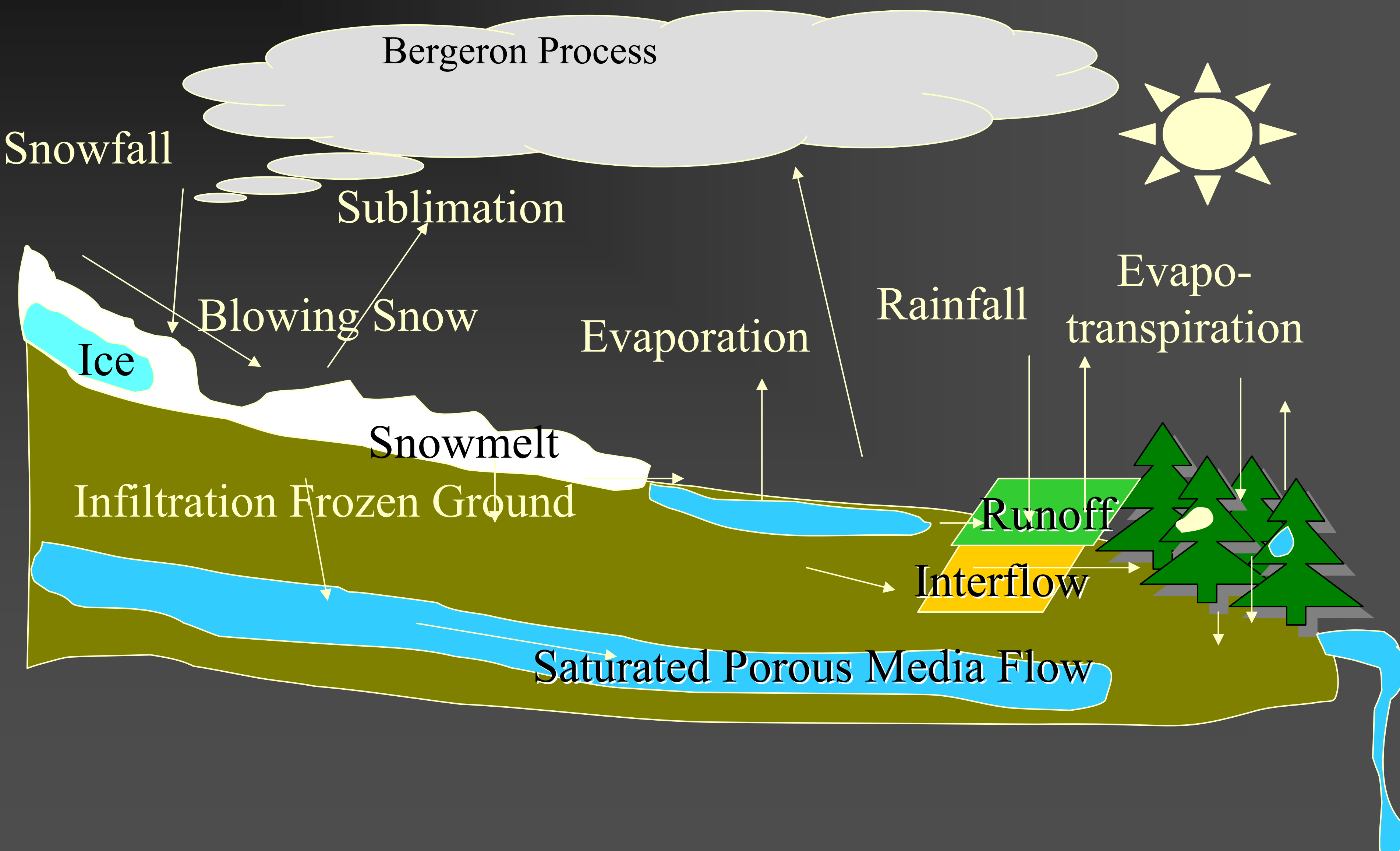
Hydrological Cycle – elsewhere….



The hydrological cycle model.

The hydrological cycle model with percentages and directional arrows denoting flow paths. Global average values are shown as percentages.

Cold Regions Hydrological Cycle



Distinctive Aspects

- Snow storage, redistribution, melt
- Infiltration to frozen ground
- Thick organic soils, sometimes frozen
- Poorly defined drainage areas
- Cool surface for evaporation
- Frozen rivers and lakes
- Seasonality of energy inputs
- Sparse(r) data network

Why Physically-based Hydrological Modelling?

- **Robust** - can be more confidently extrapolated to different climates and environments and performs better in extreme situations (floods, droughts).
- **Scientifically Satisfying** - represents a compilation of what is understood about hydrology.
- Can **interface with chemistry and ecology** - aquatic chemistry and hydroecological modelling require a sound hydrophysical base.
- Elevates hydrological *practice* to hydrological *science*.

What field information can help us design models?

- Identification of the principles governing the primary physical processes responsible for most water movement in basin (structure and processes).
- Fundamental boundary and initial conditions that affect these processes (parameters).
- Length scales for self-similarity and variability associated with the properties affecting these processes (scale).

Process observation and modelling

- Understanding of hydrological processes results from observing at multiple scales.
- Modelling in hand with observations provides a way to test and anticipate algorithms, gaps & assumptions

- Different processes are important in different environments
- No universal algorithm scale, structure, approach

Necessary Elements of Cold Regions Hydrological Modelling

consideration of the following:

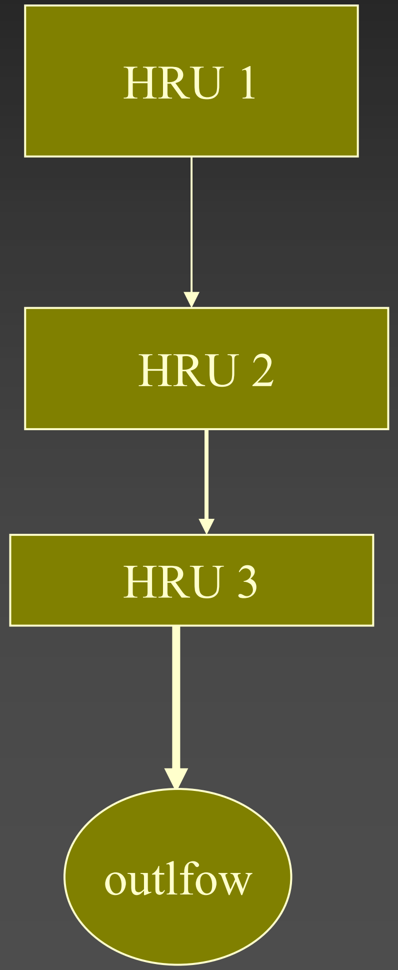
1. Transport of water in liquid, vapour and frozen states (runoff, percolation, evaporation, sublimation, blowing snow);
2. Coupled mass and energy balances;
3. Phase change in snow & soils (snowmelt, infiltration in frozen soils, soil freezing and thawing);
4. Snow and rain interception in forest canopies;
5. Episodic flow between soil moisture, groundwater and base flow.

Hydrological Response Units

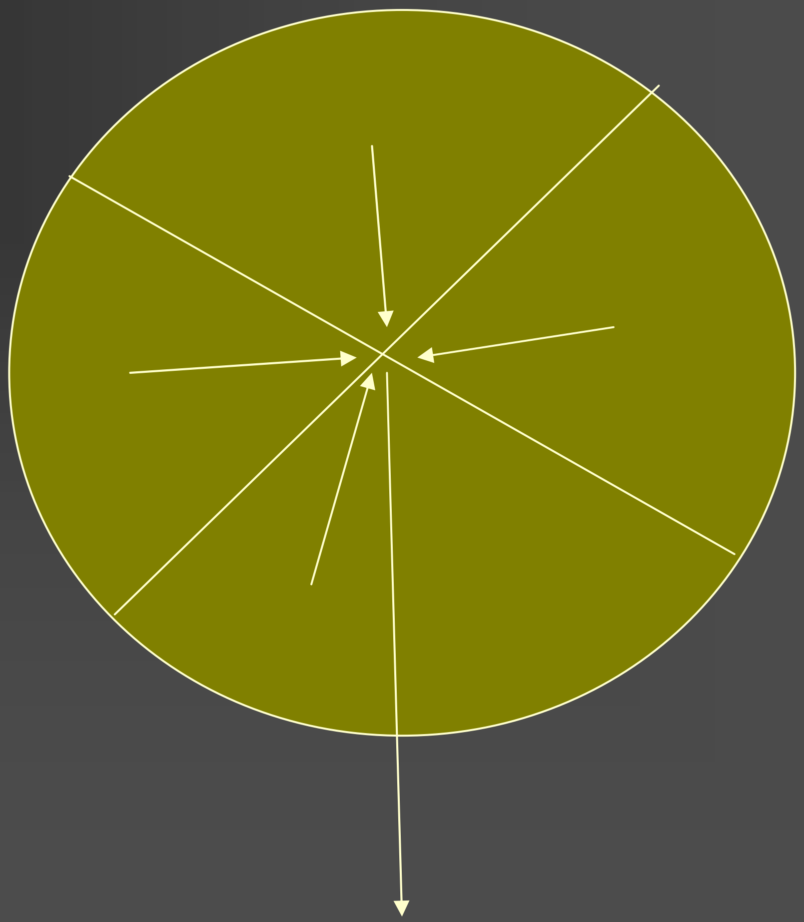
- A HRU is a spatial unit in the basin that has 3 groups of attributes
  - biophysical structure - soils, vegetation, slope, elevation, area (determine from GIS, maps)
  - hydrological state – snow water equivalent, snow internal energy, intercepted snow load, soil moisture, water table (track using model)
  - hydrological flux - snow transport, sublimation, evaporation, melt discharge, infiltration, drainage, runoff (determine using fluxes from adjacent HRU)
- HRU need not be spatially continuous but must have some approximate geographical location or location in a hydrological sequence

Hydrological Response Units

Sequential HRU –
landscape connectivity



Grouped HRU – must drain to stream



Rationale for CRHM Platform

- Frustration with adding process algorithms to existing hydrological models
- Frustration with trying to fit inappropriate structure of existing models to basins
- Frustration with inability to fit gridded or other conceptual spatial representations to reality.
- Frustration with models that only focus on streamflow response to precipitation
- Frustration with attempts to teach modelling to hydrologists using older computer languages, no user interface, limited documentation of models
- Frustration with the lack of a graphical system to evaluate model inputs and outputs

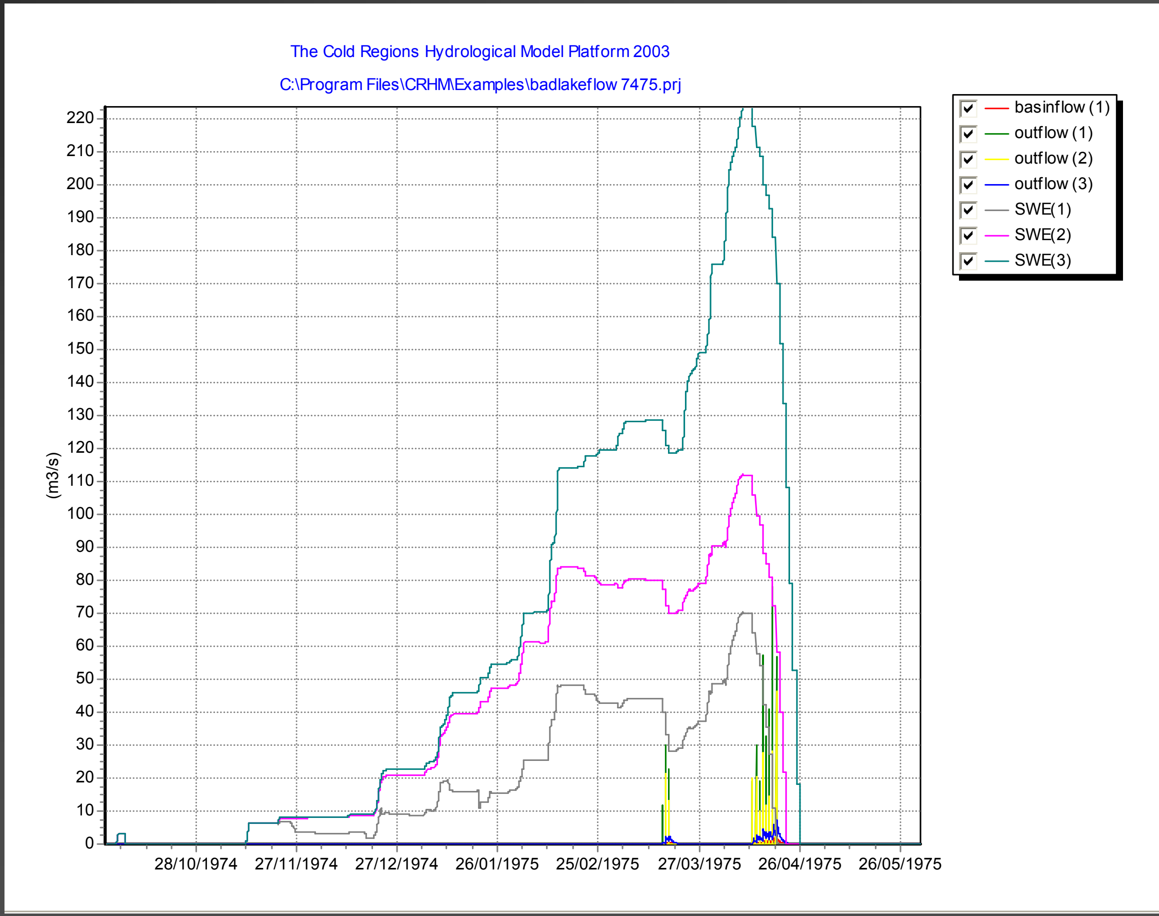
CRHM Objectives

To develop a *hydrological cycle simulation system* that:

- **is spatially distributed such that the water balance for selected surface areas can be computed;**
- **uses natural landscape units that have hydrological importance;**
- **is physically based so that the results contribute to a better understanding of basin hydrology and are robust and so that process parameters can be transferred regionally;**
- **is sensitive to the impacts of land use and climate change;**
- **Reflects landscape sequencing (e.g. catena) in natural drainage basins;**
- **does not require the presence of a stream in each land unit;**
- **is flexible: can be compiled in various forms for specific needs;**
- **is suitable for testing individual process algorithms.**
- **is easy to use for all hydrologists and useful for teaching**
- IS NOT DEPENDENT UPON CALIBRATION!

Cold Regions Hydrological Model Platform (CRHM)

- Started in late 1990s as NWRI land use hydrology model. BEERS
- Attempted to write Canadian modules for USGS MMS
- 1999 Tom Brown developed CRHM platform in windows environment
- Development of modules from MAGS, PAMF, NERC, Quinton-CFCAS, IP3 and other research
- Multiple developers: Brown, Gray, Granger, Hedstrom, Pomeroy



Building Physically-based, Distributed Hydrological Models with CRHM

- uses a library of physically-based hydrological and energy balance process modules;
- handles the following aspects of the modelling process:
  - data pre-processing,
  - module and model building,
  - results analysis
- is easy to use: employs a Windows environment with pull-down menus.
- has an extensive HELP file and open module code
- DLL version permits creating your own module and linking it into CRHM – community model development

Cold Regions Hydrological Model

DATA COMPONENT

Preparation of spatial and meteorological data.

- Spatial data (e.g. basin area, elevation, cover type) is analyzed using a Geographic Information System (GIS) that assists the user in basin delineation, characterization and parameterization of Hydrological Response Units (HRU). CRHM takes in ArcGIS files with this information. The user can also simply enter this information in a menu for less complex basins
- Time-series meteorological data include air temperature, humidity, wind speed, precipitation and radiation.
- Adjustments for elevation (lapse rate), snowfall versus rainfall, interpolation between input observations (stations)
- Filters permit adjustment to data, changing time interval, creating synthetic data using mathematical functions, interpolating data
- Unit conversions to consistent SI units
- Visualization of input data allows checking for quality

Observation Files

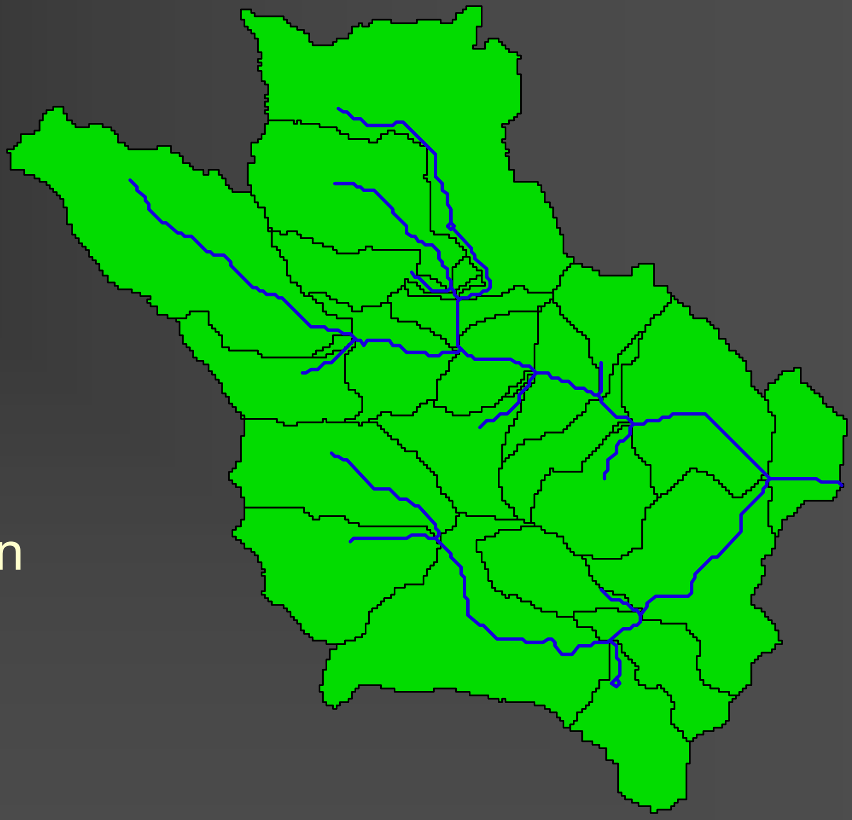
- Created using weather station or other outputs
- Sets model time step interval
- Possible to have observations with varying time steps
- Interpolation, synthesis tools to fill in missing data or create synthetic data
- Observations are interpolated onto HRU
- Visualization tools useful in assessing reliability of observations

Parameters

- Parameters describe basin, define HRU and set operation of process modules (examples: tree height, soil type, fresh snow albedo)
- Parameters set based upon understanding of basin and HRU (limits imposed in model)
- Assumption that substantial transferability of process parameters exists for similar HRU
- If not known from basin then can be looked up or guessed at
- No facility to calibrate parameters exists in CRHM (but some have figured it out anyway)

CRHM GIS Interface

- The interface automates the parameterization of CRHM.
- UseTOPAZ and ARC/INFO AML coding to divide the watershed into sub-basins.
- Each sub-basin is defined as a polygon with drainage information, ID, and can be assigned other parameters.
- The next step is to link the sub-basin to other spatial information (land cover, fetch, etc.) in order to derive relevant HRU’s.



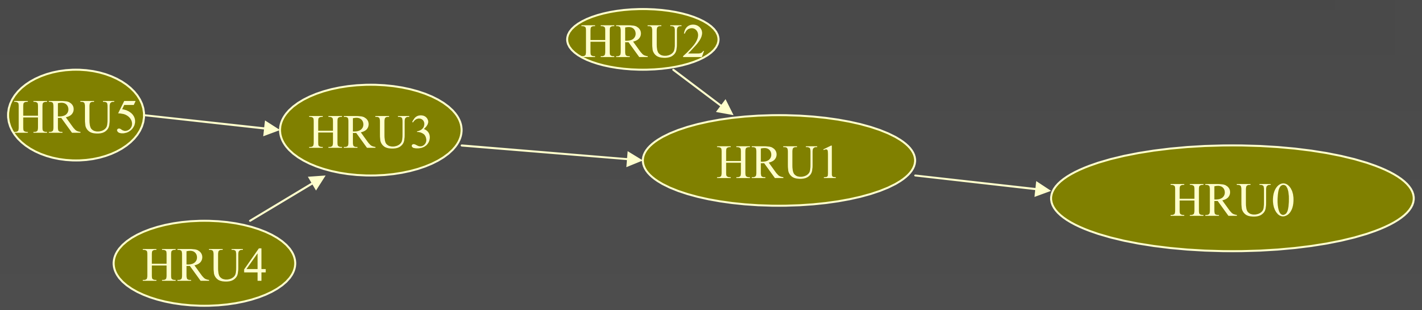
Cold Regions Hydrological Model

MODEL COMPONENT

- Utilizes Windows-based series of pull-down menus linked to the system features.
- Modules, (process algorithms) are selected from the library and grouped together by the CRHM processor.
- Modules have a set order of execution with a common set of variables and parameters.
- Modules are created in C++ programming language.
- Macro modules can be created from within the model using a simple macro language.

CRHM Routing

- HRU routing conceptualizes more complex reality in characteristic sequences
- HRU to HRU
- Can include lake, wetland
- Groundwater routed separately from near surface and surface water
- Flexible – HRU can route sequentially or accumulate in an outflow HRU



Groups and Structures to Adapt to Real Basin Hydrology

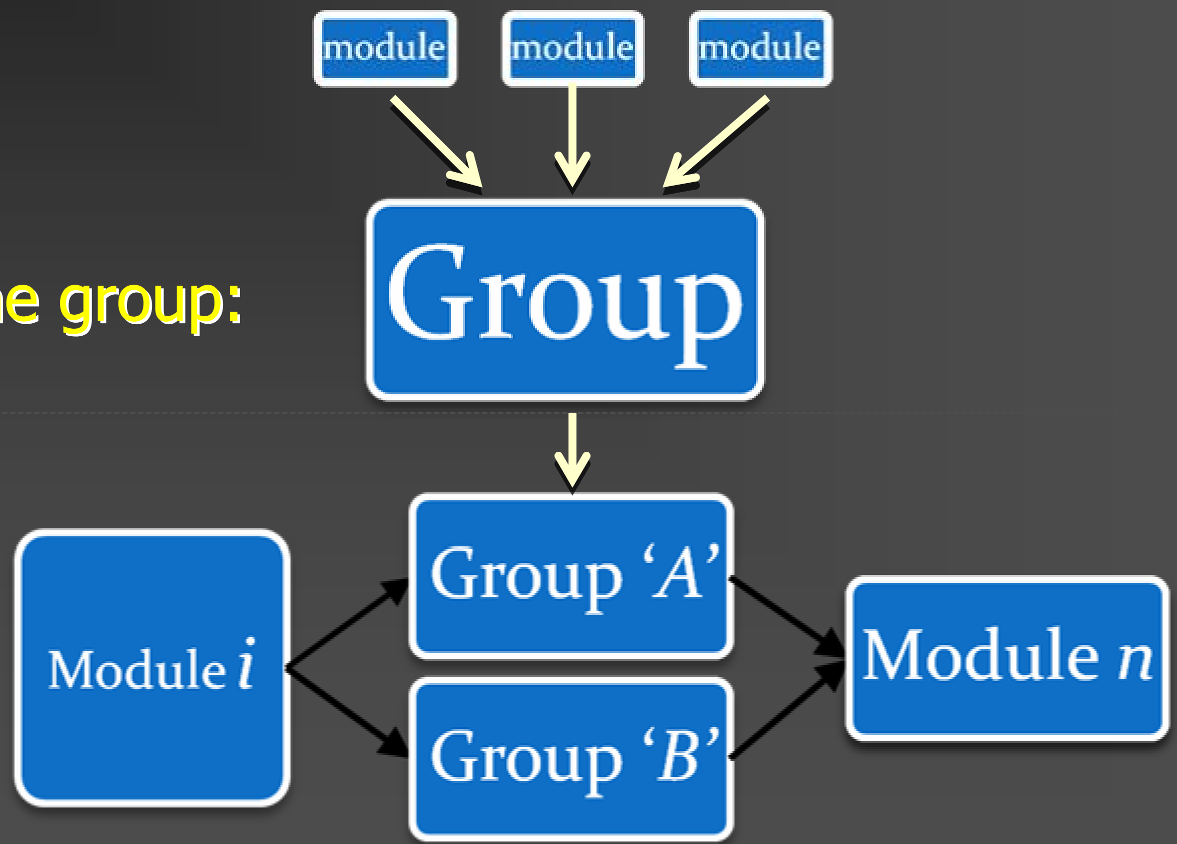
- **Group. A collection of modules executed in sequence for all HRUs.**
  - collection of modules which can be used in place of specifying the individual modules.
  - if groups are defined with same modules, then can execute modules in parallel using different parameters or driving observations.
  - If groups are defined as different 'models', it is possible to execute the models in parallel using identical parameters and driving observations to check different responses.
- **Structure. A parallel collection of modules or Group assigned to an HRU and run in sequence.**
  - Comparison of algorithms
  - Customization of model to HRU characteristics - diverse sets modules to be representative of the HRU and basin.
  - Dynamic structural change *due to excess water or lack of it.*

Groups

- A collection of modules executed in sequence for all HRUs.

Define group:

Model incorporation:



Groups

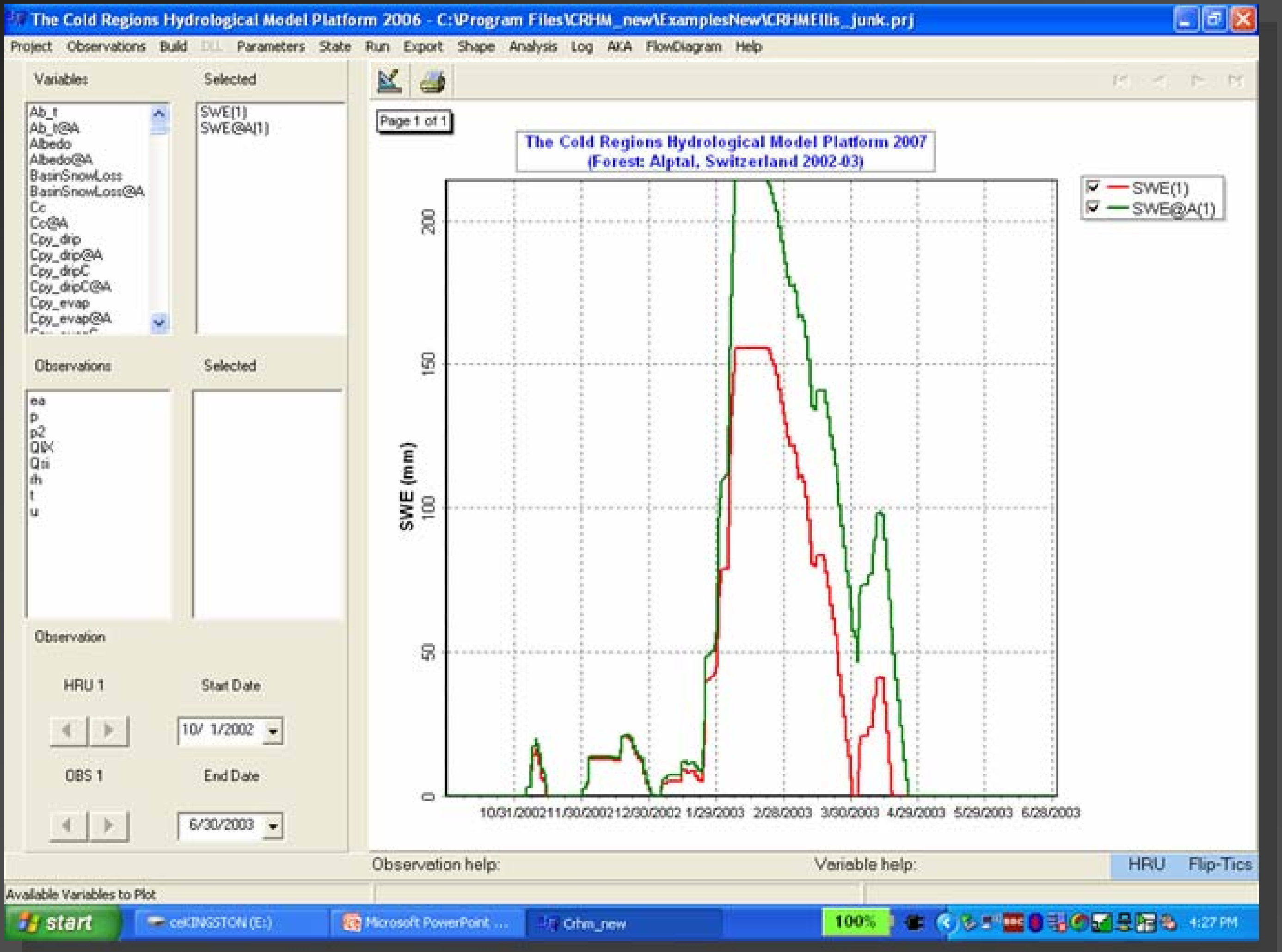
Group application:

1. If groups are defined with the same modules, it is possible to execute the models in parallel using different parameters or driving observations.

2. If groups are defined as different modules, it is possible to execute the models in parallel using identical parameters and driving observations to check different responses.

Groups

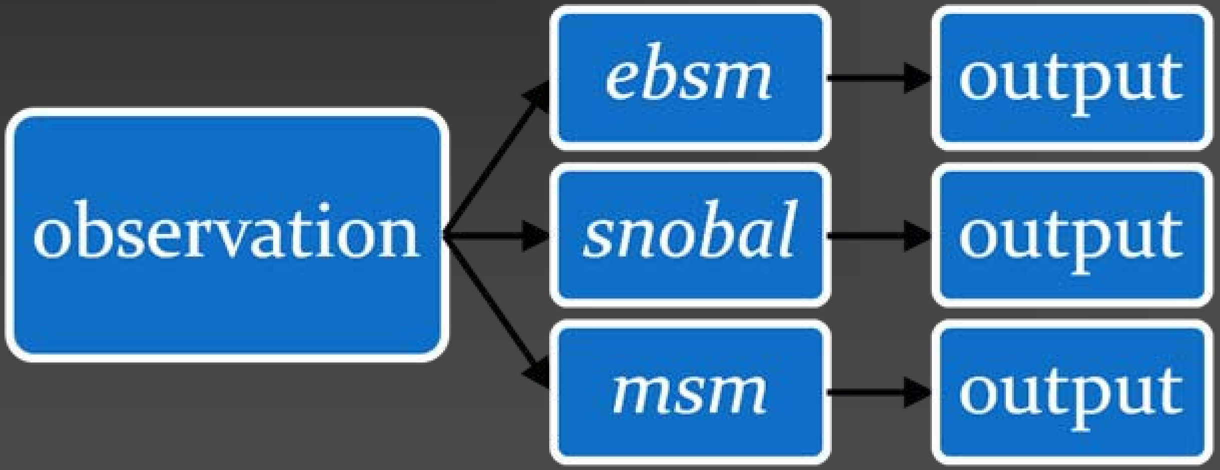
- E.g. estimate sub-canopy SWE for forests of differing leaf-area-index



Structures

- Running <u>similar</u> modules in *parallel*

e.g. snowmelt



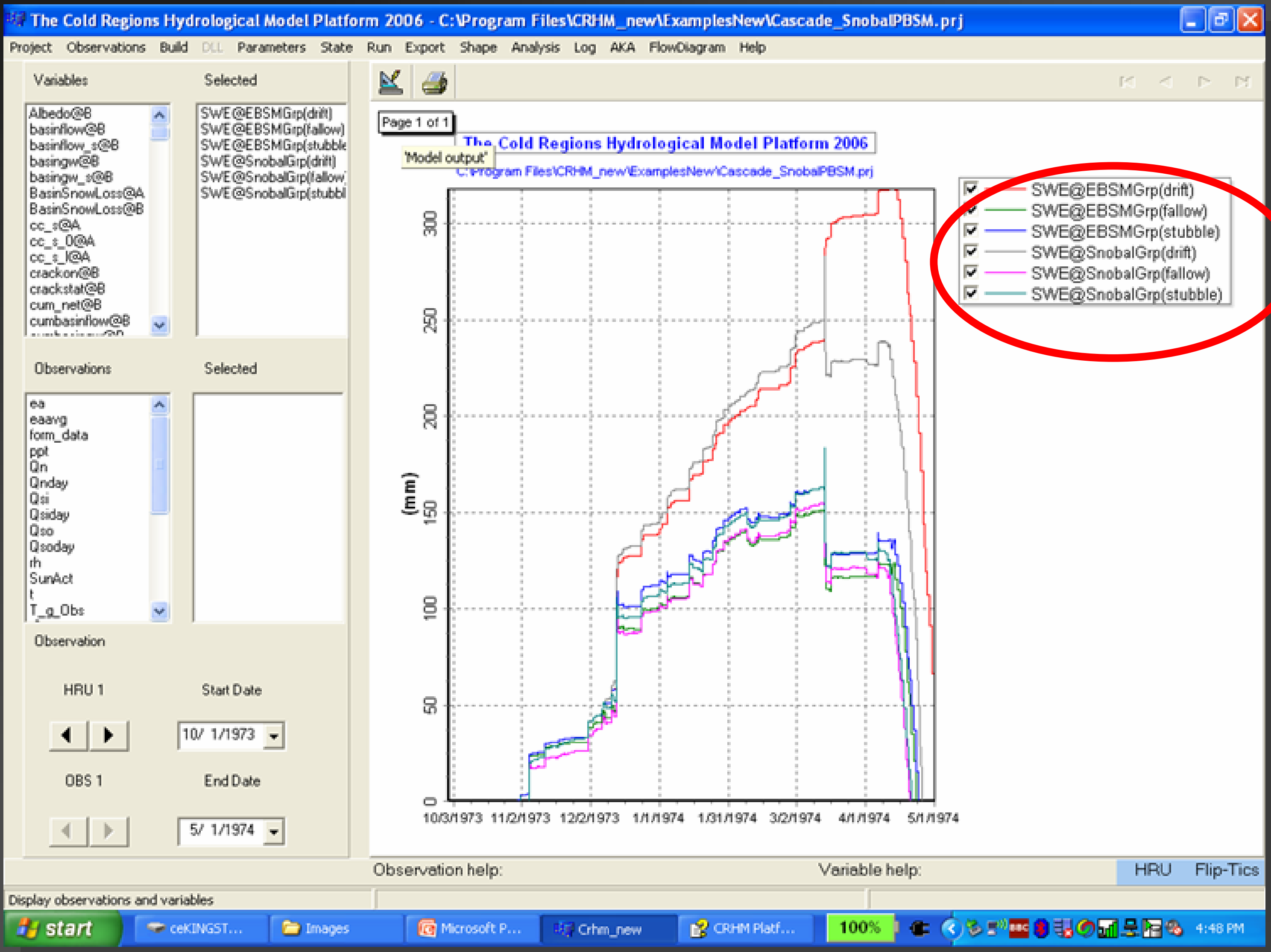
Structures

Structure application:

1. Algorithm comparison. Intercomparison of algorithms with similar driving data and parameters
2. Mixed Land Use in Basin. Permits differing model structure for differing HRU (e.g. forest versus farmland
3. Dynamical Structural Change. Permits change in model structure in response to changing hydrological state (e.g. change grassland to a slough when leaving a drought). The decision about which module to use would be made by a preceding module based upon the availability of moisture.

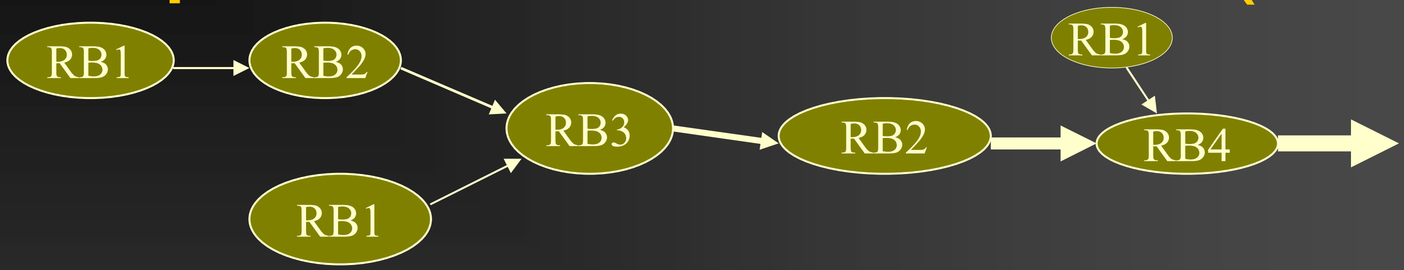
New Capabilities: Structures

e.g. comparison of SWE estimation by *EBSM* and *SNOBAL:*



Able to give structures meaningful names

Representative Basins (RB)



- Permits upscaling of CRHM to large, complex basins using groupings of sub-basins
- RB sub-basins determined in detail as assemblies of HRU
- RB types repeated with identical module structure, similar parameters but differing geometry
- Many RB types allowed in the larger basin
- Muskingum routing module routes RBs through streams, lakes, wetlands
- Basin model is a network of RBs linked by a routing module.

Cold Regions Hydrological Model

ANALYSIS COMPONENT

- Used to display, analyze and export results (Excel, ASCII, Obs).
- Statistical and graphical tools are used to analyze model performance, allowing for decisions to be made on the best modelling approach.
- Sensitivity-analysis tools are provided to optimize selected model parameters and evaluate the effects of model parameters on simulation results.
- Mapping tools use ArcGIS files to map ouputs for geographical visualization.

CRHM Modules

DATA ASSIMILATION

- Data from multiple sites
- Interpolation to the HRUs

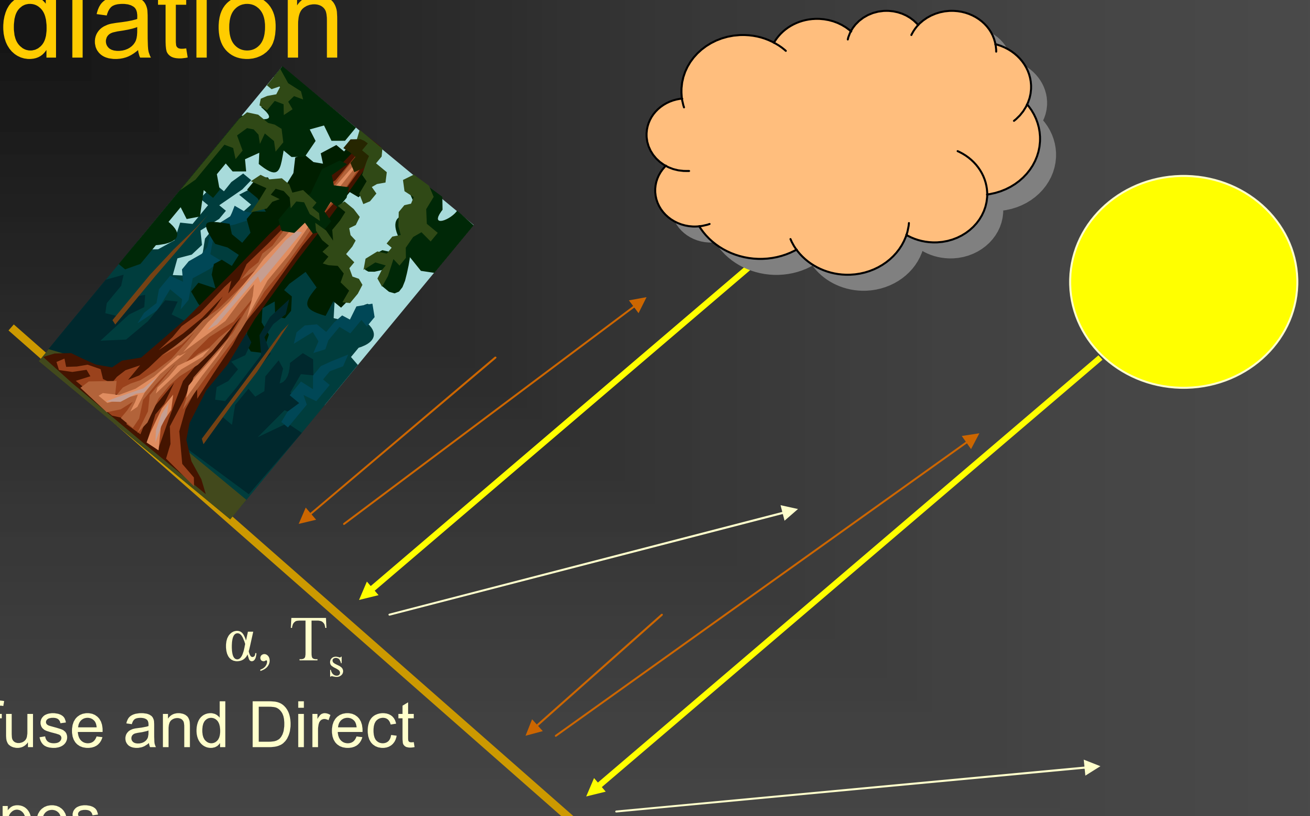
SPATIAL PARAMETERS

- Basin and HRU parameters are set. (area, latitude, elevation, ground slope, aspect)

PROCESSES

- Infiltration into soils (frozen and unfrozen)
- Snowmelt (open & forest)
- Radiation – level, slopes
- Wind speed variation – complex topo
- Evapotranspiration
- Blowing snow transport
- Interception (snow & rain)
- Sublimation (dynamic & static)
- Soil moisture balance
- Pond/depression storage
- Surface runoff
- Sub-surface runoff
- Routing (hillslope & channel)

Radiation



- Diffuse and Direct
- Slopes
- Longwave
- Forest canopy
- Albedo estimation
- Limited data requirements

References: Brunt, Brutsaert, Garnier & Ohmura, Granger & Gray, Gray and Landine, Pomeroy et al., Satterlund, Sicart et al.

Shortwave Radiation

- Direct and diffuse
- Uses lat/long, sunshine hours or measured incoming shortwave to estimate direct and diffuse radiation to a level plane
- Correction for slope, aspect, self-shading using Garnier and Ohmura
- A variety of albedo routines
- Forest canopy transmissivity model

Longwave Radiation

- Can be estimated as part of net radiation from shortwave using Granger and Gray algorithm
- Incoming longwave can be estimated from Brutsaert relationship modified by Sicart et al. – requires incoming shortwave, air temperature, humidity
- Outgoing longwave from surface temperature of vegetation or snow
- Forest canopy and surrounding topography effects on longwave

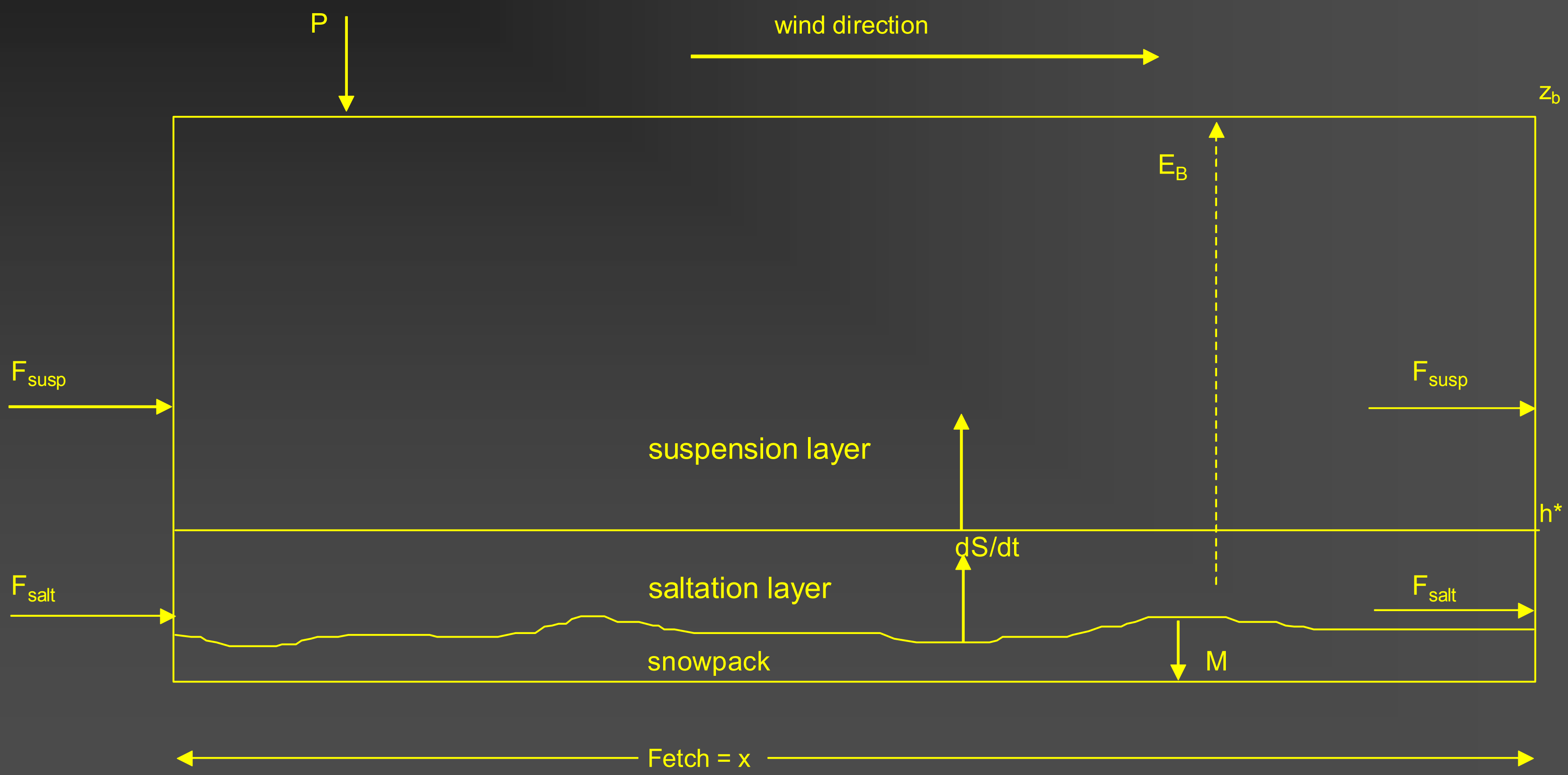
Blowing Snow – ‘water’ transport

Blowing snow modelling

- Saltation and suspension transport
- Sublimation loss
- Threshold condition of snowpack
- Vegetation, horizontal fetch effects
- Links to windflow module for complex terrain
- Full PBSM or simplified version available

Blowing Snow

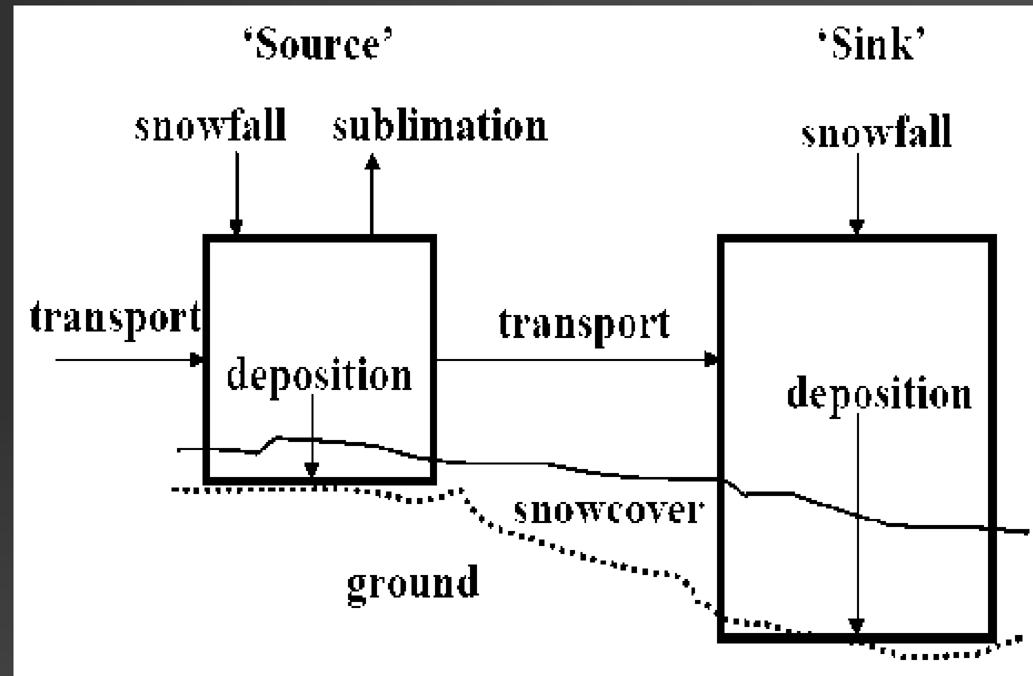
$$\frac{dS}{dt}(x) = P - p\left[\nabla F(x) + \frac{\int E_B(x)\,dx}{x}\right] - E - M \ ,$$



References: Pomeroy & Gray, Pomeroy & Male, Li & Pomeroy, Pomeroy & Li

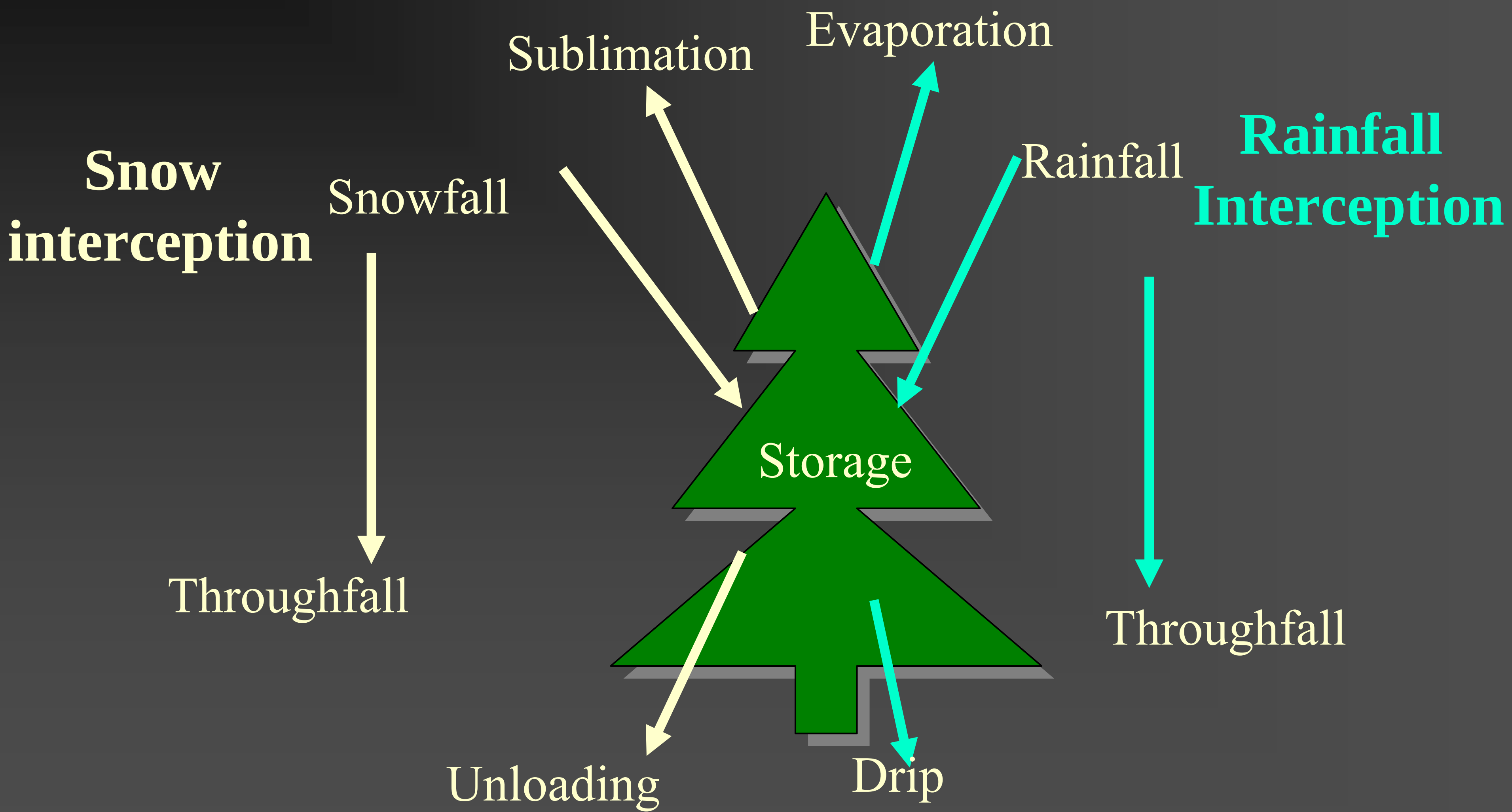
Distribution of Blowing Snow over Landscapes

Blowing snow transport, and sublimation relocate snow across the landscape from *sources* to *sinks* depending on fetch, orientation and area.



Fallow Field → Stubble Field → Grassland → Brush → Trees

Interception: snow and rain

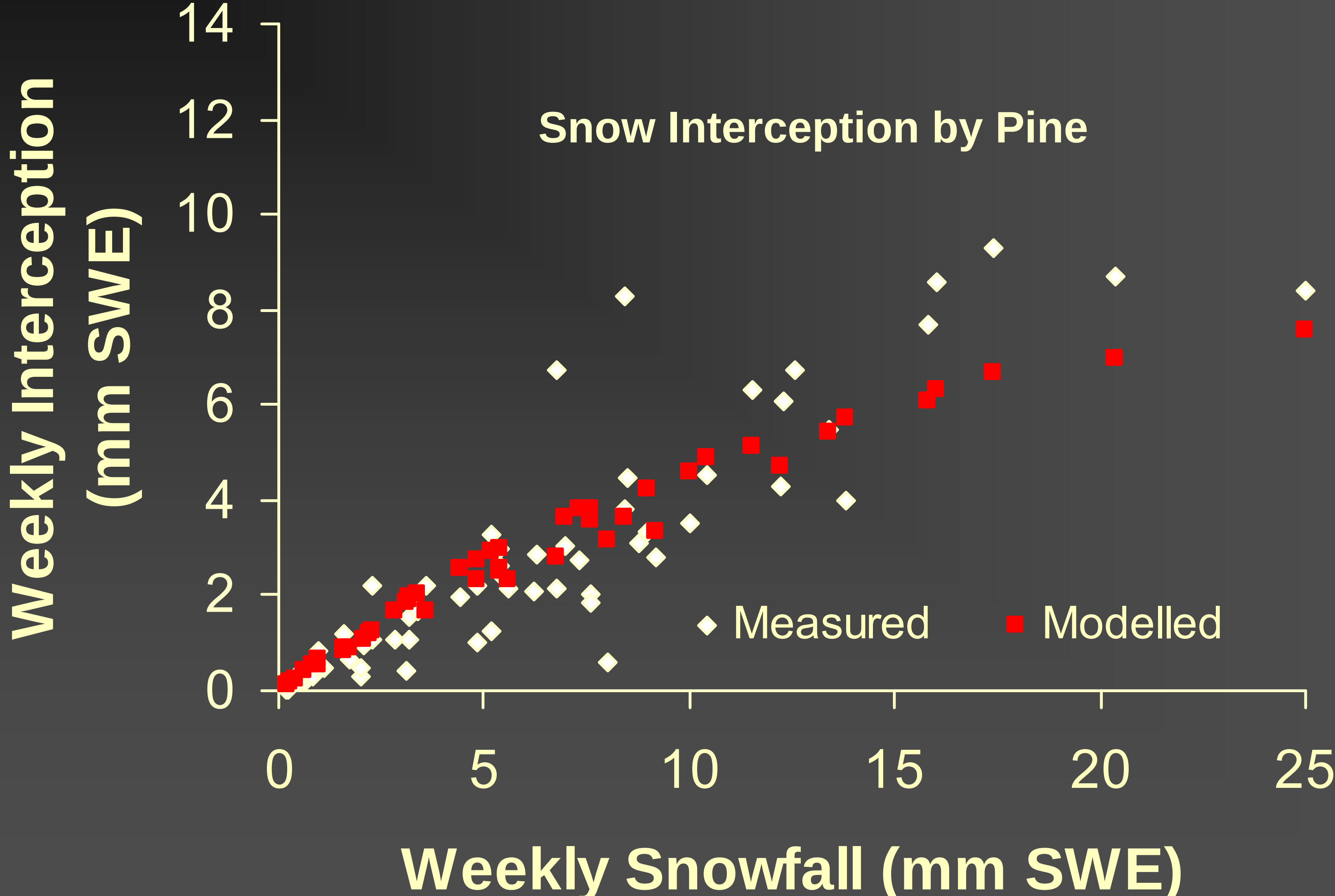


References: Rutter et al., Granger & Pomeroy,
Hedstrom & Pomeroy, Parviainen & Pomeroy, Pomeroy et al 1998

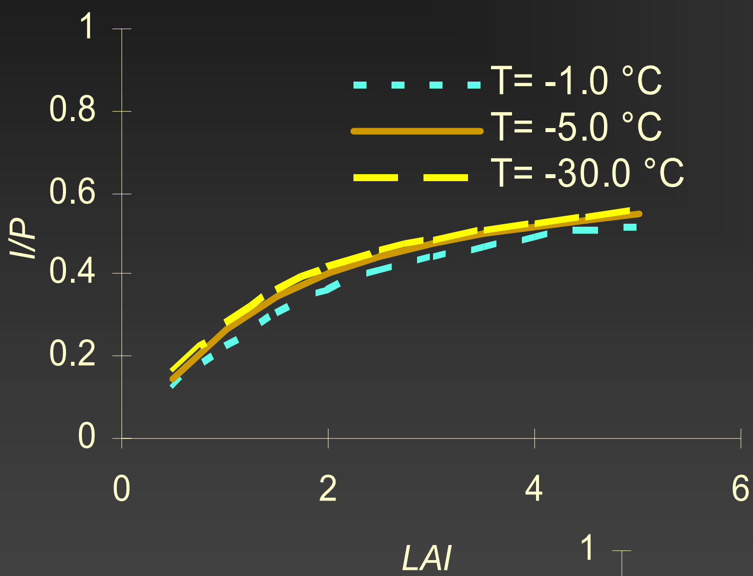
Interception Efficiency I/P Controlled by

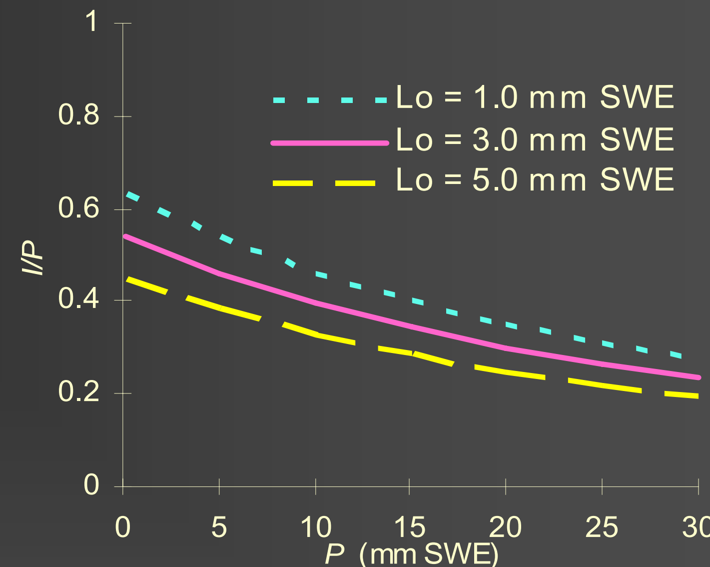
- Leaf + stem area index (surface to collect snow)
- Air temperature (elasticity of branch, adhesion and cohesion of snow)
- Wind speed (particle trajectory, impact rate, branch bending, scouring)

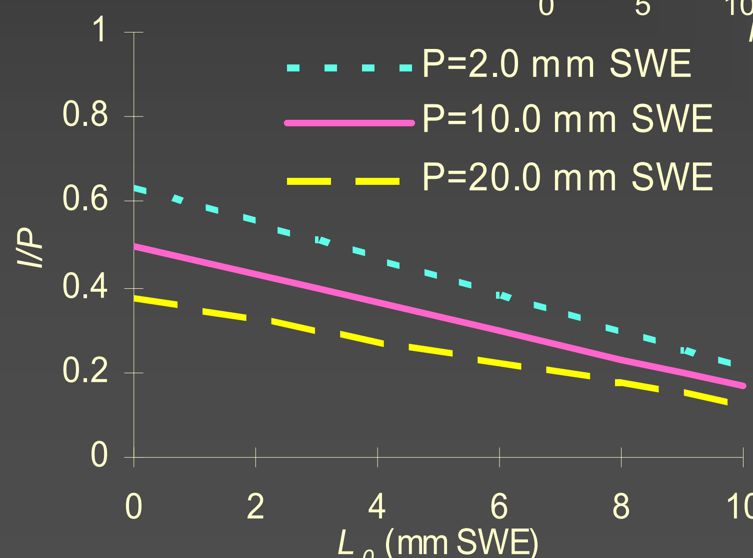
Weekly Snow Interception



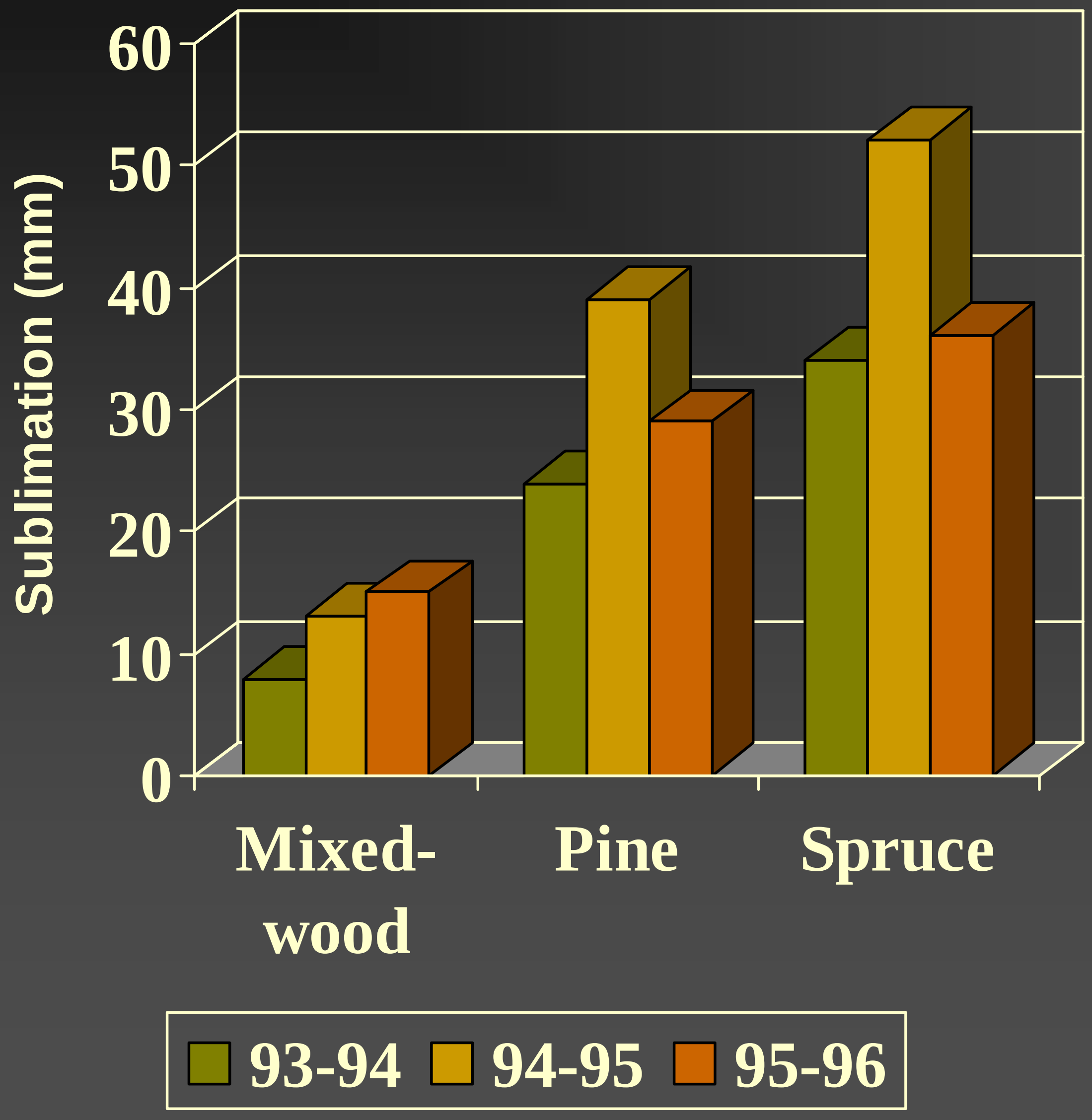
Interception Efficiency - model







Annual Sublimation Losses



Sublimation loss as a percent of annual snowfall.

- Spruce 38% to 45%
- Pine 30% to 32%
- Mixed-wood 10% to 15%

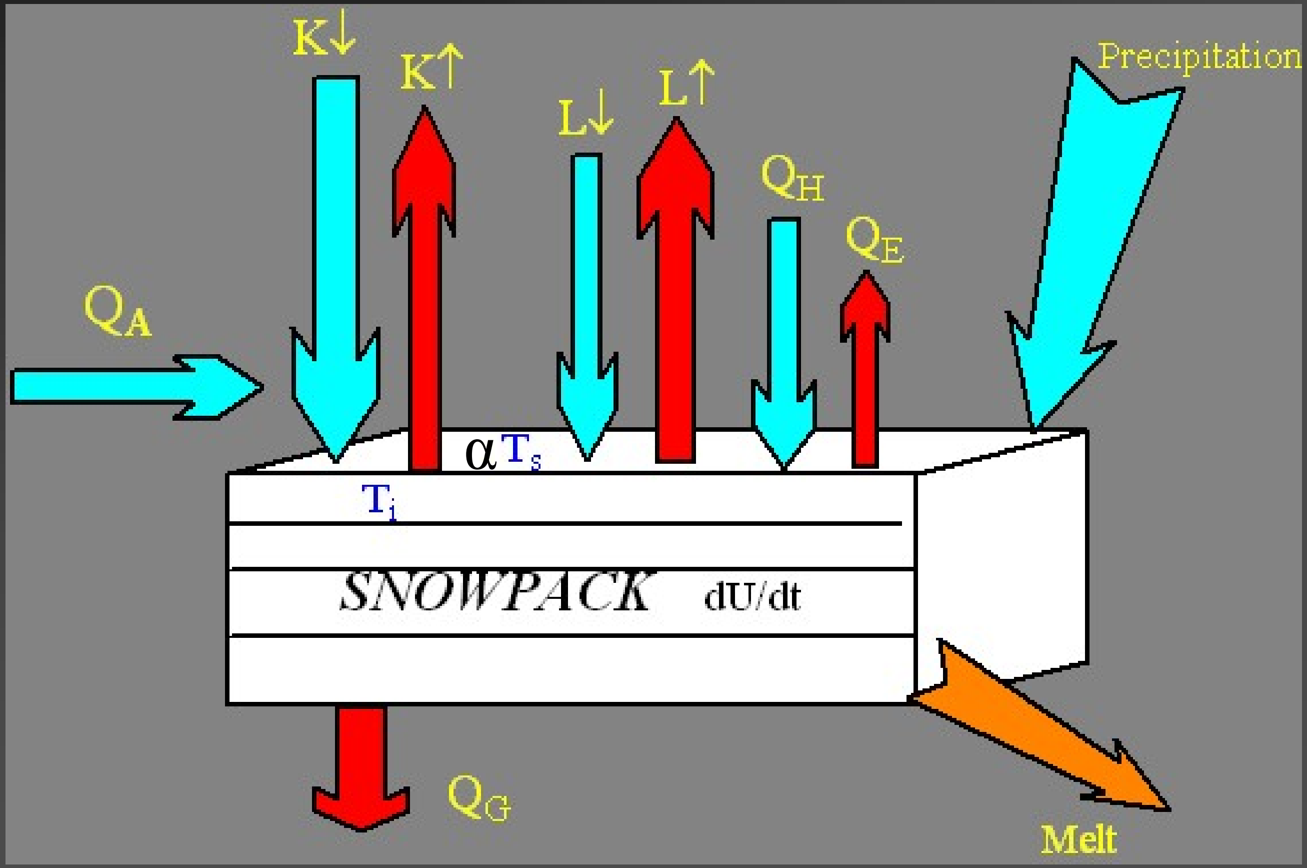
Snowmelt

- Degree Day Method has problems in open environments, slopes & forests.
- Energy Balance CAN be estimated using reliable methods

$$M=[Q_N+Q_h+Q_e+Q_g+Q_p-du/dt]/(\rho L_f B)$$

Snowmelt

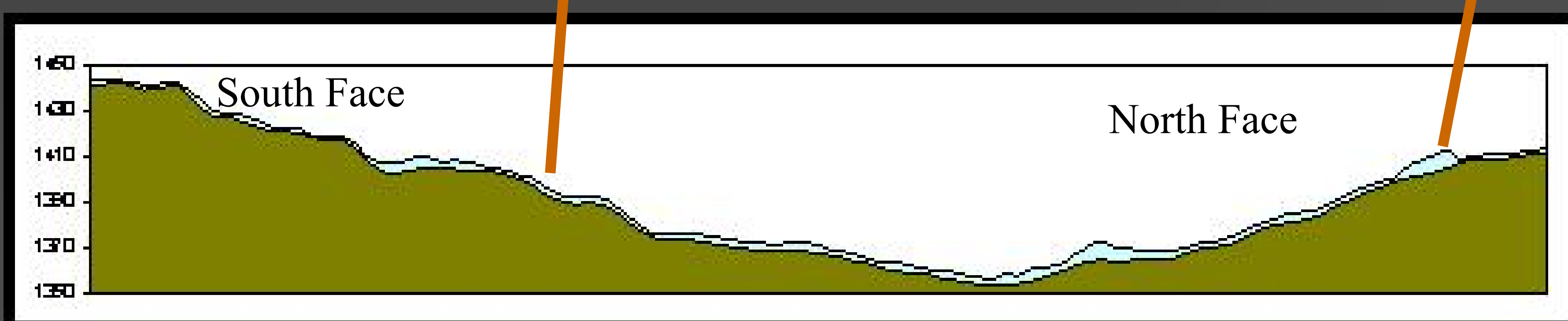
$$Q_m + Q_n + Q_H + Q_E + Q_G + Q_D = \frac{dU}{dt} \, , \qquad M = \frac{Q_m}{\rho_w B h_f} \, ,$$



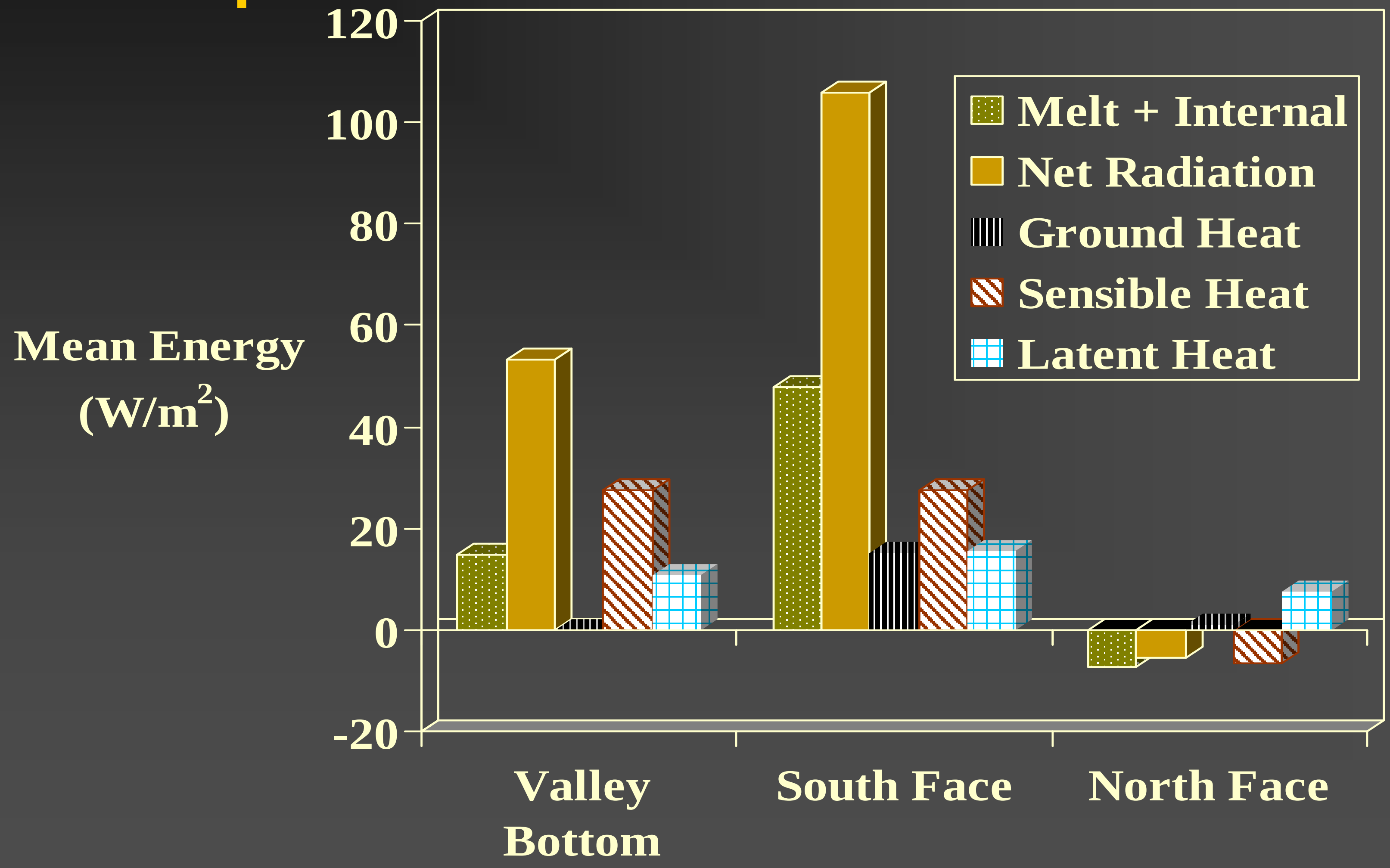
- -Daily EB
- -Hourly EB
- -Advection
- -SCA Depletion
- -Meltwater Flow
- -Degree Day
- -Radiation Index

References: Gray & Landine, Kustas et al., Essery, Shook, Marks et al. 1999

Snow cover depletion is not even!



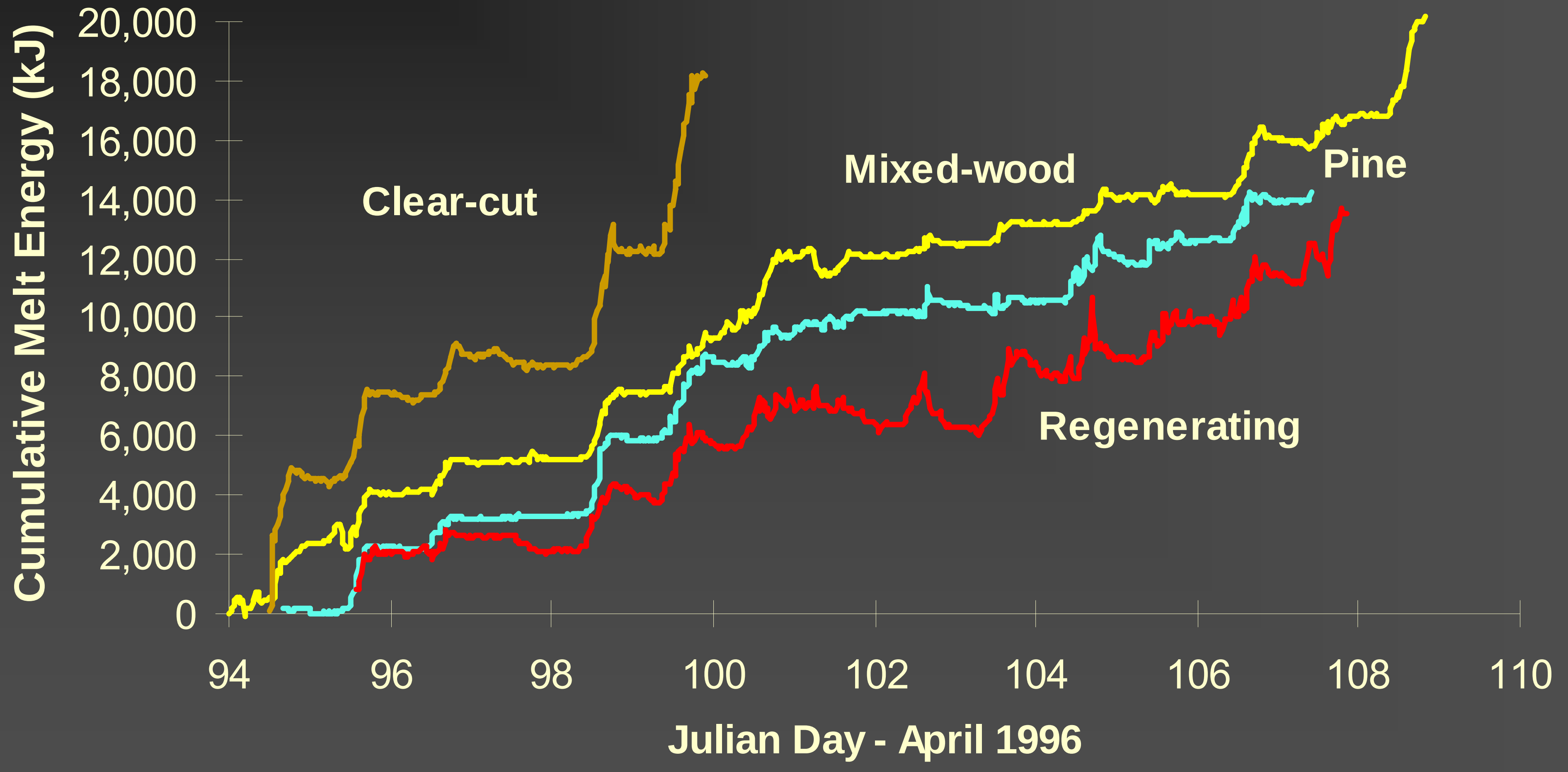
Melt Energy Variability on Slopes



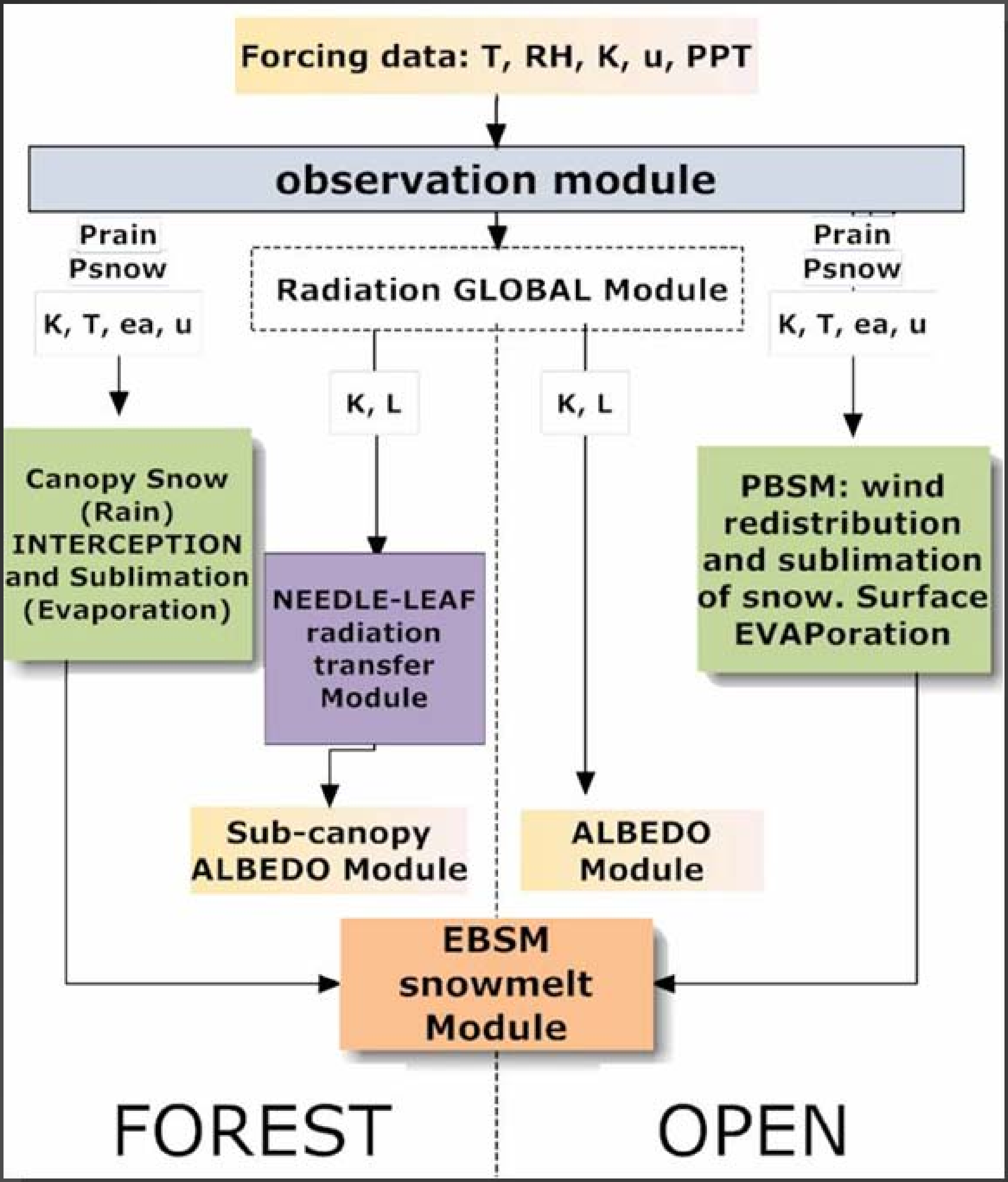
Forest Snowmelt (Pomeroy & Dion, '96)

- Sensible and latent heat fluxes very small
- Snowmelt rate under mature forests 3 times less than in open sites.

Snow Melt Rate in Forests



Forest Cover Modules



Forest Canopy Effects on Radiation

Shortwave irradiance: The transmissivity (τ) of the canopy layer to above-canopy shortwave irradiance ($K\downarrow$) is estimated as a function of the effective-leaf-area index ($LAI`$) and solar elevation angle (θ) by:

$$\tau = \exp[-1.081\ (\theta)\ \cos(\theta)\ LAI` / \sin(\theta)]$$

Sub-canopy longwave irradiance ($Lsc\downarrow$) is determined as the sum of above-canopy longwave irradiance ($L\downarrow$) and forest emissions weighted by the relative proportions of canopy-cover (1- v) and open sky (v) of the overhead forest scene:

$$Lsc\downarrow = L\downarrow\ (v) + (1-v)\varepsilon\sigma T^4$$

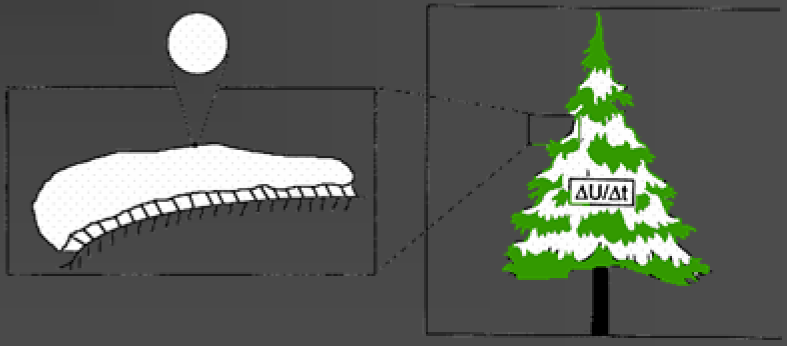
where ε is the emissivity of the forest (~0.98) , σ is the Stephan-Boltzmann constant ($W\ m^{-2}\ K^{-4}$) and T is the physical temperature of the forest (K).

Snow Interception and Sublimation

Interception : Intercepted snow and rain by the canopy is subject to sublimation and evaporation back to the atmosphere, respectively. The amount of snowfall, *P* (kg m^{-2}) that may be intercepted by the canopy prior to unloading is related to the (i) antecedent intercepted load, *Lo* (ii) the maximum intercepted load, *I** (which is related to LAI` and the density of falling snow) and the 'canopy-leaf' contact area, *Cp* via (Hedstrom and Pomeroy, 1998):

$$I = (I^* - Lo)(1 - \exp[-Cp\, P / I^*])$$

Sublimation: estimated by a multi-scale model approach: *ice-sphere* to *branch* to *canopy*

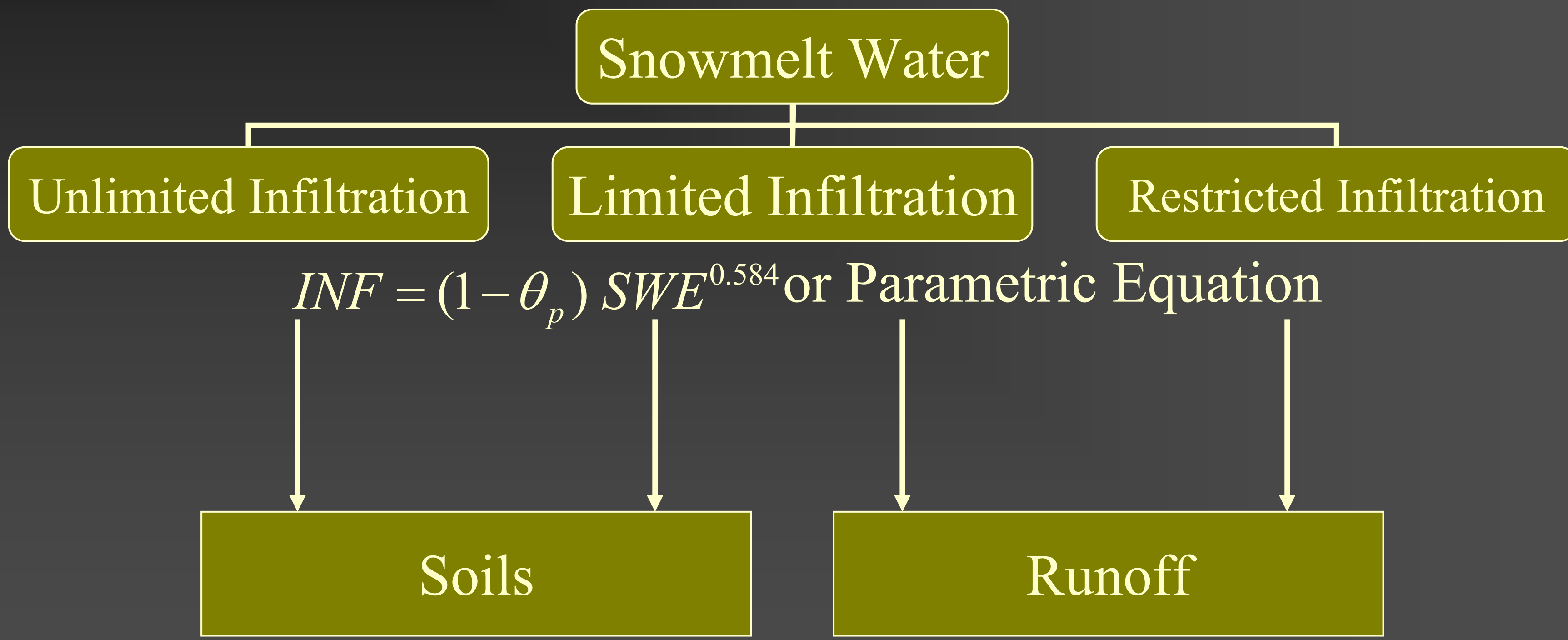


Duration of Melt, T

- Controls runoff, infiltration, snow-covered period, contributing area
- Can be simply described as a function of SWE, S and melt rate, M.

$$T = \frac{SWE}{M}$$

Infiltration into Frozen Soils

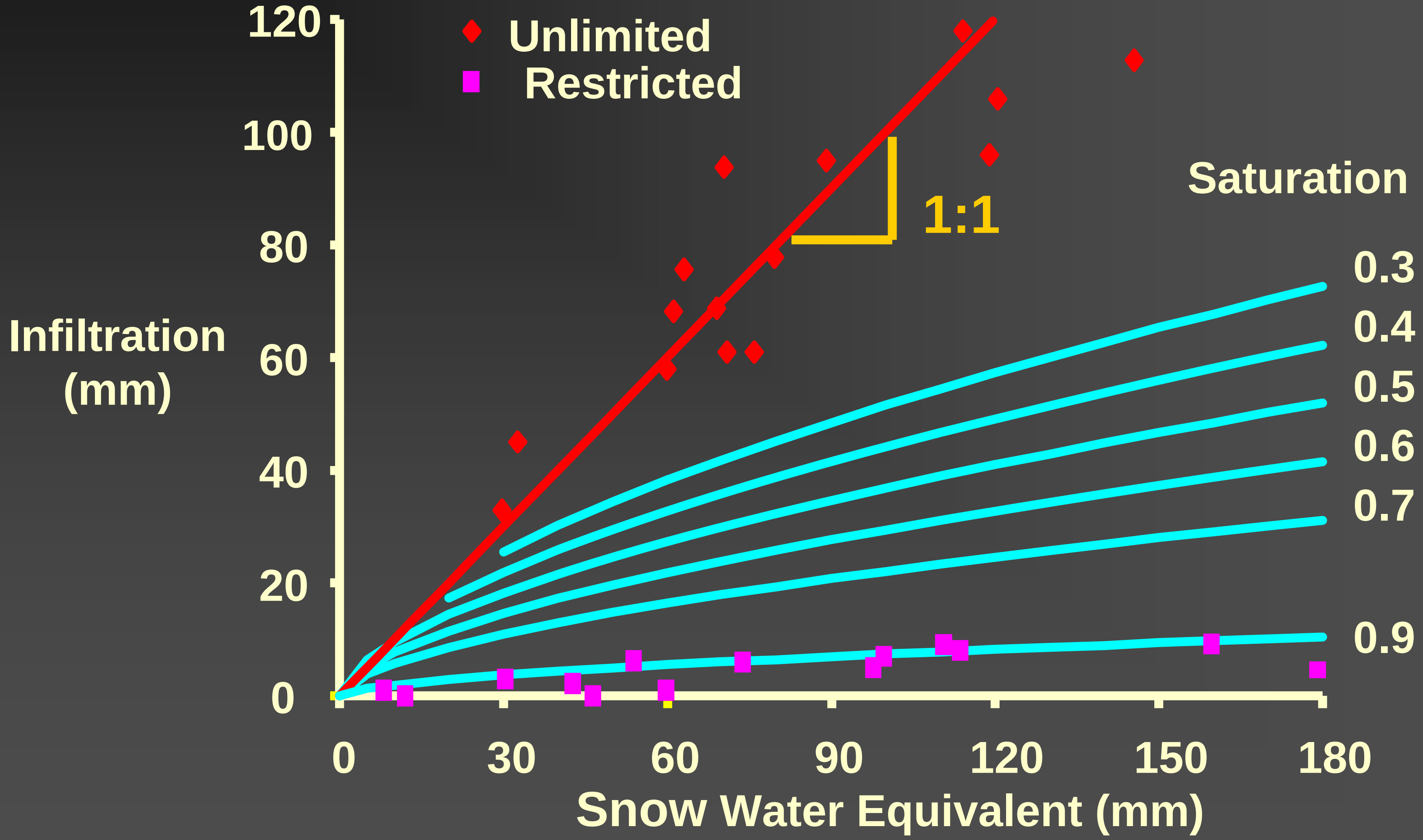


References: Granger et al., Gray et al., Zhao & Gray

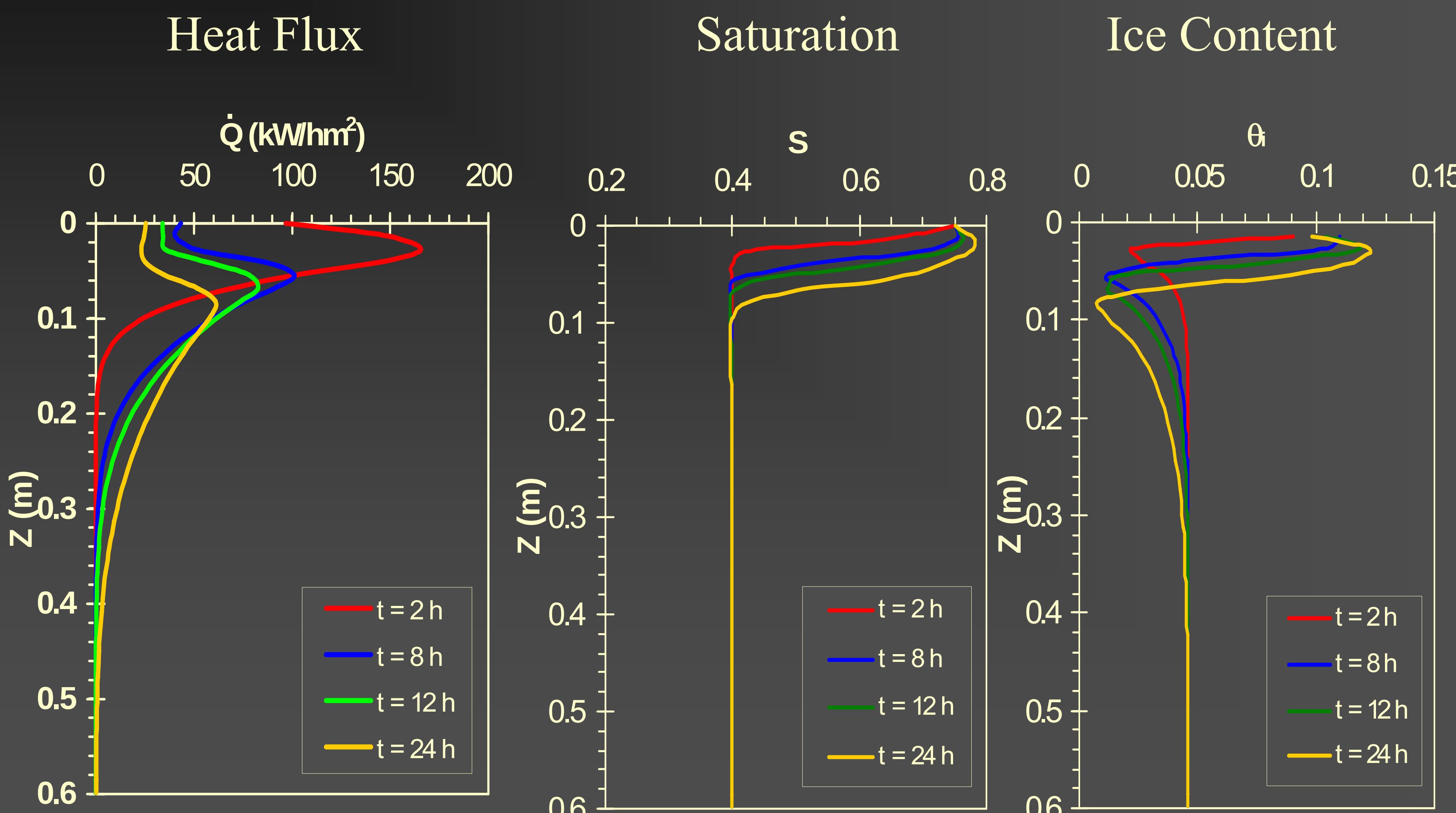
Infiltration to Frozen Soils

- Frozen soils can be permeable, but show reduced infiltration compared to unfrozen conditions
- 'Frozen' means a frost depth of at least 0.5 m
- Simple grouping of soil types and physically-based equations

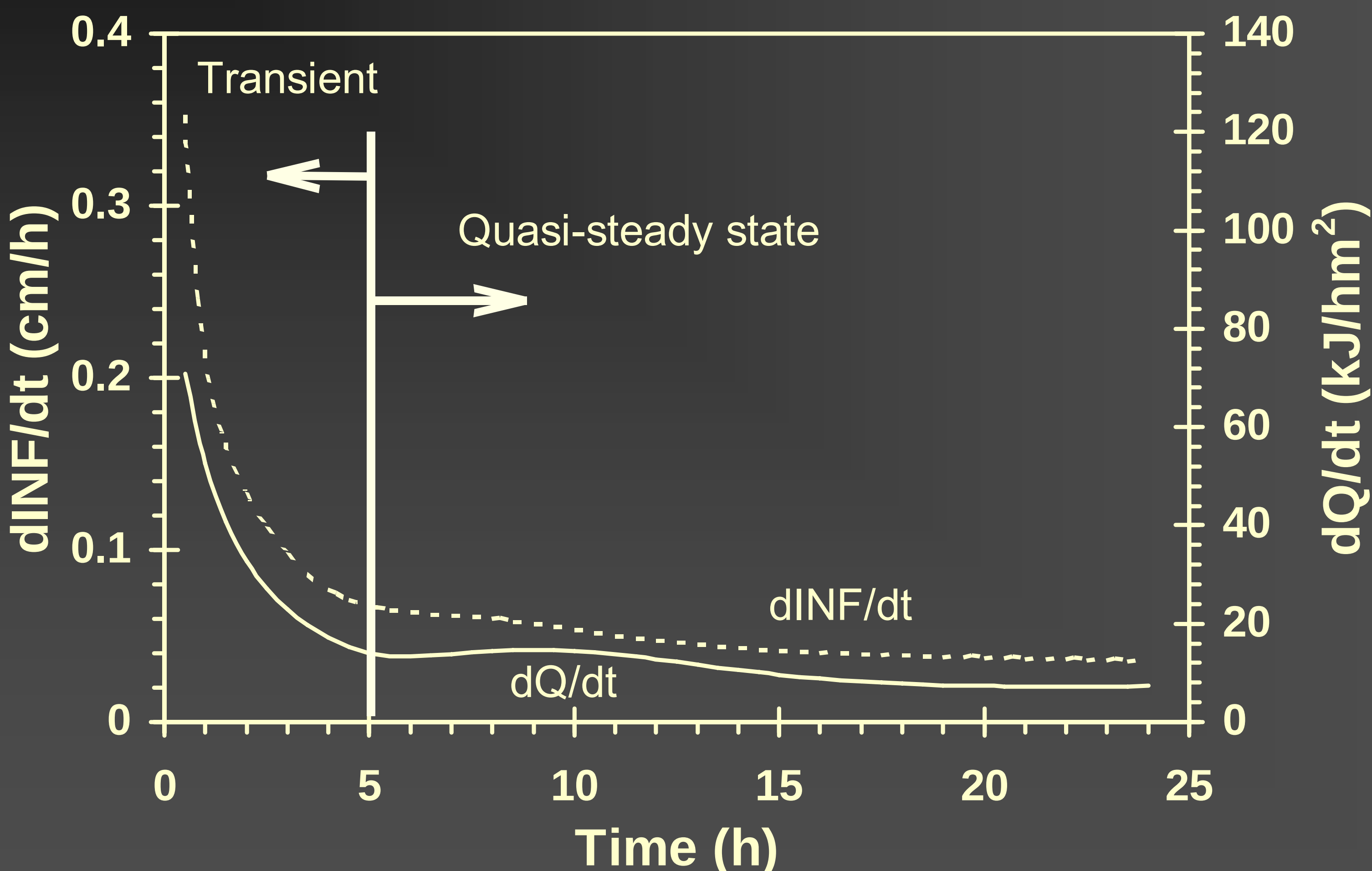
Empirical Model of Infiltration into Frozen Soils - Prairie Environment



Infiltration to Frozen Soils



Infiltration Rate and Ground Heat Flux during Snowmelt Infiltration



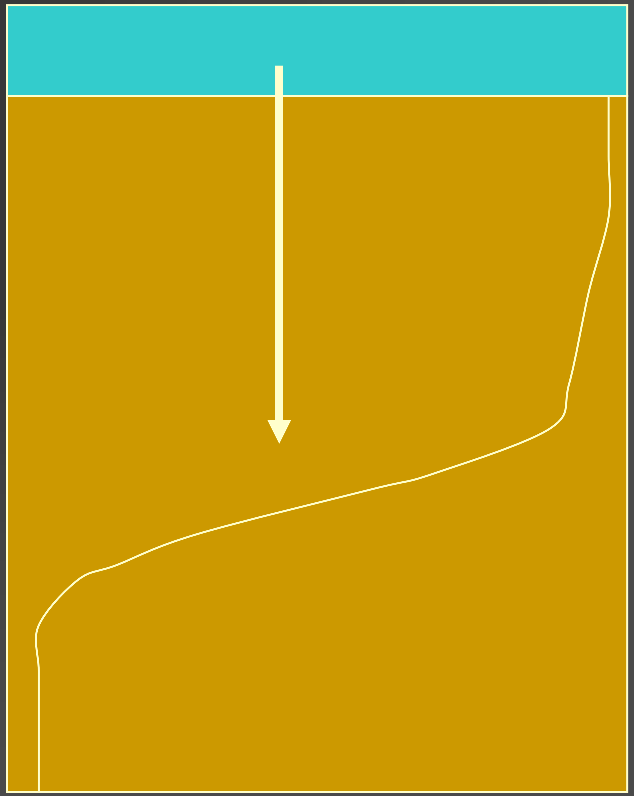
Parametric Equation for Infiltration to Frozen Soils

$$INF = C \cdot S_0^{2.92} \cdot (1 - S_I)^{1.64} \cdot \left(\frac{273.15 - T_I}{273.15} \right)^{-0.45} \cdot t_0^{0.44}$$

C is a coefficient
S_o is surface saturation
S_I is saturation in the top 40 cm
T_I is initial soil temperature
t_o is infiltration opportunity time

Infiltration into Unfrozen Soils

Green Ampt Infiltration
Depends on Ponding Time
Iterative Solution

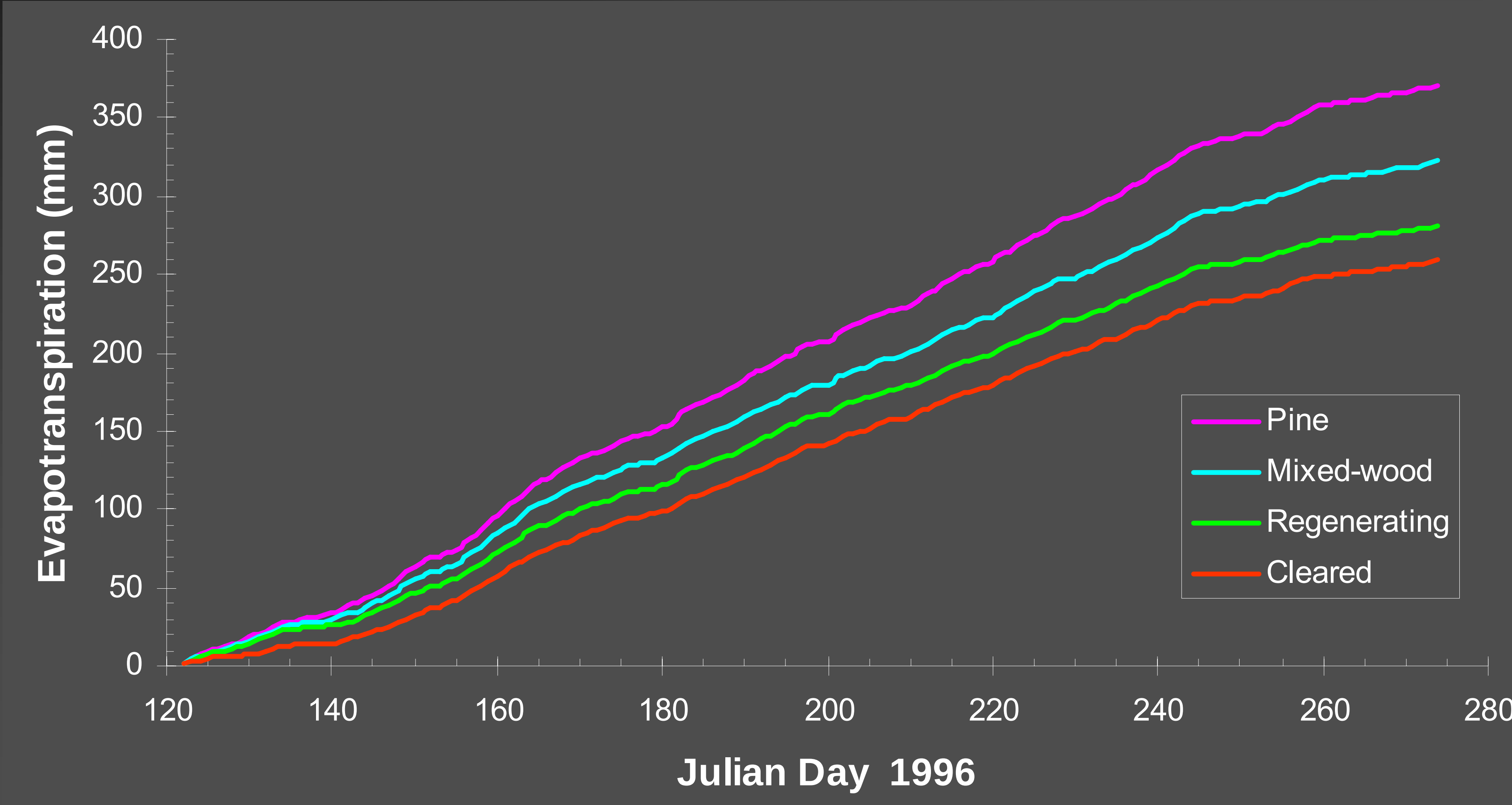


References: Green & Ampt, Ogden and Saghafian, Pietroniro in Pomeroy et al

Evaporation

- Empirical models fail in spring (cold soils), over permafrost and with changing land use
- Penman-Monteith energy balance hard to implement & parameterise
- Granger extension of Penman offers a physically based, practical solution (Granger '90)

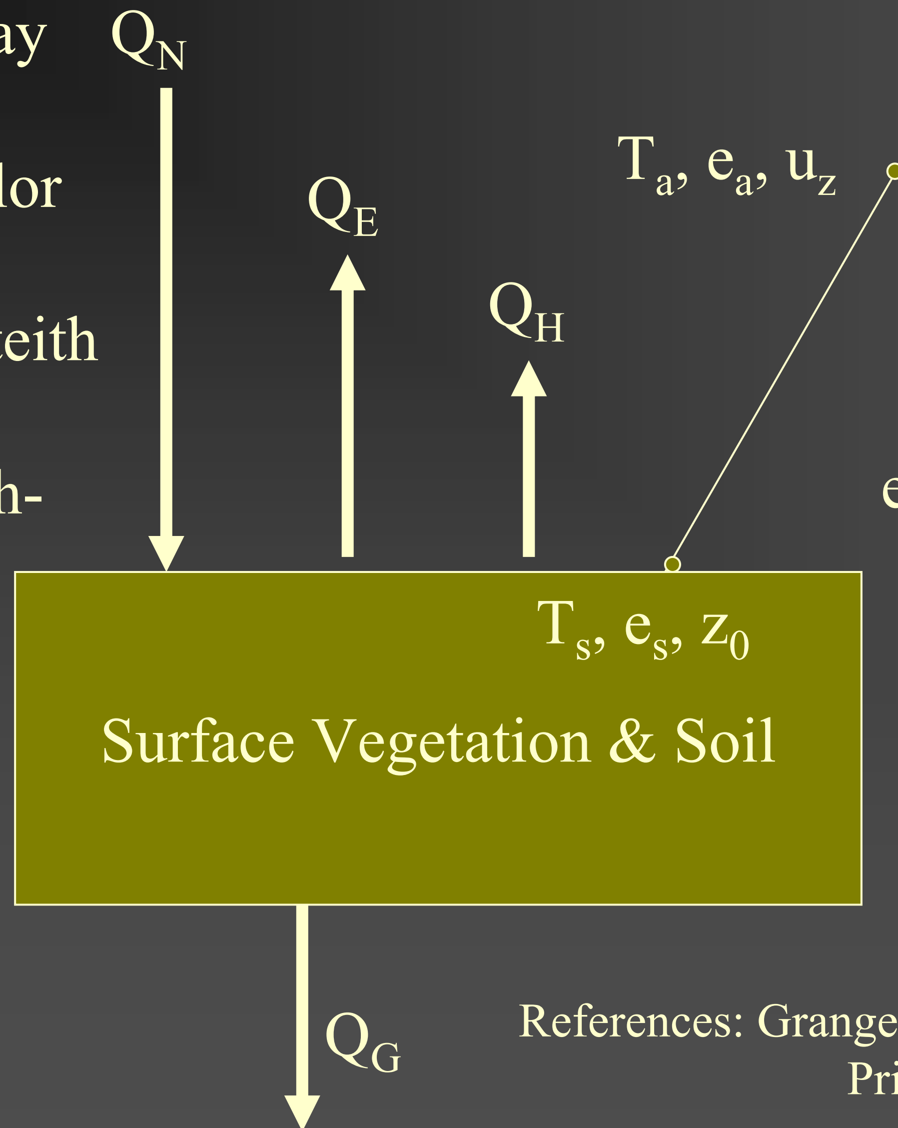
Evaporation Modelling – Land cover effects Granger & Pomeroy '97



Evaporation

$$Q_E = \frac{G[s(Q^* - Q_G) + C\ vdd_a / r_a]}{sG + \gamma}$$

Granger-Gray
or
Priestly-Taylor
or
Penman-Monteith
or
Shuttleworth-Wallace



$Q_A = Q_N - Q_G$

$e_s = f(e_a, T_a - T_s)$

Water drawn from
1) canopy
2) recharge zone
3) deep soil
4) groundwater

References: Granger & Gray, Granger & Pomeroy, Priestly & Taylor

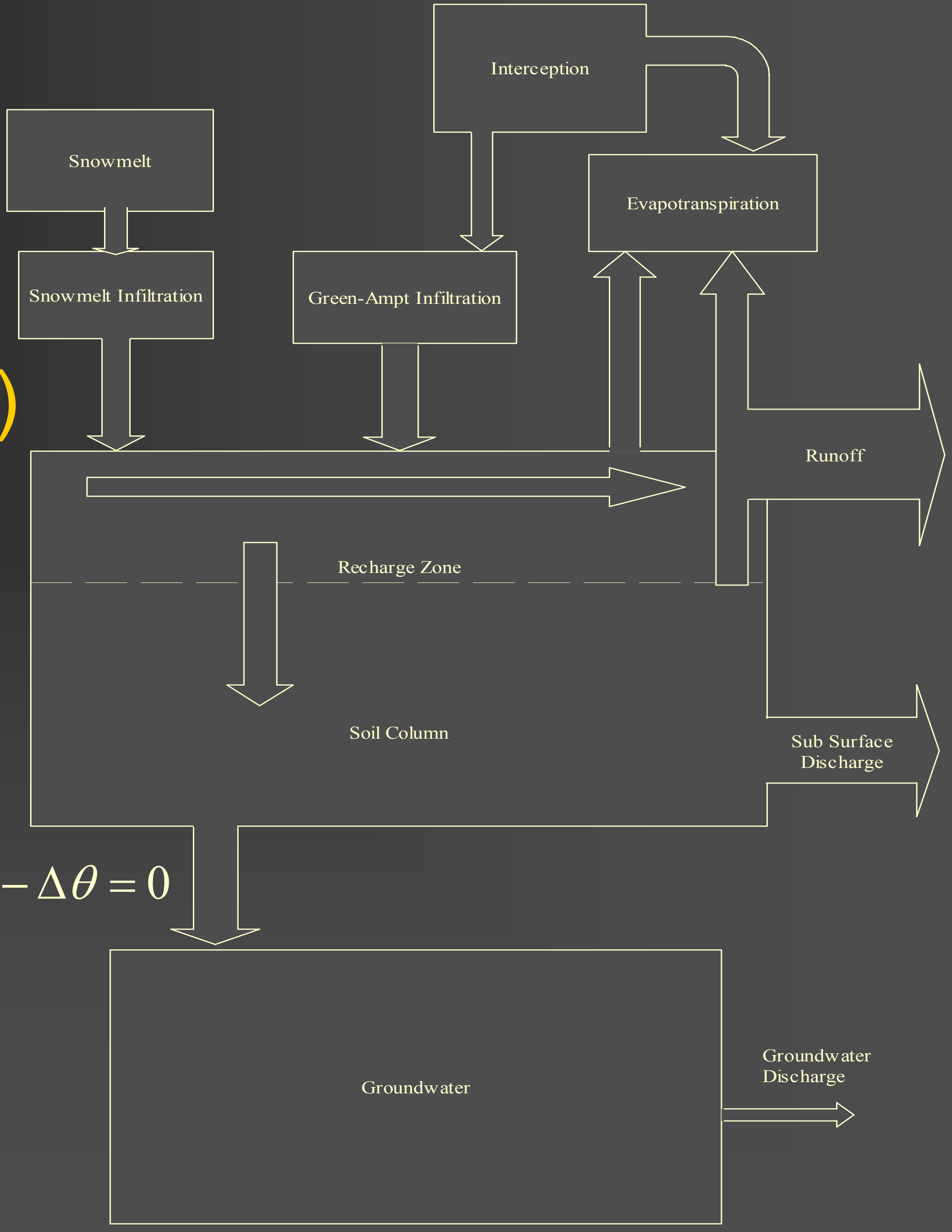
Soil Moisture Balance (SMBAL)

Mass balance and flow from
2 soil layers &
groundwater

$$INF - GW - SSR - E_{SURFACE} - Trans - \Delta\theta = 0$$

Alternative is SOIL,
better for northern soils and
sub surface flow generation

References: Leavesley et al.
Dornes et al



New Modules

- *Soil-*
  - Depressional storage
    - sub-HRU
    - can form subsurface runoff or ground water recharge or fill and spill.
    - transfer of flows between HRUs
  - Pond storage
    - all of HRU water covered.
    - parameterization of maximum pond storage.
    - possible to: (i) leak to subsurface flow or groundwater recharge (ii) fill and spill.
  - Interflow between HRU
    - subsurface flow can enter downhill HRU as surface or subsurface flow.

Routing – Clark Lag and Route

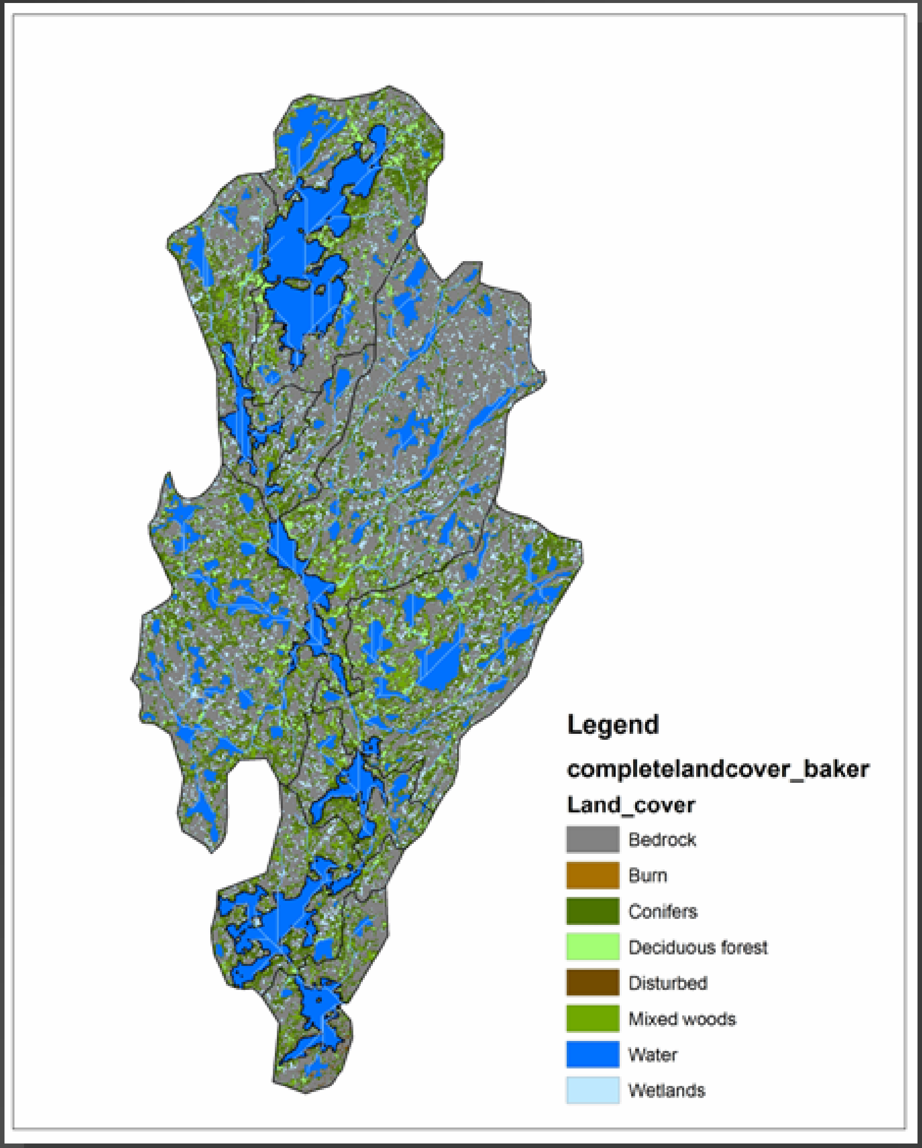
Clark (1945) showed that routing a flood wave through a reach of a stream channel could be done by shifting the wave a time equal to the travel time of the reach, and then routing it through an amount of reservoir storage that gives the equivalent "action" as the channel storage in the reach. The practice visualises a reservoir that has storage characteristics, S = KO, at the outlet of a watershed. Substituting this relation for storage into the continuity equation gives:

$$\frac{I_1 + I_2}{2} - \frac{O_1 - O_2}{2} = \frac{k(O_2 - O_1)}{\Delta t}$$

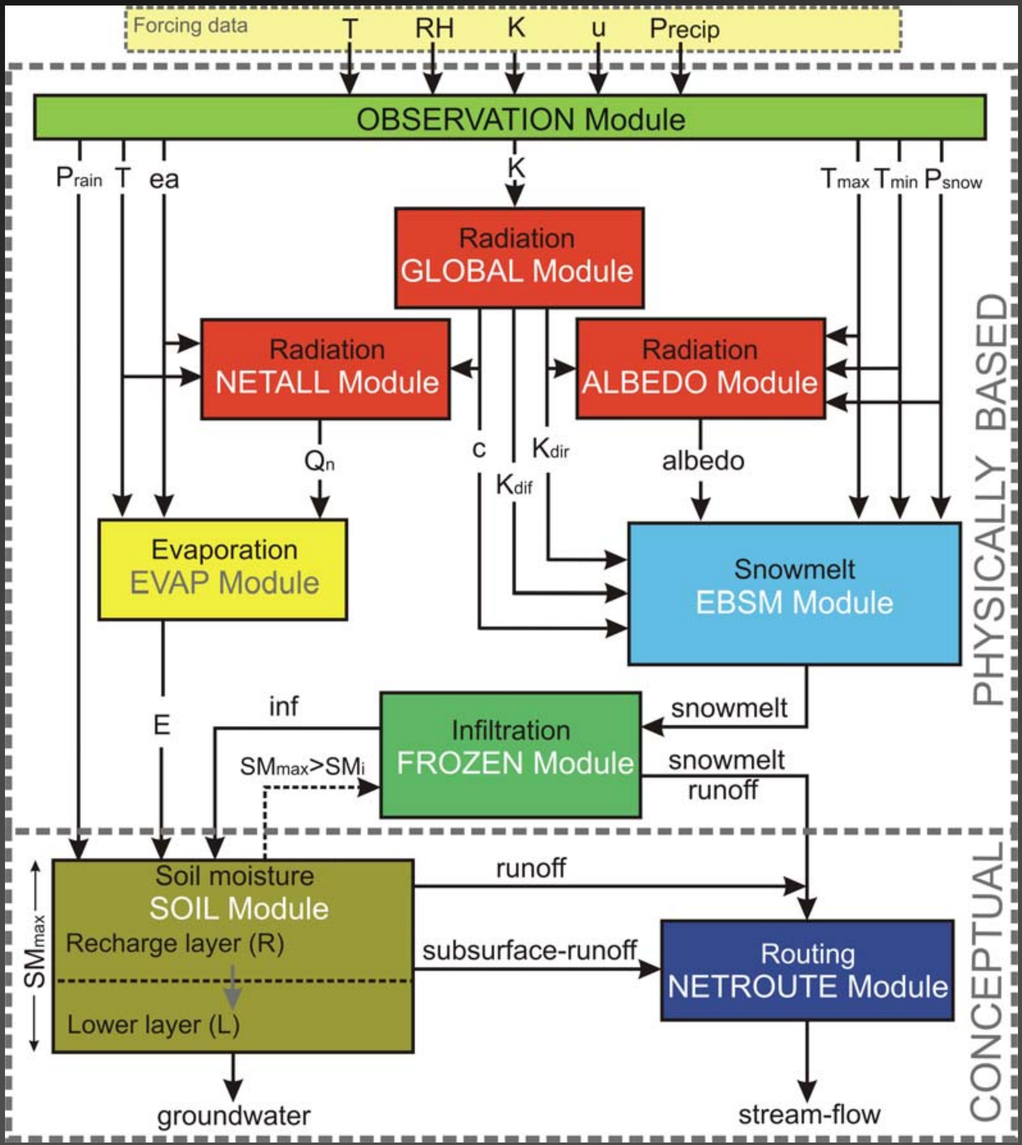
Where I_1, I_2, O_1 and O_2 are respectively inflow and outflow rates at the beginning and end of routing interval, Δ t. k, the storage constant can be obtained from the hydrograph or other analyses.

Baker Creek, NWT

- Sub-arctic shield lakes
- Parameterized CRHM with 16 HRU’s - 8 trunk lakes and their contributing areas
- The storage interaction between HRU’s was manipulated within the model to evaluate effect on water budget



CRHM Test - Yukon



Modular structure

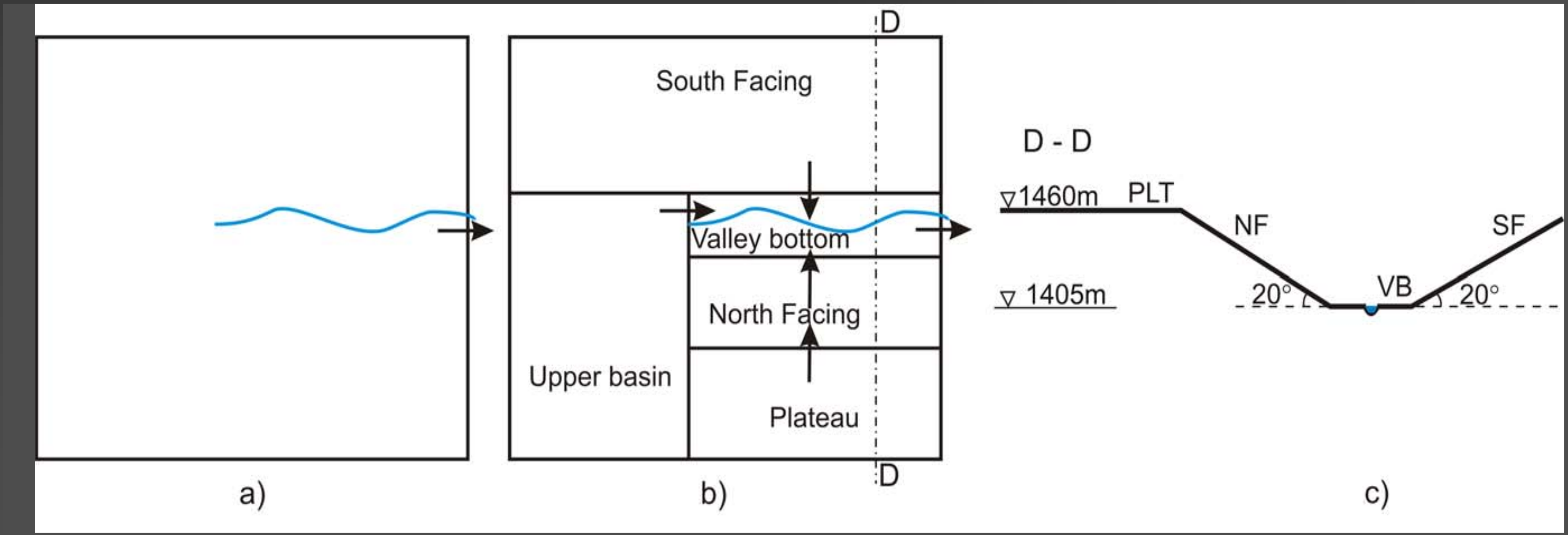
HRU based

$$INF = 5 \cdot (1 - \theta p) \cdot SWE^{0.584}$$

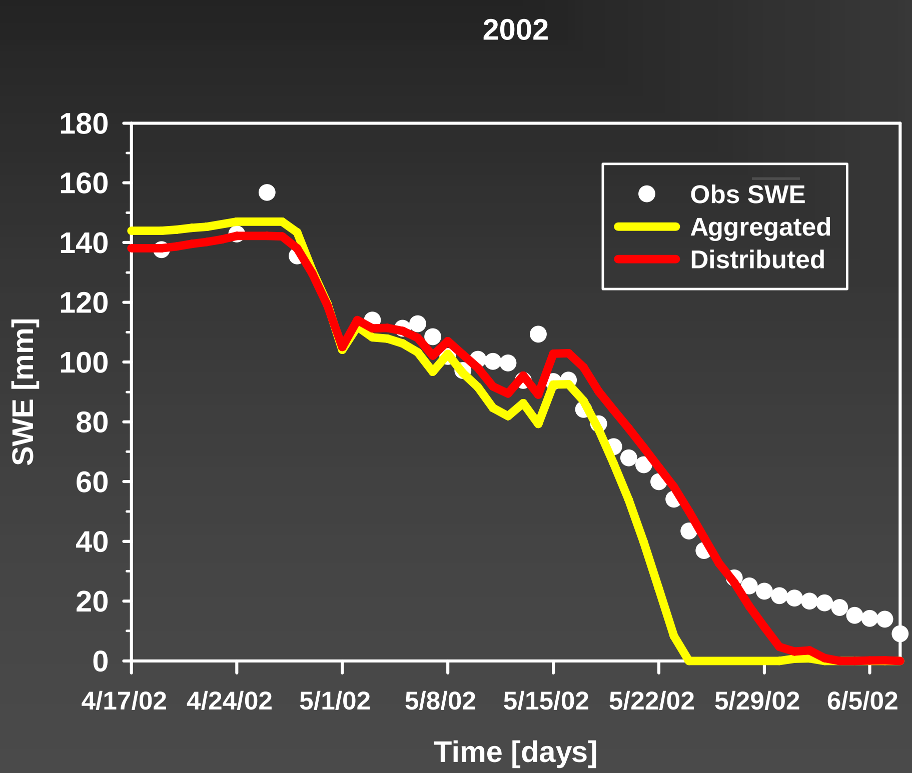
$$INF = C \cdot S_0^{2.92} \cdot (1 - S_I)^{1.64} \cdot \left(\frac{273.15 - T_I}{273.15} \right)^{-0.45} \cdot t_0^{0.44}$$

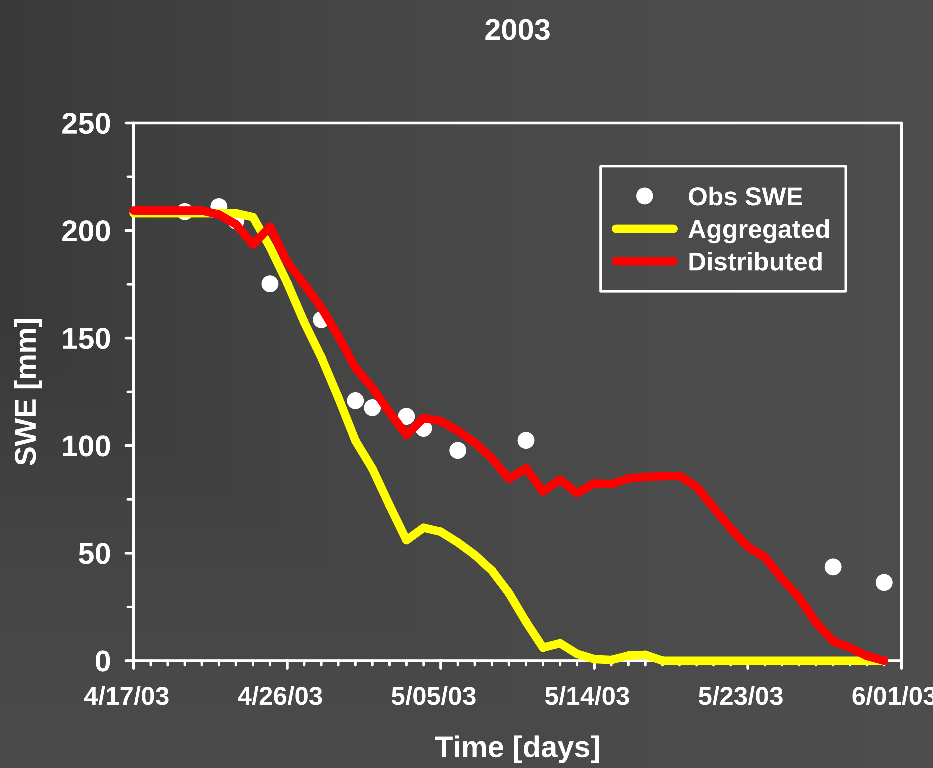
Modelling Approach

Aggregated vs. Distributed

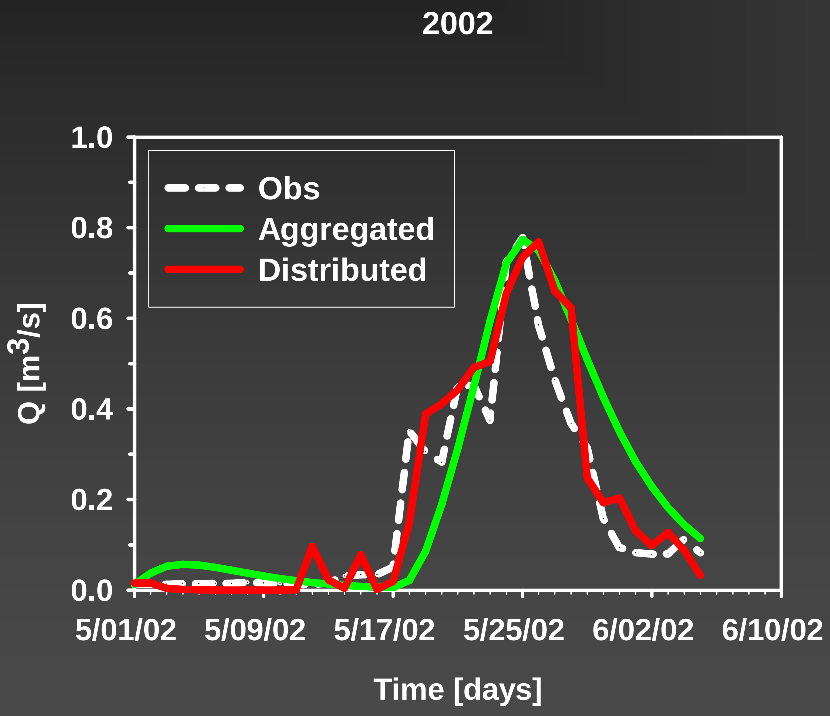


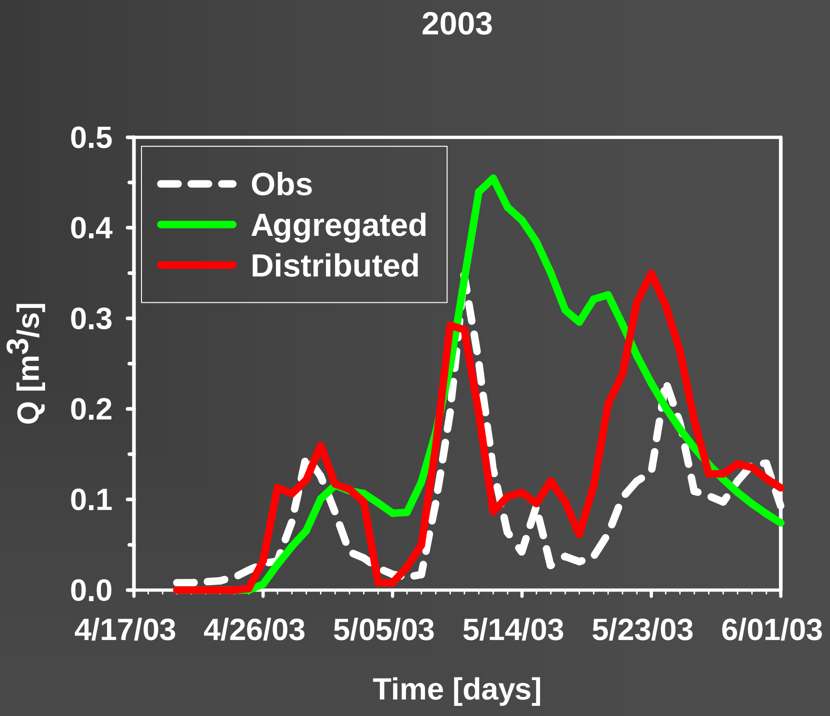
Basin Areal SWE
NF, SF, and VB





Basin discharge





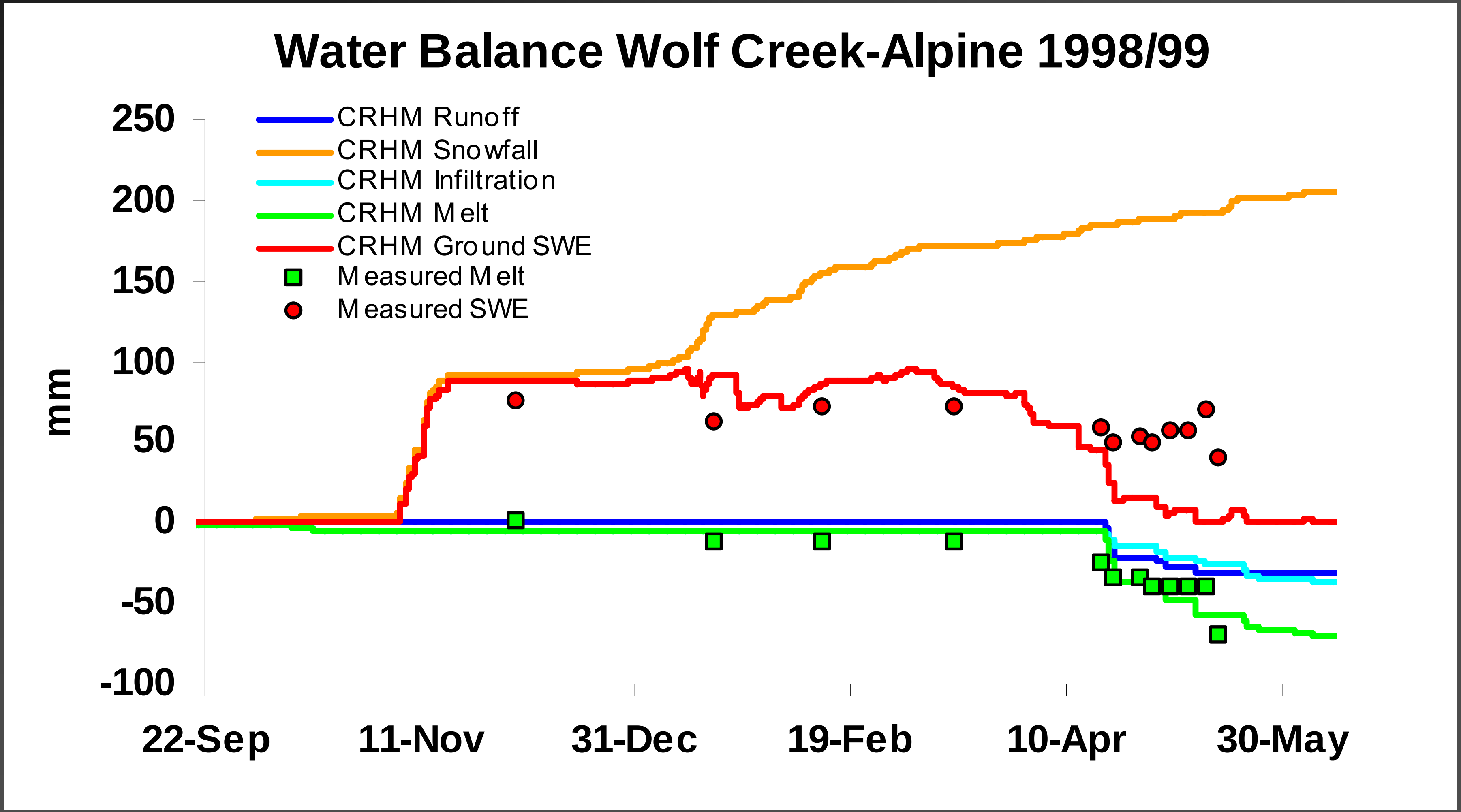
CRHM Evaluation – open environment snow dynamics and spring runoff

- Modules: radiation, blowing snow, energy balance snowmelt, evaporation, infiltration to frozen soils, soil moisture balance, hillslope flow, routing
- Parameters: from local scale observations
- HRU structure: based on observed landscape units for processes

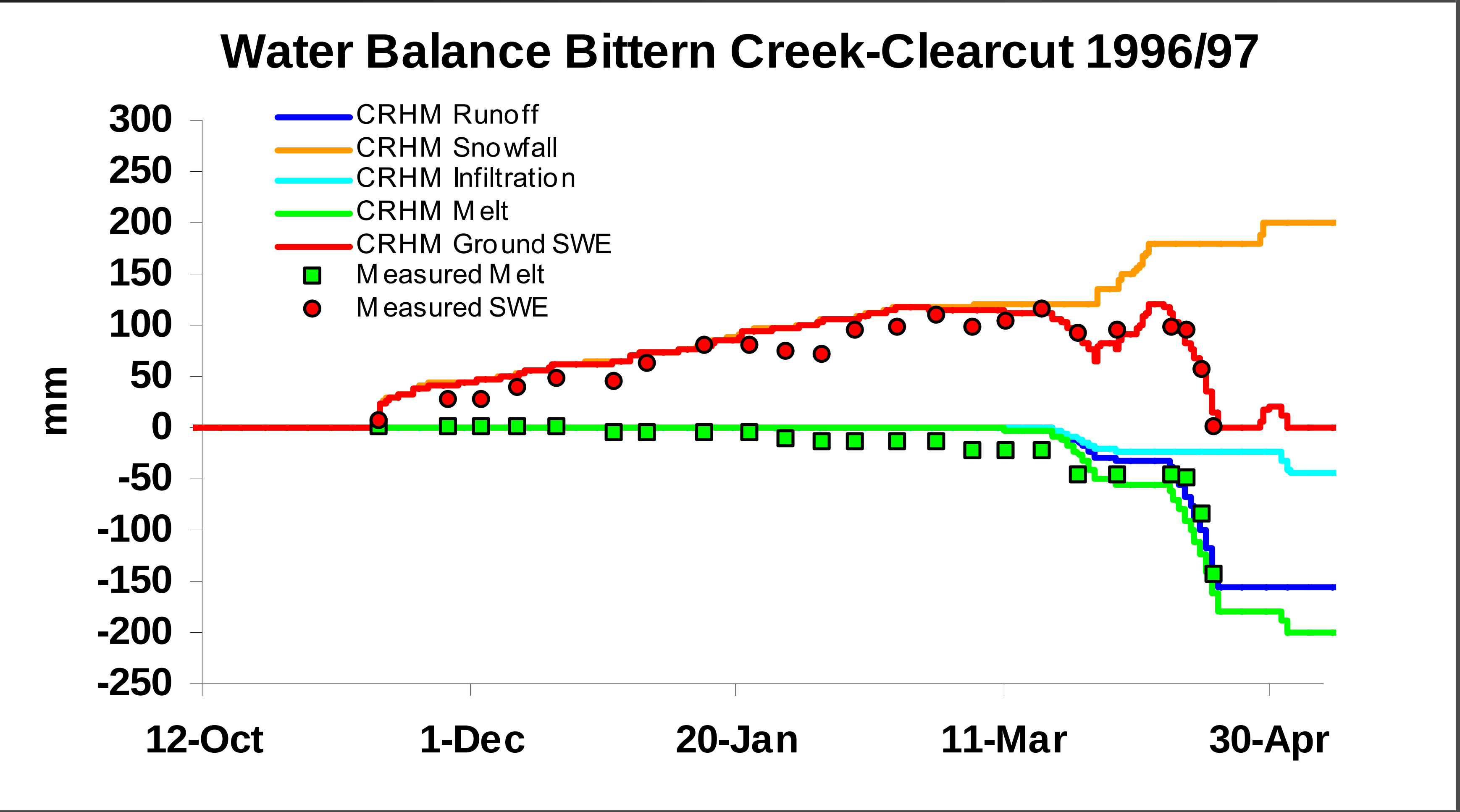
Parameter Estimation

- Blowing snow: fetch, vegetation height
- Radiation: land surface albedo
- Snowmelt: initial snow albedo
- Infiltration: fall soil moisture content, cracking
- Evaporation: vegetation type, height
- Soil moisture balance: soil type, vegetation type, groundwater connection
- Hillslope flow: porosity, bulk density, thermal conductivity, initial frost table depth
- Routing: lag time, storage

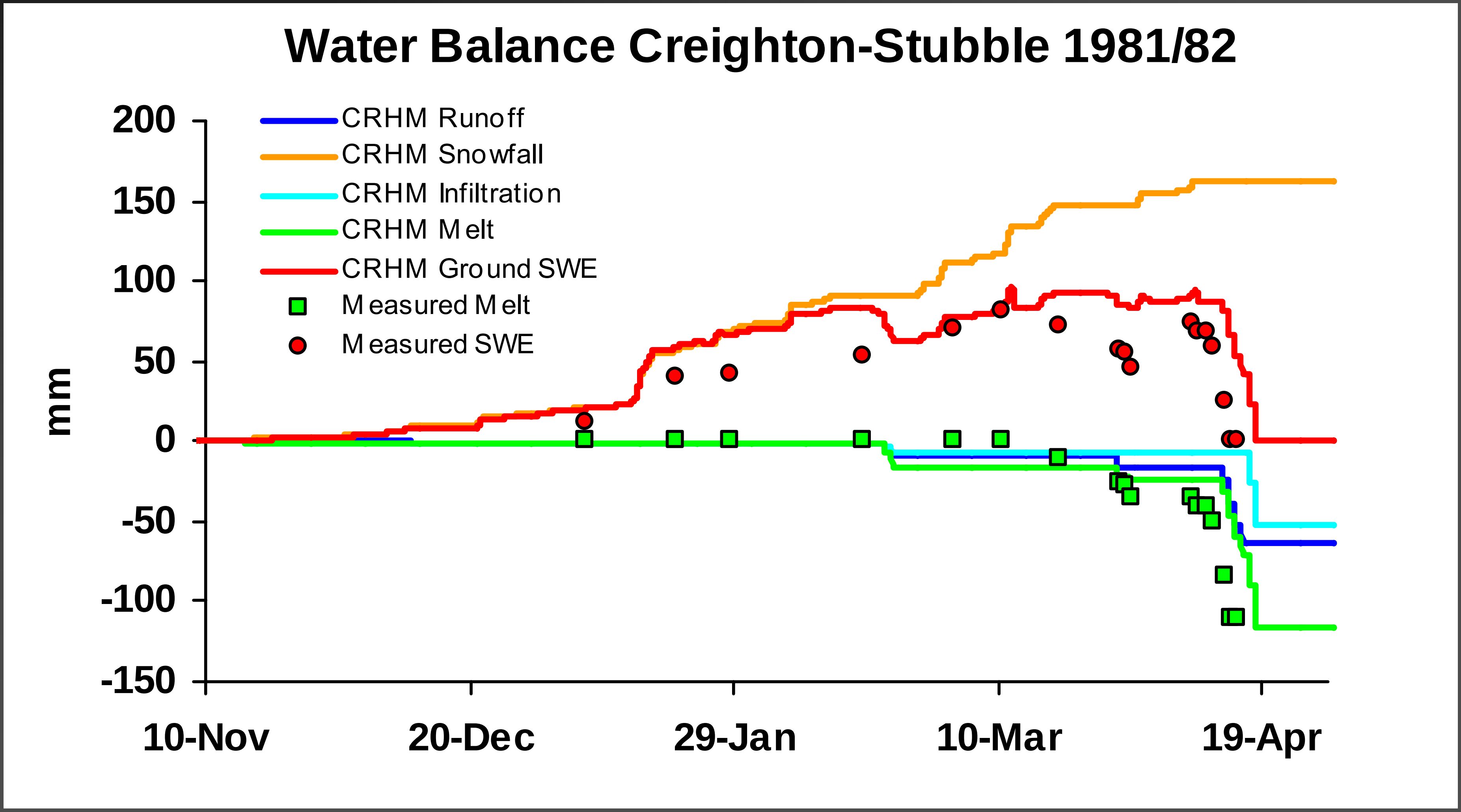
Sub-arctic alpine tundra



Boreal forest clearing



Prairie wheat field



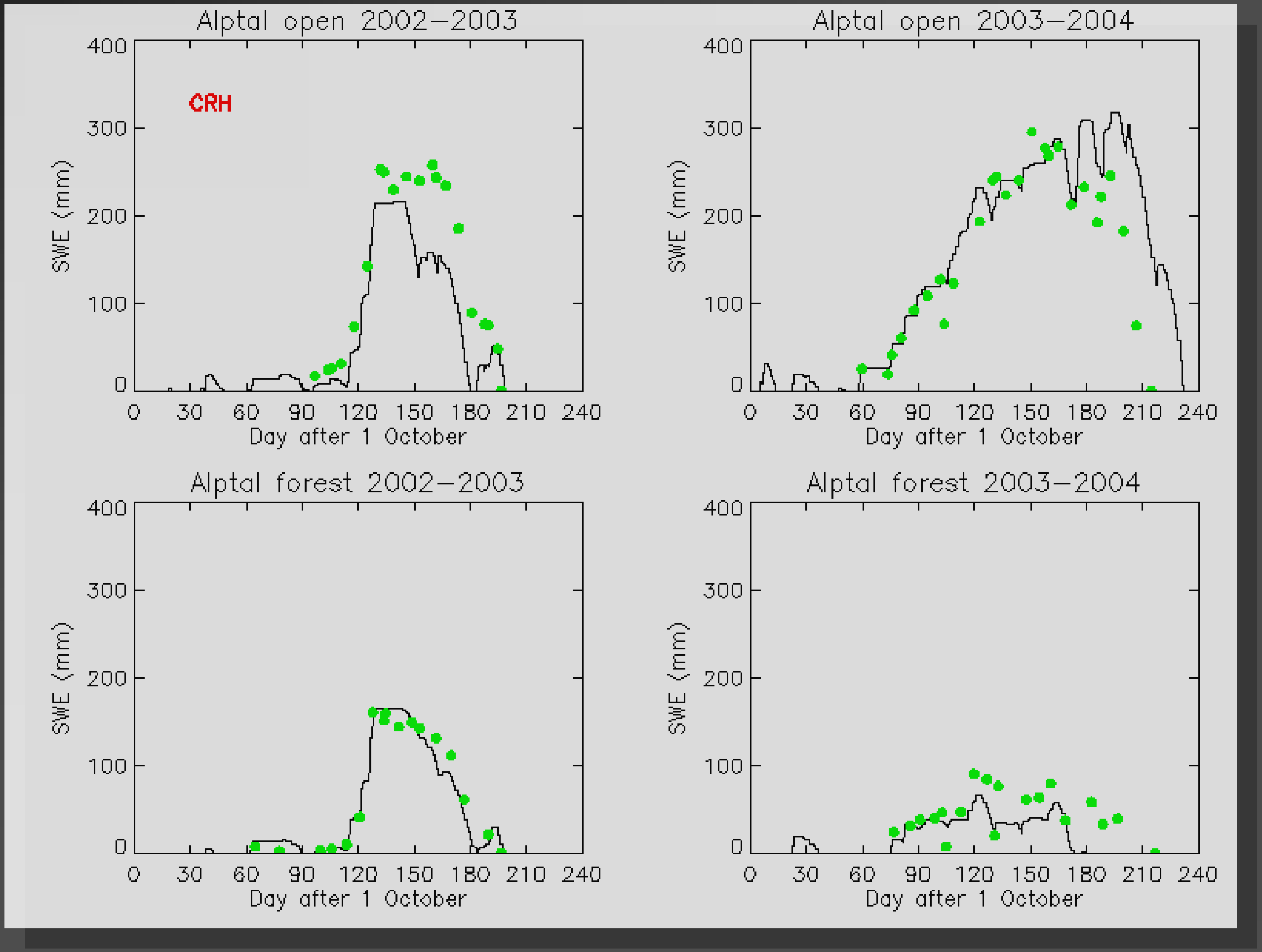
Effect of forest cover on snow accumulation and melt

SnowMIP2 runs: Alptal, Switzerland:

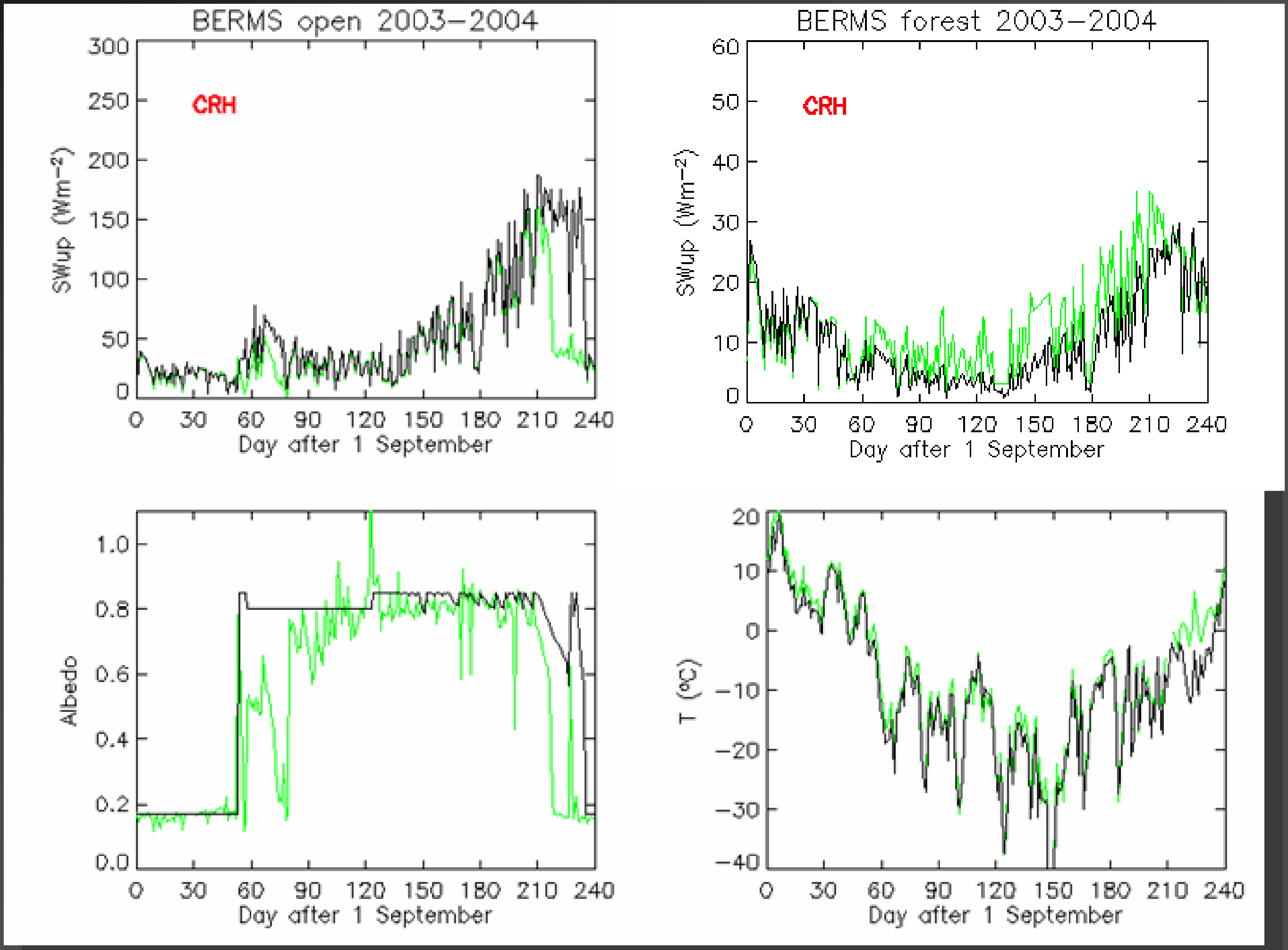
2002-03 | 2003-04

open site

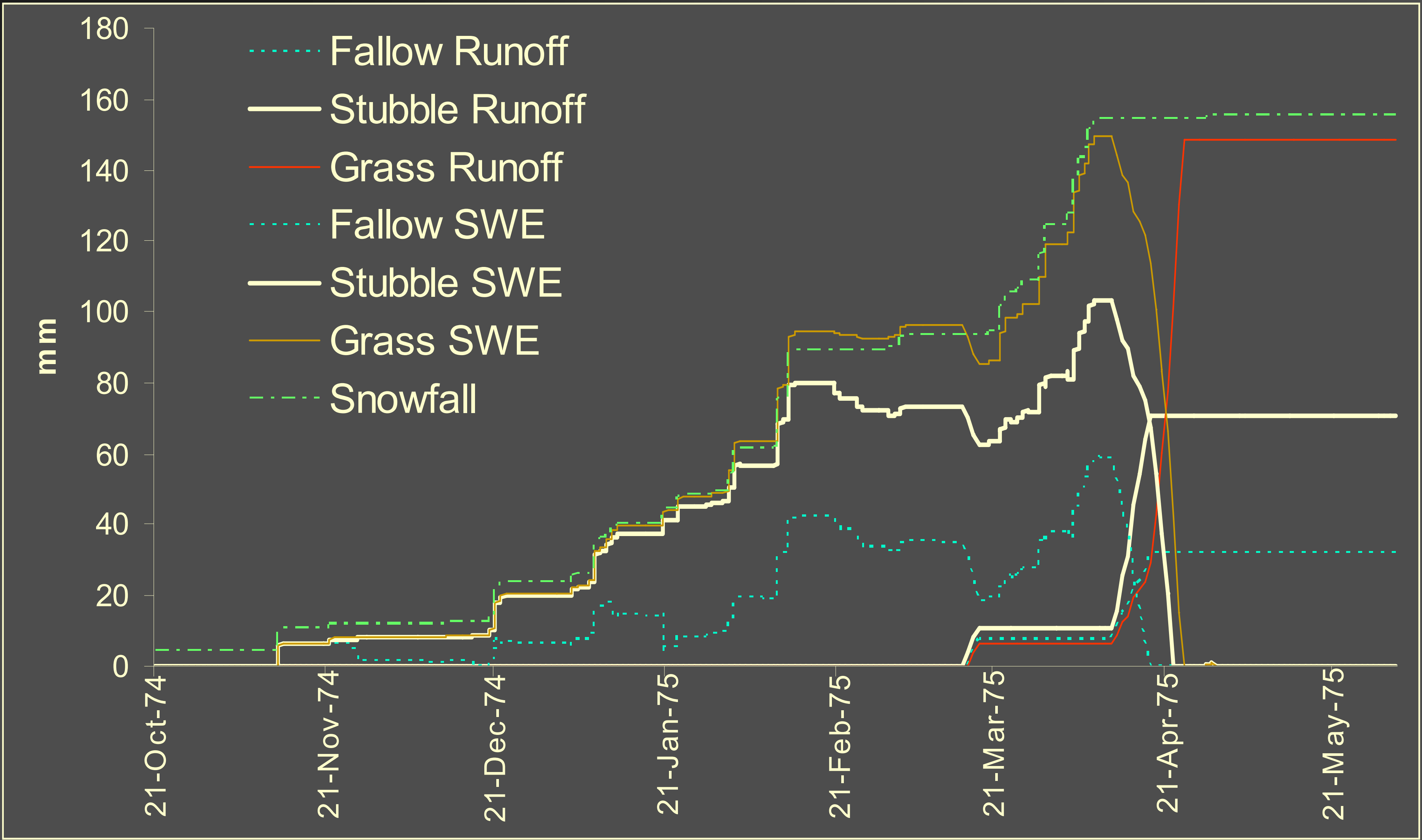
forest site



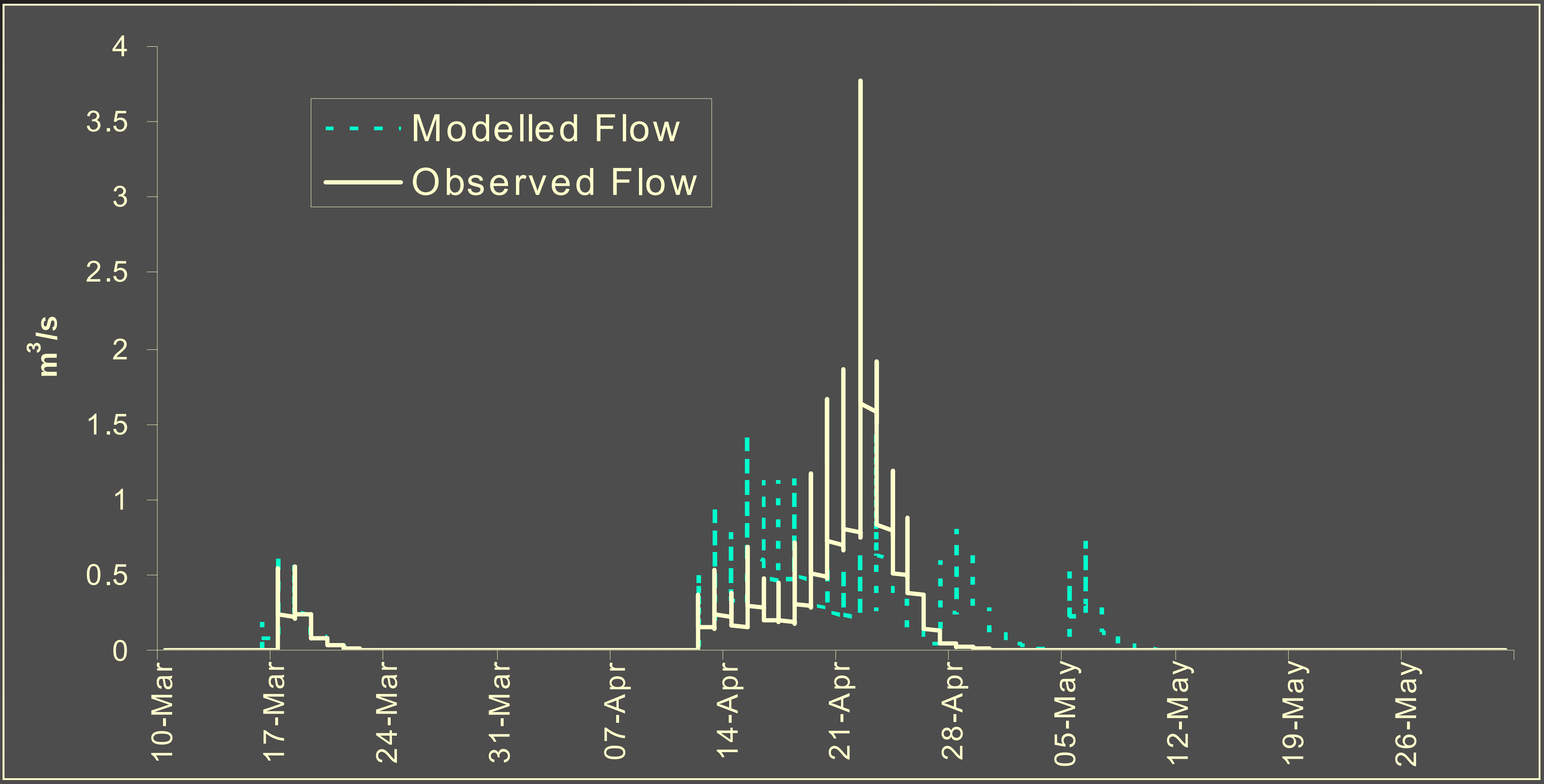
SnowMIP2 runs: BERMS, Sask



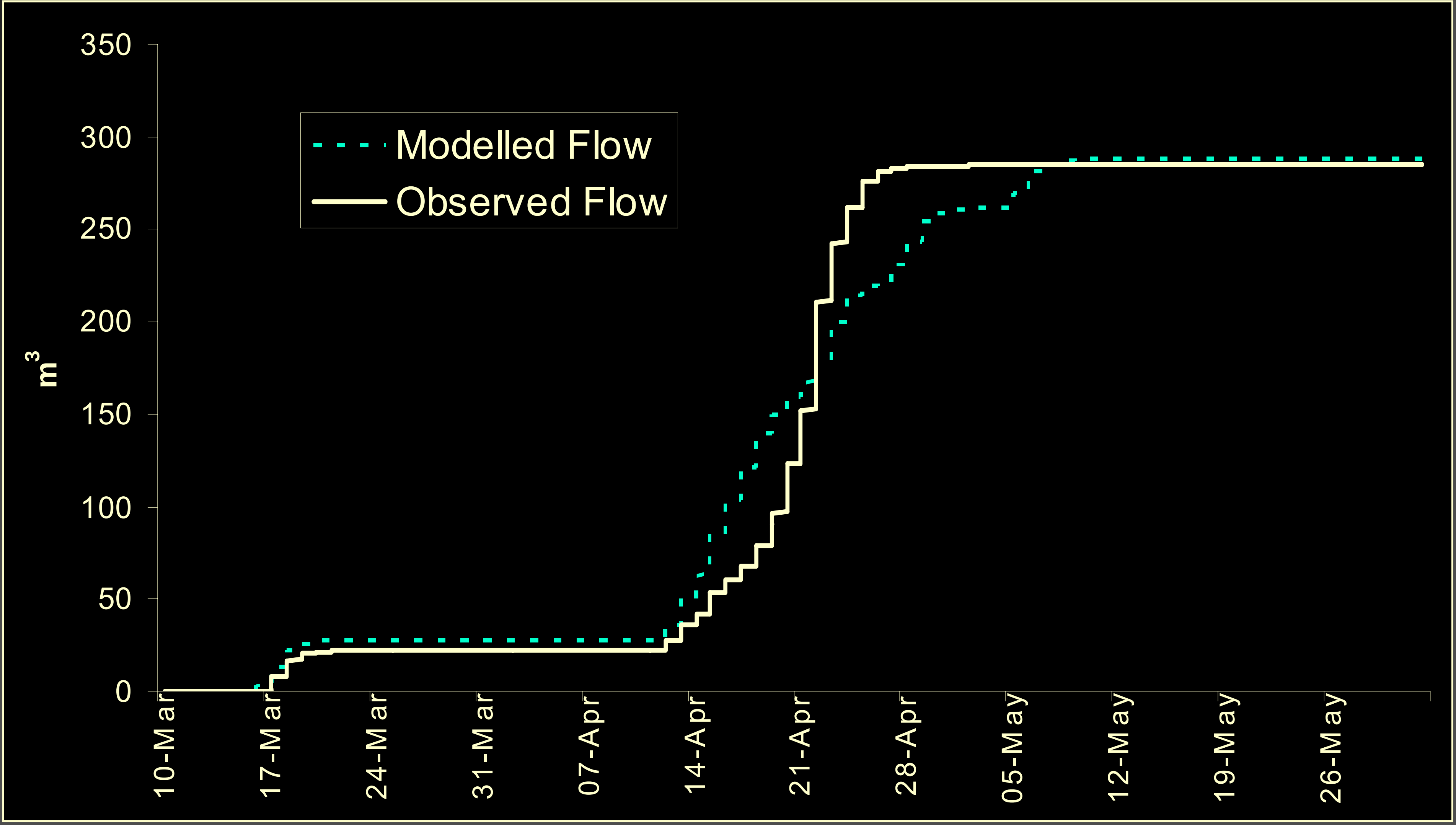
Snow Accumulation, Melt & Runoff Simulation in Prairies



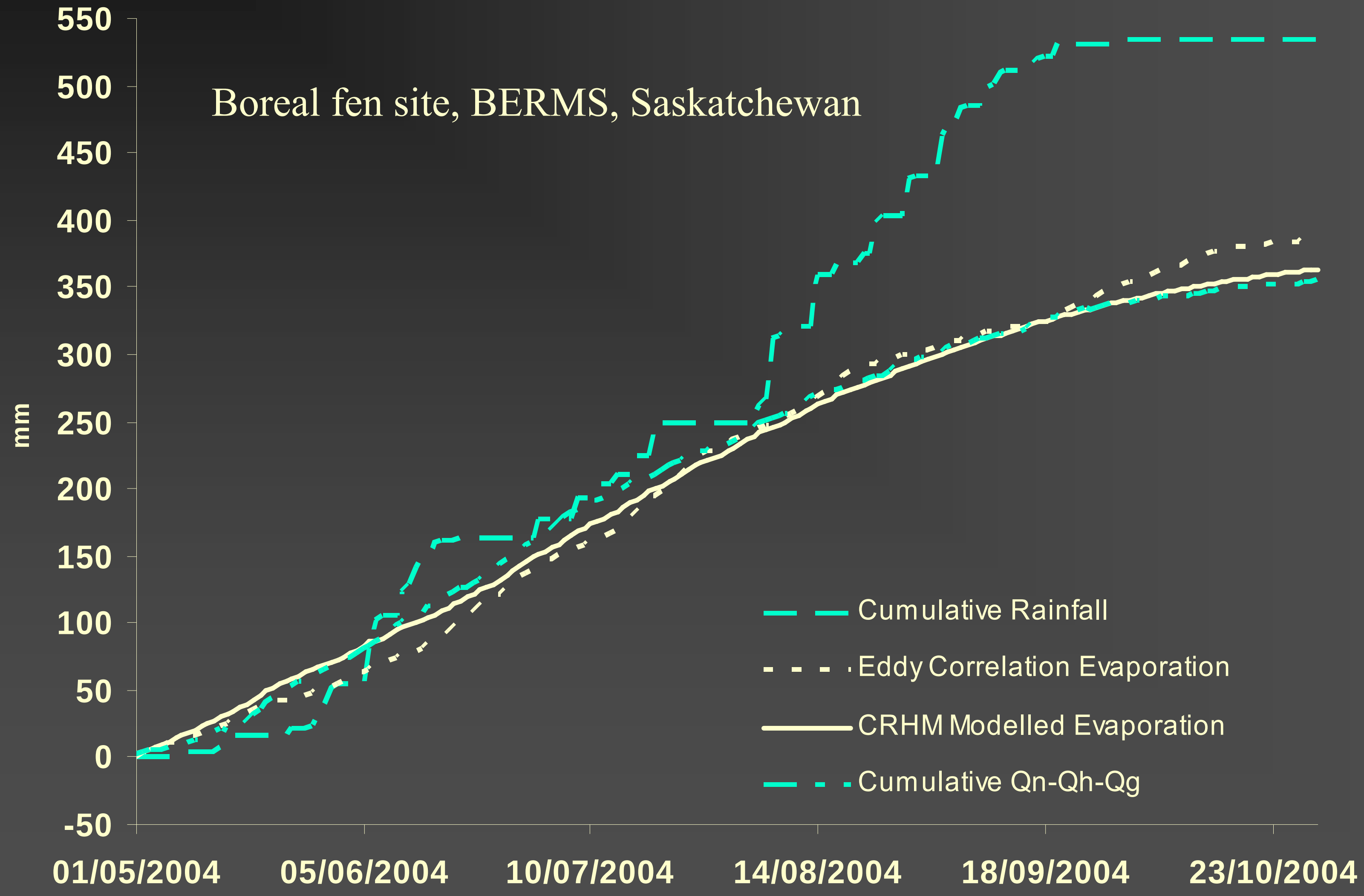
Basin Hydrograph – no calibration



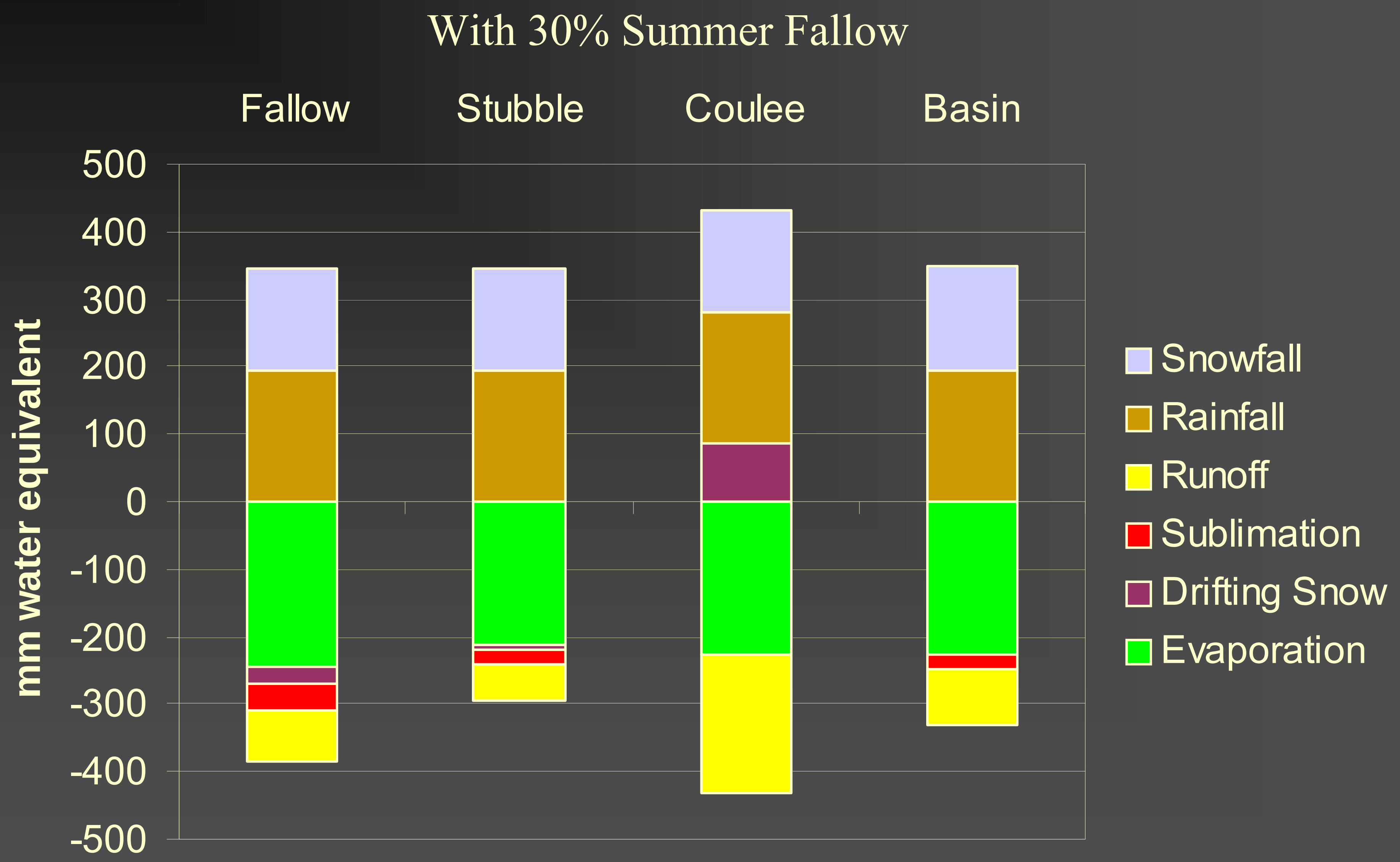
Water Export Simulation – no calibration used



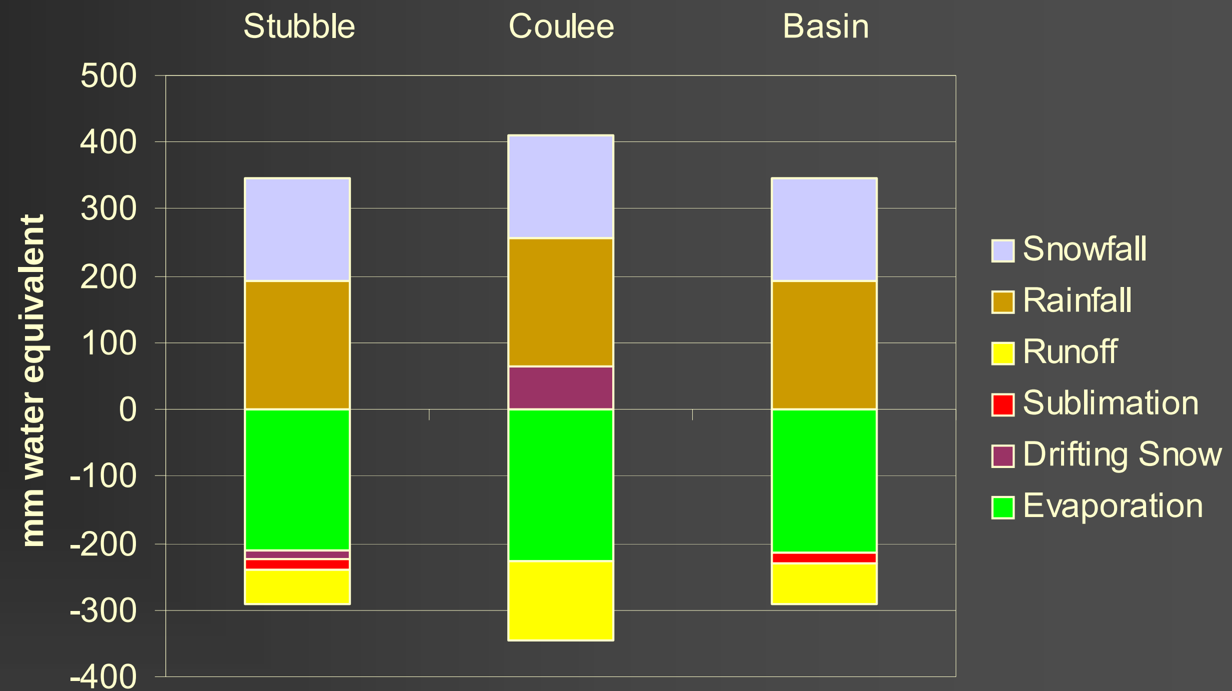
Evaporation – summer testing

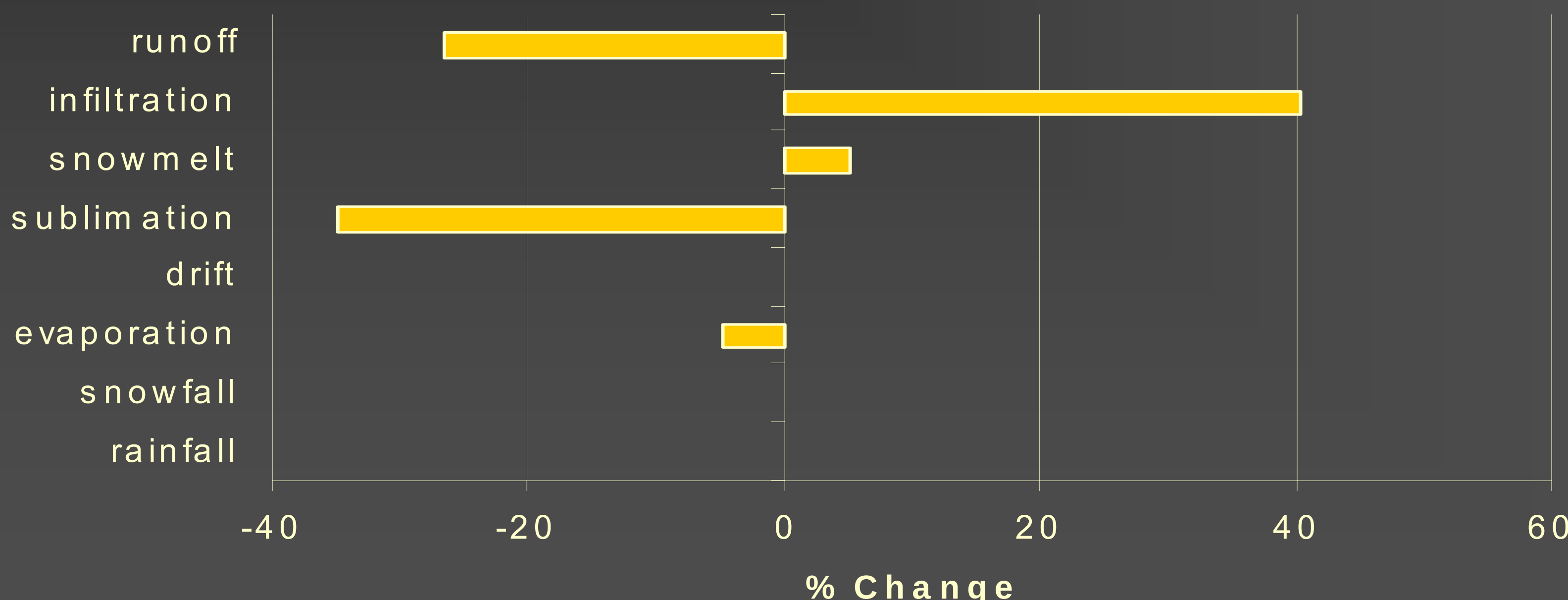


Prairie Basin Water Balance



Changed to Continuous Grain Cropping





Conclusions

- Process algorithms can form the basis for physically-based hydrological model structure and parameter selection
- Flexible model structure and physically based components can lead to appropriate and robust hydrological simulation
- Errors in simulation identify gaps in understanding of processes, structure or parameters
- A process based modular model is able to simulate key components of the cold regions hydrological cycle from an understanding of principles, and without calibration of parameters except for routing
- Modular models are relatively simple to update as our science advances.

Problem Set

- Using an observation file provided
- Develop a process hydrology project that
  - Calculates snow accumulation, snowmelt, infiltration, evaporation and runoff over at least three HRU (land types)
  - Set parameters for this project
  - Show the sensitivity of the runoff to changes in paramters