Multiscale Modelling of Mountain, Forest and Prairie Hydrology

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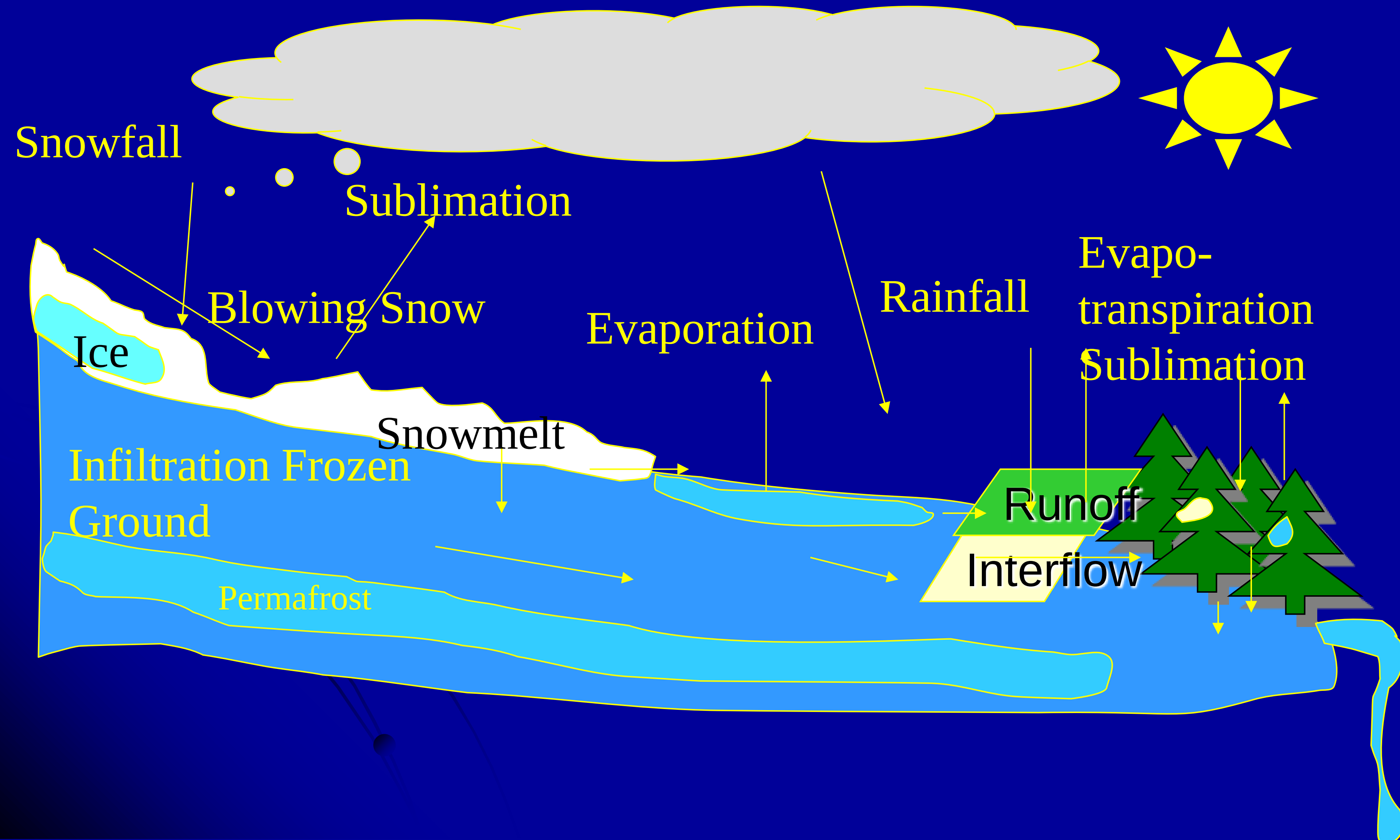
Cold Regions Hydrological Cycle



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.**
- **Flexible – permits assessment of land use and climate change impacts on streamflow regime, soil moisture, wetlands, snowpack, groundwater, chemistry, etc.**
- **Can interface with chemistry and ecology - aquatic chemistry and hydroecological modelling require a sound hydrophysical base.**
- **Elevates hydrological *practice* to hydrological *science.***

Information Needs to Design Models

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

Observations Clustered in Small Basins Improve Understanding

Appropriate Hydrological Modelling

- Model structural complexity needs to be appropriate for primary governing processes, parameter & meteorological data availability.
- Detailed parameter information is normally limited outside of research basins
- Basin discretization using hydrological response length scales found to be very useful
- Accurate interpolation of meteorological variables is critical.
- Structure, parameters and scale are informed by the results of process studies and distributed modelling at a network of research basins.

Cold Regions Hydrological Model Platform: CRHM

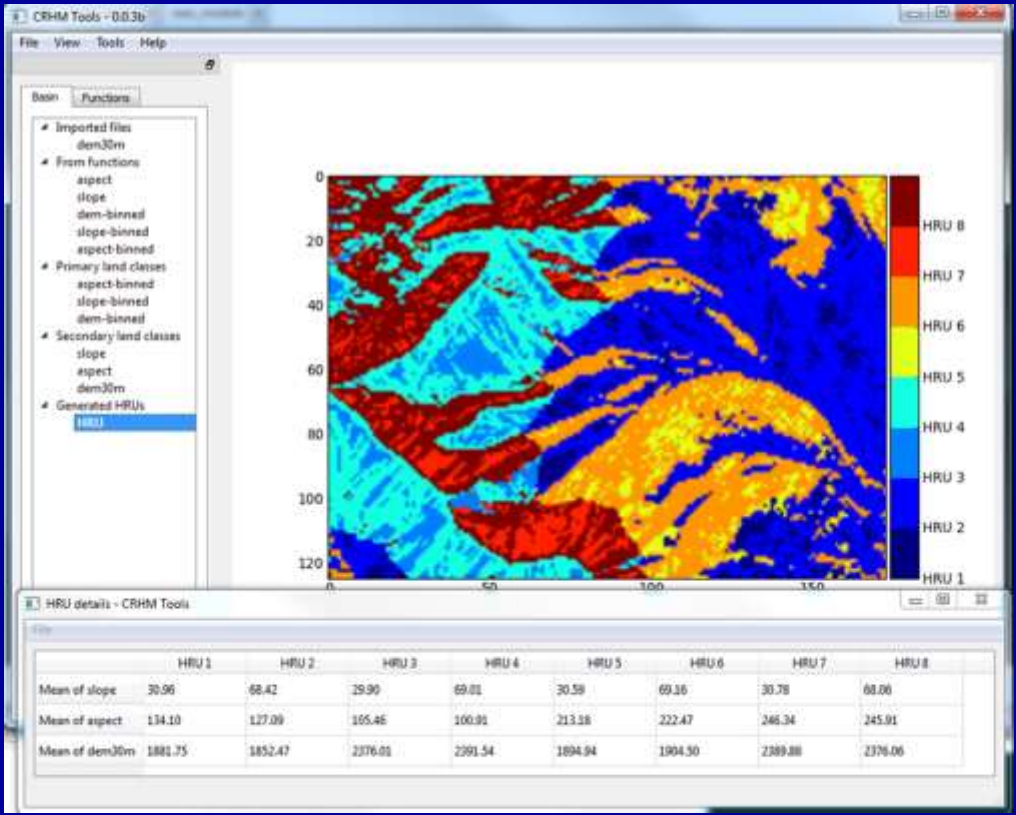
- Modular – purpose built from C++ modules
- Parameters set by knowledge rather than optimization
- Hydrological Response Unit (HRU) basis
  - landscape unit with characteristic hydrological processes/response
  - single parameter set
  - horizontal interaction along flow cascade matrix
  - Model tracks state variables and flows for HRU
- Coupled energy and mass balance, physically based algorithms applied to HRUs via module selection
- HRUs connected aerodynamically for blowing snow and via dynamic drainage networks for streamflow
- Flexible - can be configured for prairie, mountain, boreal, arctic basins
- Sub-basins connected via Muskingum routing
- Visualisation tools, GIS interface
- Model failure is embraced and instructive

Pomeroy et al., 2007 *Hydrol. Proc.*

Tom Brown, CRHM Modeller

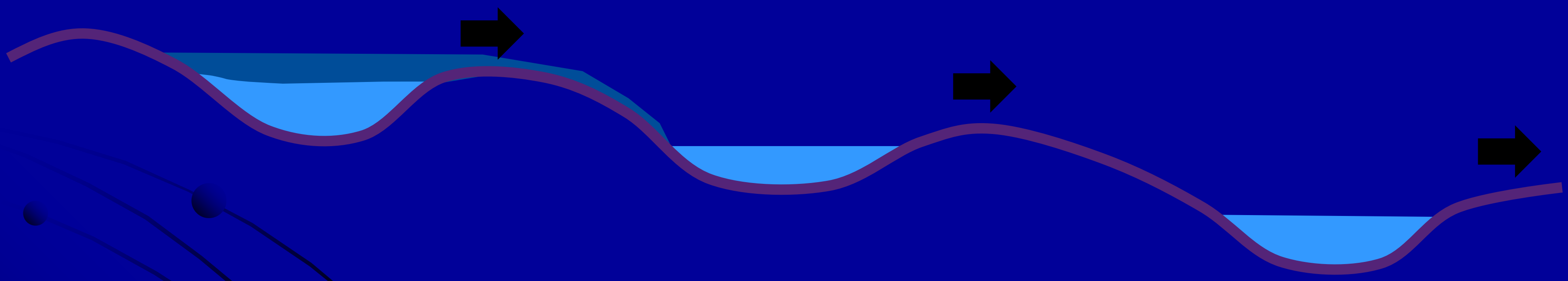
Hydrological Response Units (HRU)

- **A HRU is a spatial unit in the basin described by a single set of parameters, defined by**
  - **biophysical structure - soils, vegetation, drainage, slope, elevation, area (determine from GIS, maps)**
  - **hydrological state – snow water equivalent, internal energy, soil moisture, depressional storage, lake storage, water table (track using model)**
  - **hydrological flux - snow transport, sublimation, evaporation, melt discharge, infiltration, drainage, runoff. Fluxes are determined using fluxes from adjacent HRU and so depend on location in a flow sequence.**



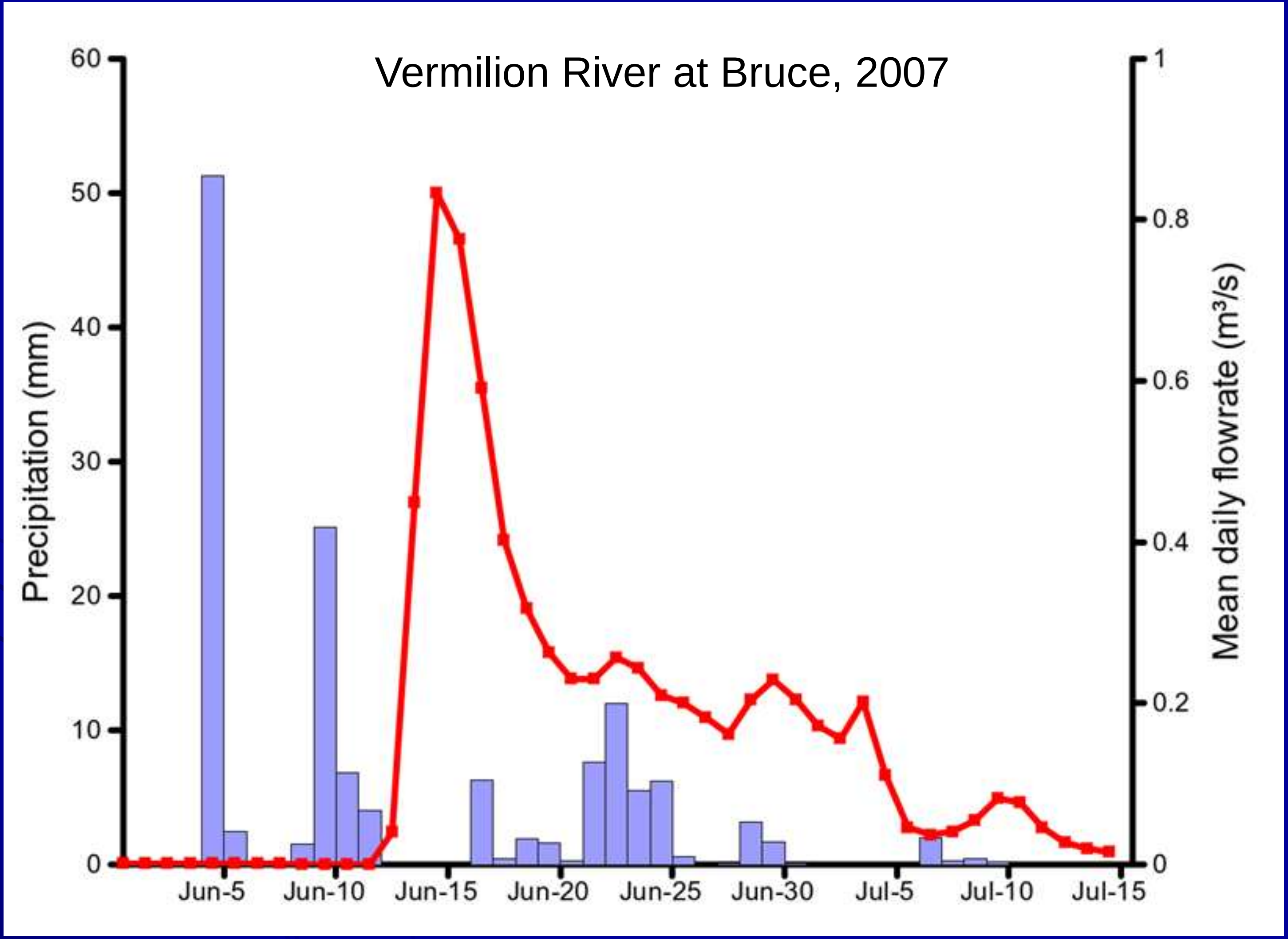
Prairie Hydrological Connectivity

The 'fill and spill' hypothesis



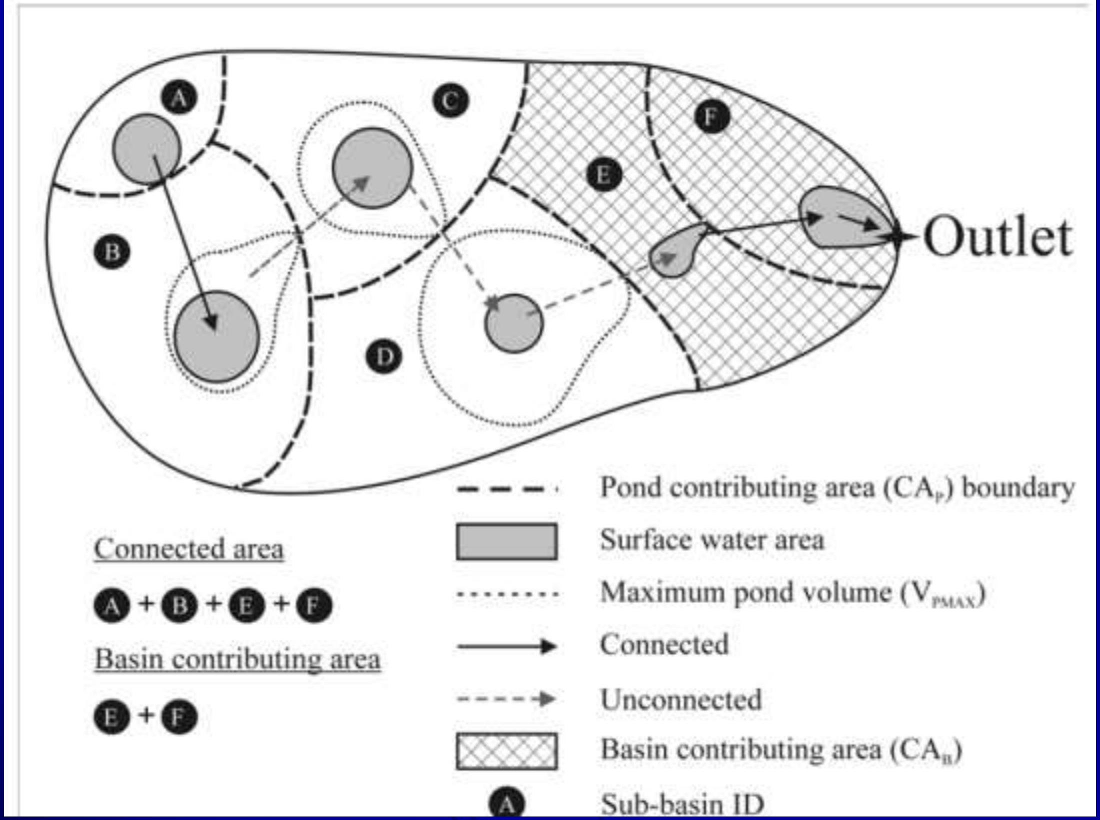
Lack of groundwater connections in this landscape – heavy tills

Impact of Fill and Spill on Hydrological Response to Precipitation

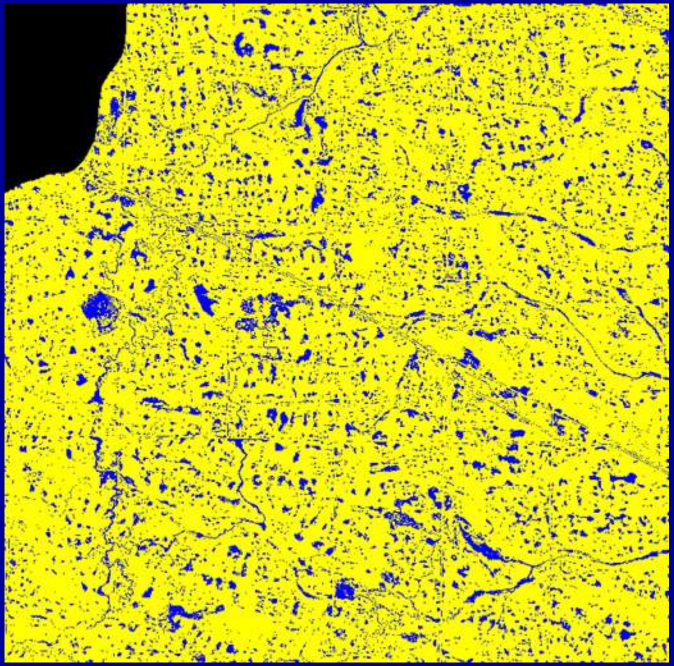


Fill and Spill Leads to Variable Contributing Area

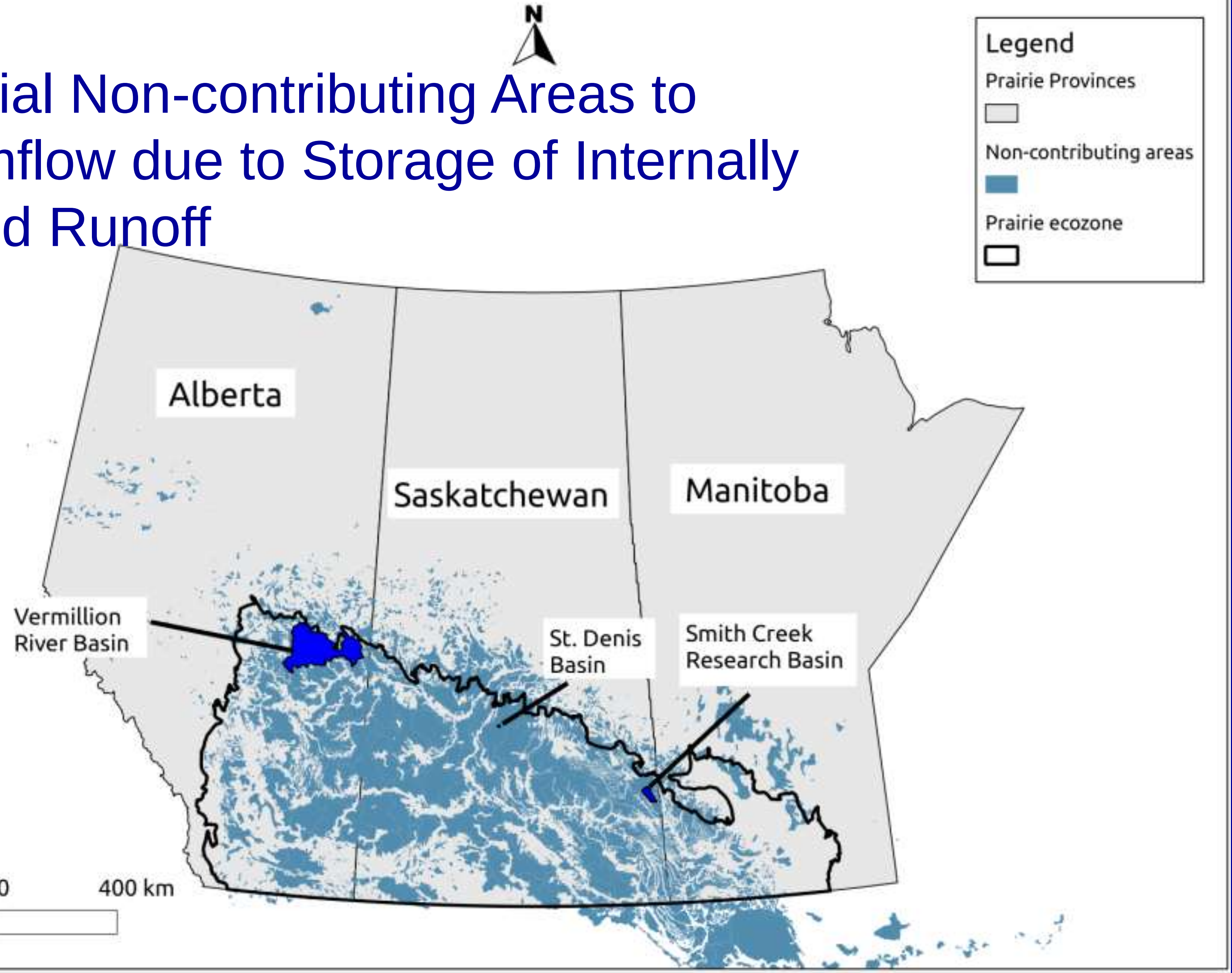
Conceptual View – Dean Shaw



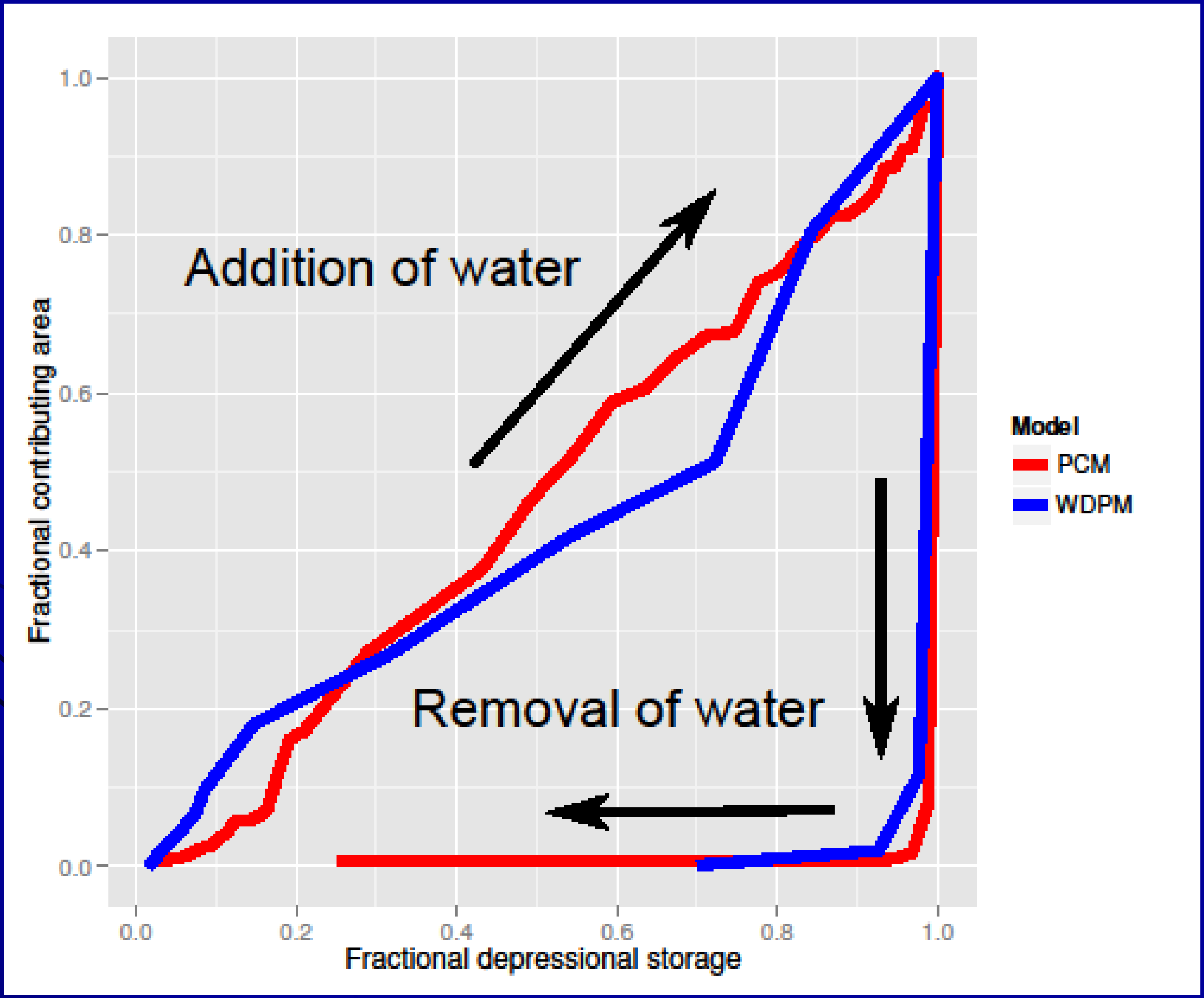
Real Wetlands, Vermilion River Basin



Potential Non-contributing Areas to Streamflow due to Storage of Internally Drained Runoff

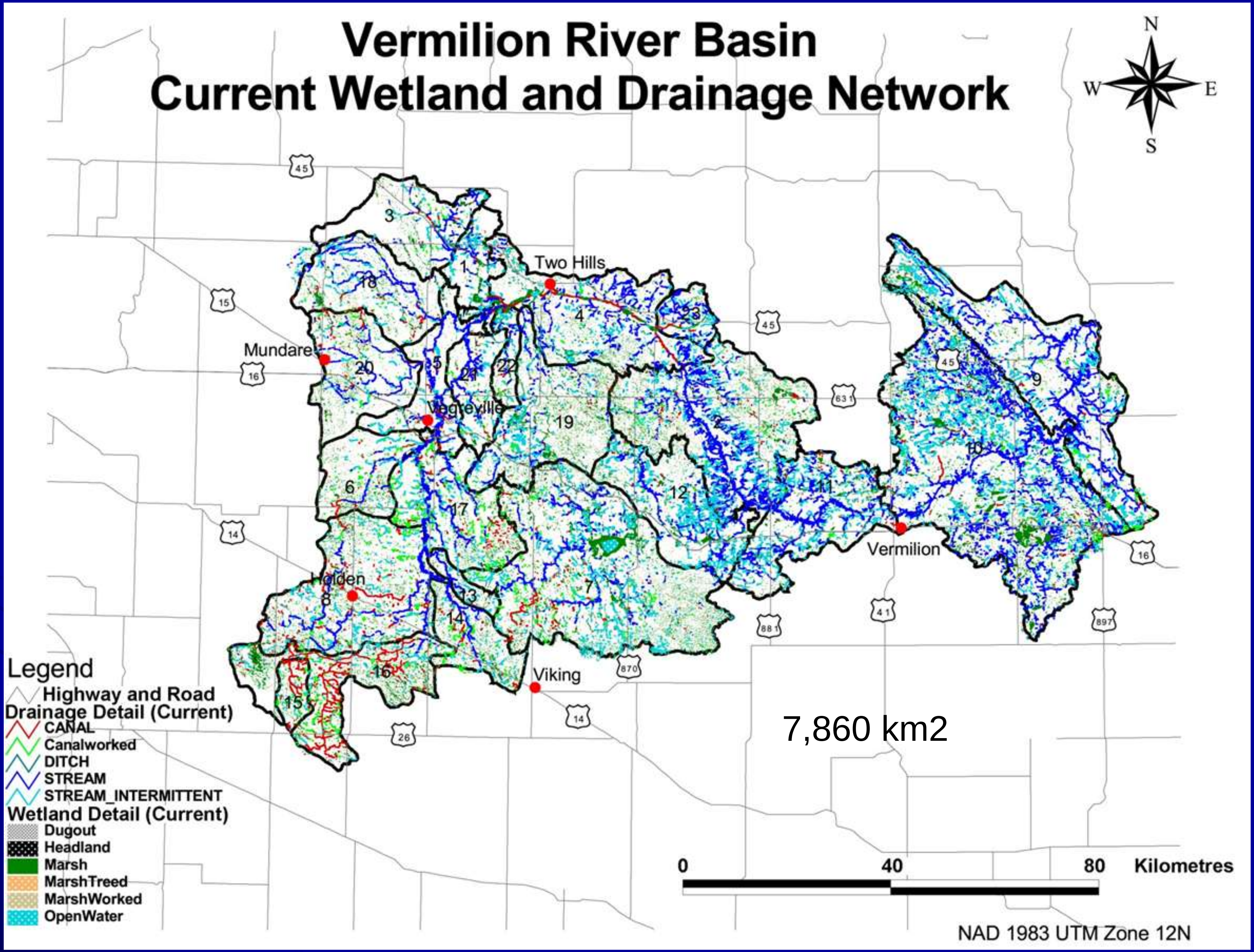


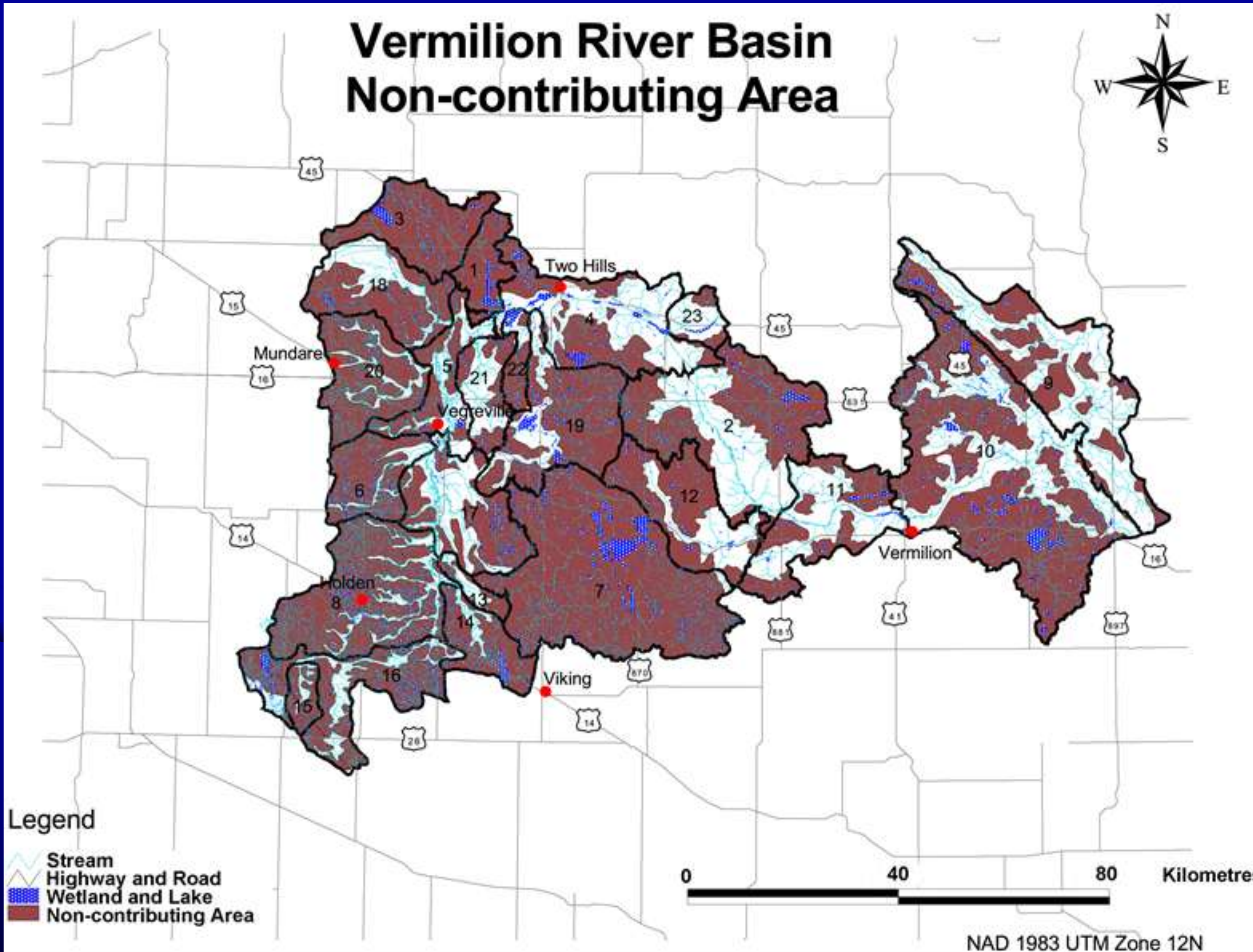
Depressional Storage – Basin Contributing Area Relationship



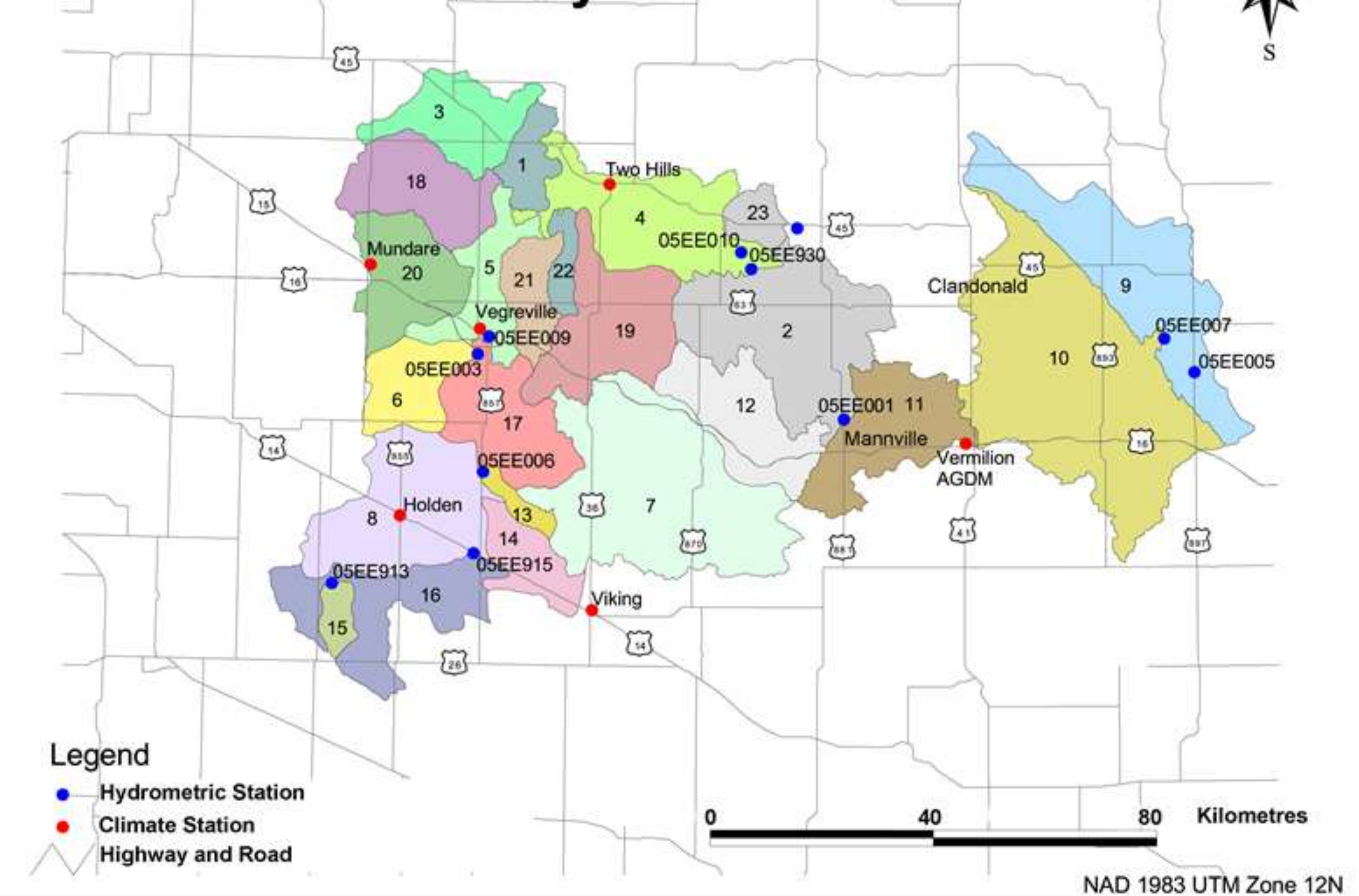
Objective

- Develop a model that can demonstrate the role of surface water storage on the hydrology of Prairie river basins.
- Apply the model to simulate streamflow.
- Modify the representation of wetlands in the model to show the impact of restoration and drainage on basin hydrology.


Vermilion River Basin
Current Wetland and Drainage Network
N
W
E
S
Two Hills
Mundare
Vegreville
Holden
Viking
Vermilion
Legend
Highway and Road
Drainage Detail (Current)
CANAL
Canalworked
DITCH
STREAM
STREAM_INTERMITTENT
Wetland Detail (Current)
Dugout
Headland
Marsh
MarshTreed
MarshWorked
OpenWater
7,860 km2
0
40
80
Kilometres
NAD 1983 UTM Zone 12N


Vermilion River Basin
Non-contributing Area
N
W
E
S
Two Hills
Mundare
Vegreville
Holden
Viking
Vermilion
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Legend
Stream
Highway and Road
Wetland and Lake
Non-contributing Area
0
40
80
Kilometres
NAD 1983 UTM Zone 12N

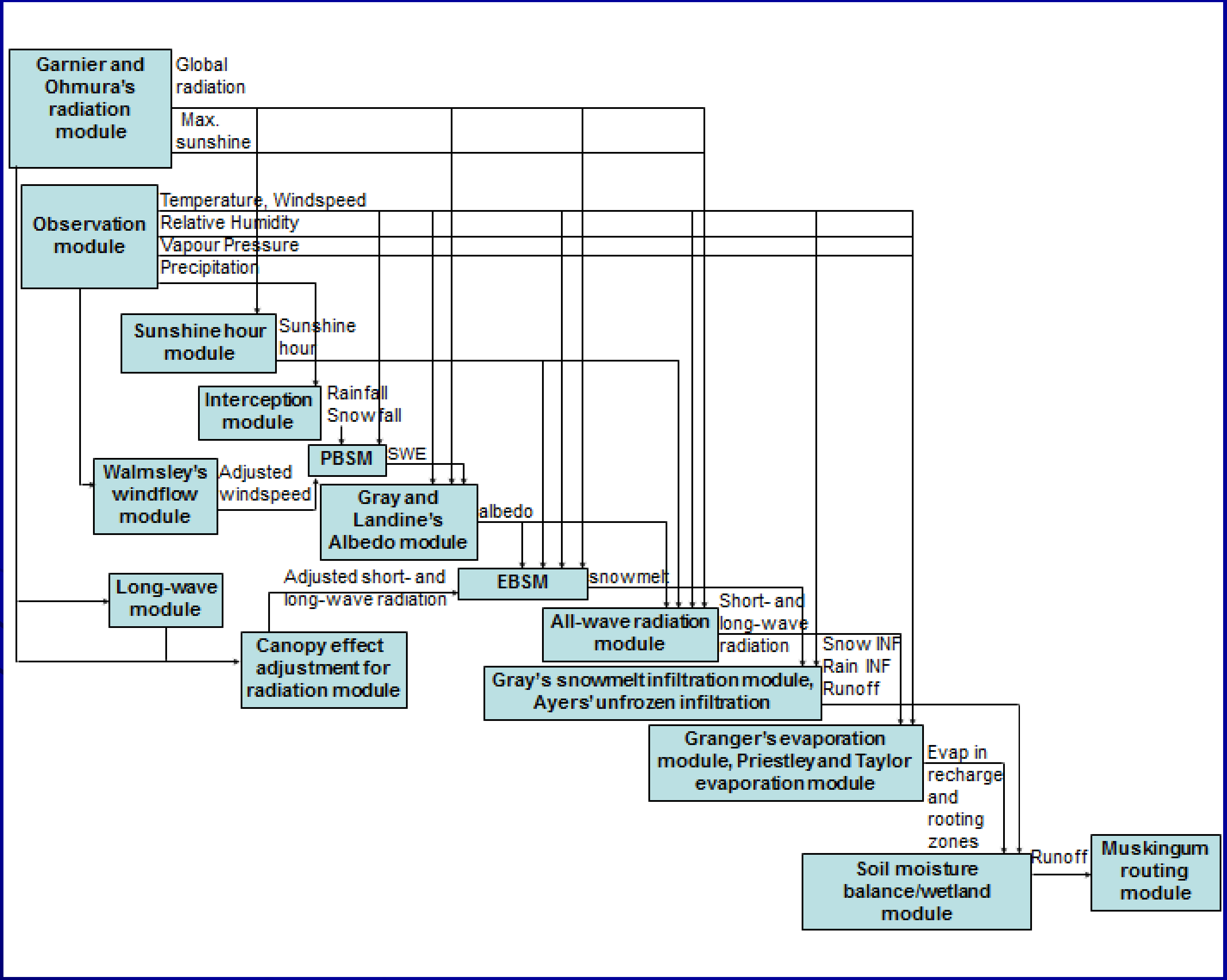
Vermilion River Basin
Climate and Hydrometric Stations



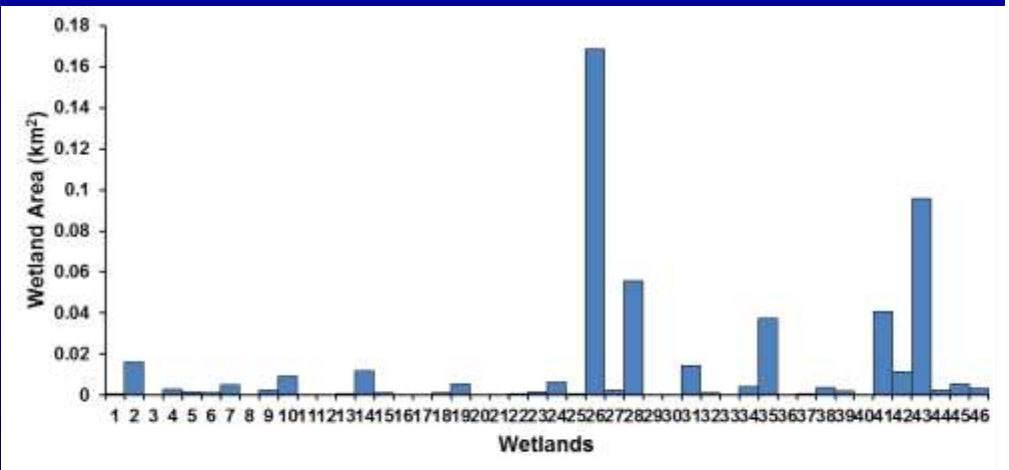
Model Setup

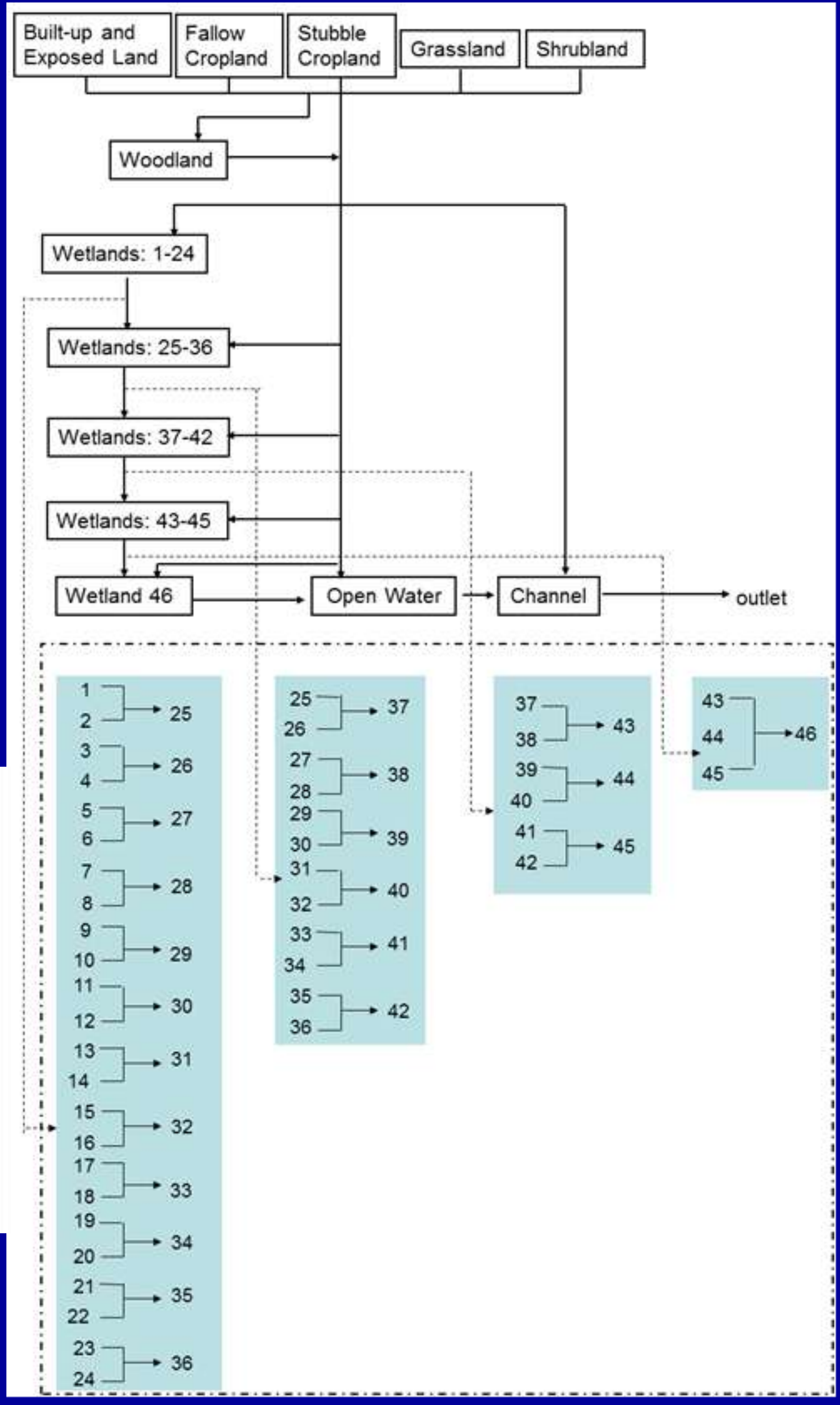
- Cold Regions Hydrological Modelling Platform (CRHM)
- Modules selected to describe hydrological processes operating in the basin.
  - Snow accumulation and melt
  - Wetland storage, drainage
  - Soil moisture storage, evapotranspiration and runoff
  - Stream routing
- Sub-basins broken into "hydrological response units" HRU corresponding to land use, drainage and soil zones.
- Sub-basins aggregated via routing module to describe total basin behaviour

Prairie Module Structure

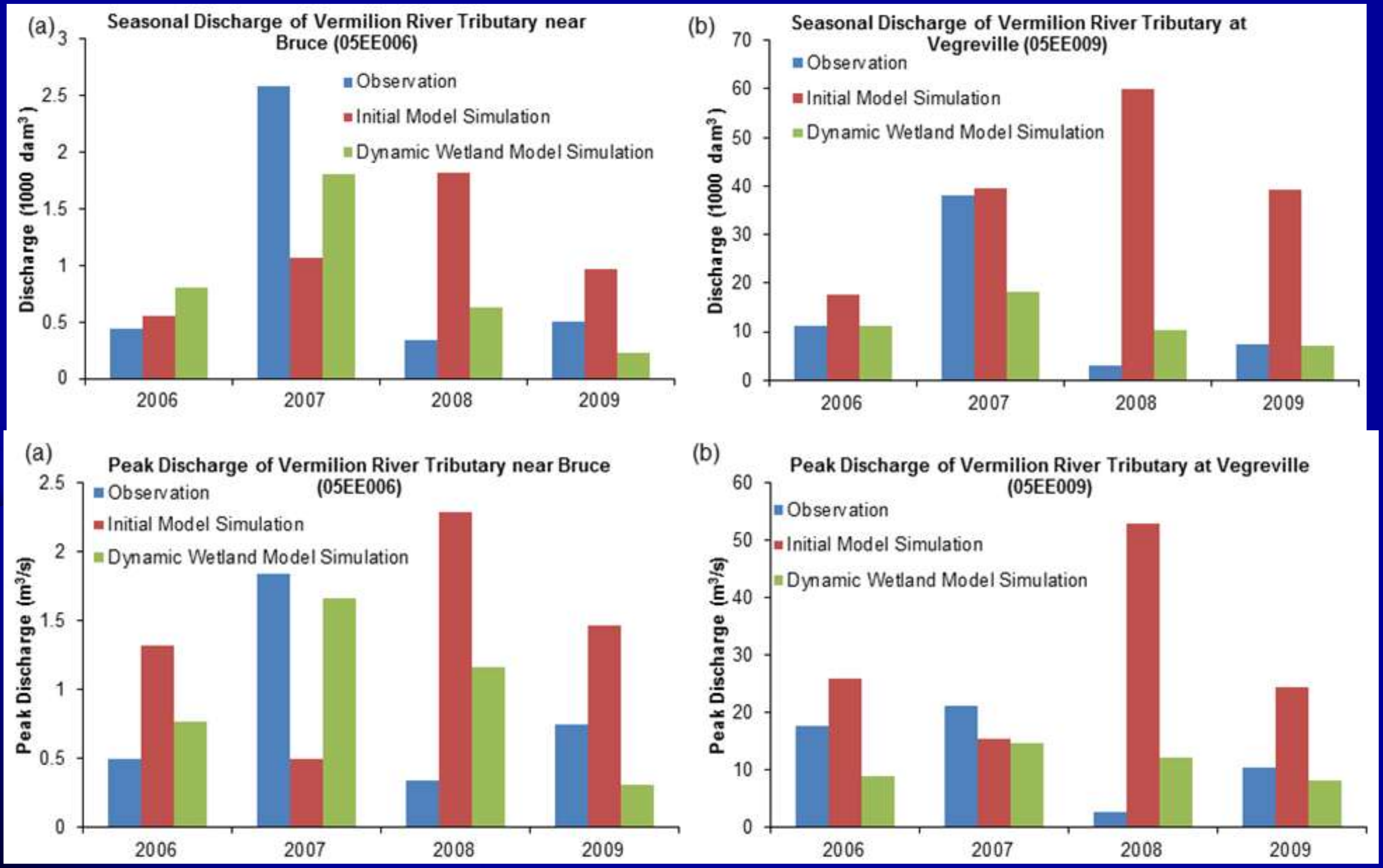


Basin and Wetland Representation





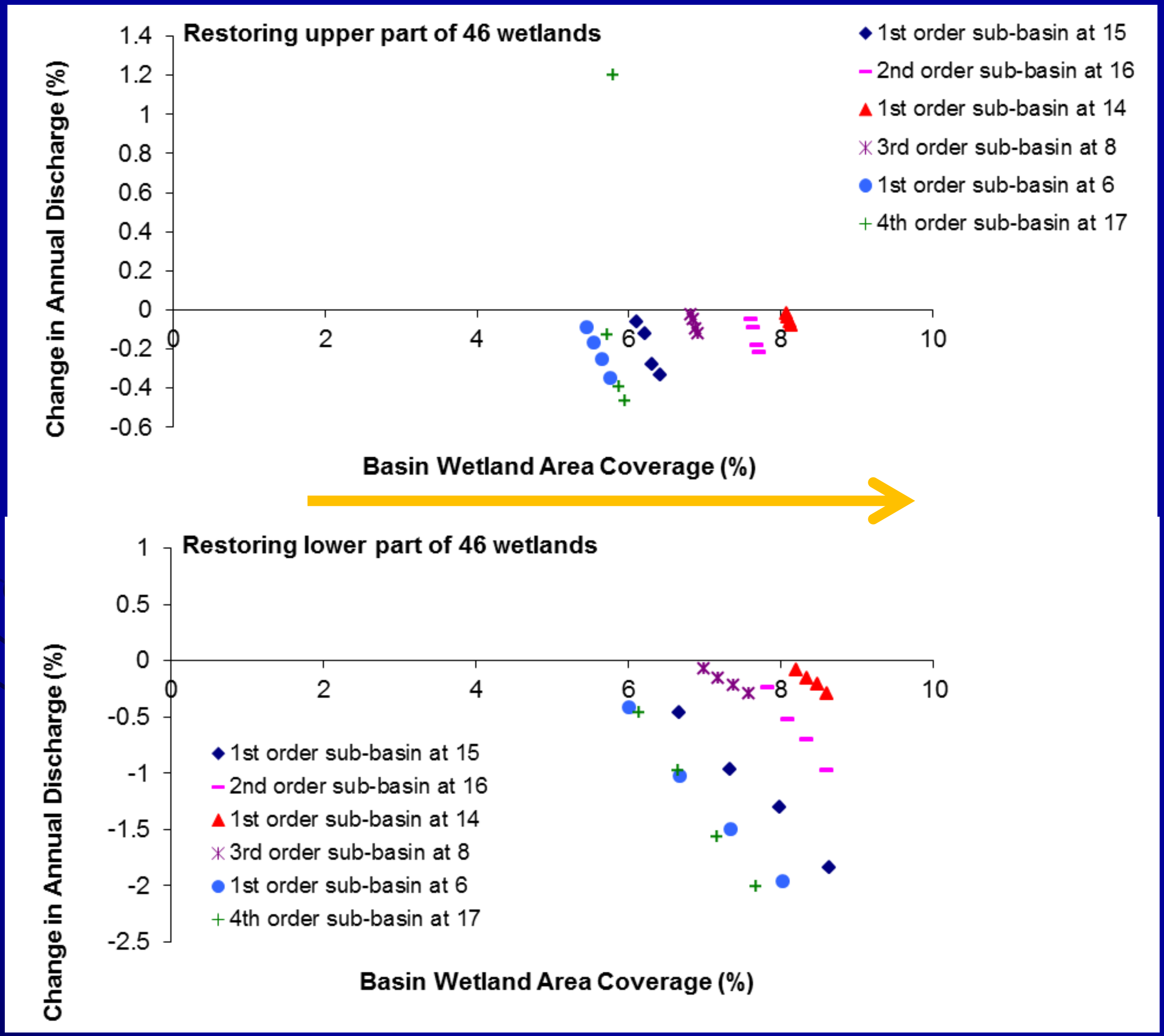
Dynamic Modelling of Wetlands Needed for Accurate Simulations



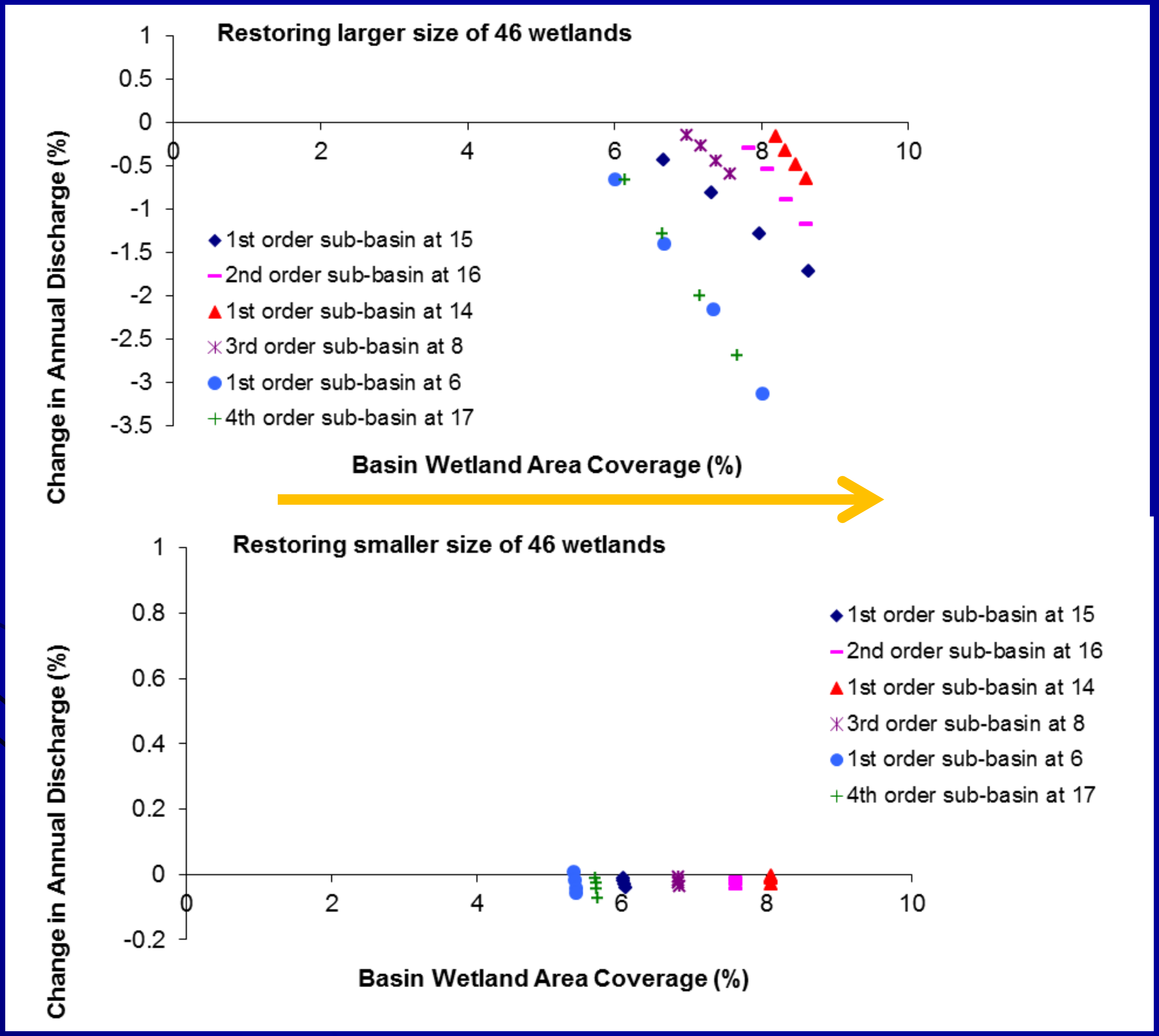
Sensitivity Analysis

- Modelled sub-basins 6, 8, 13, 14, 15, 16, 17
- Years 2005-2009 with earlier spin-up years
- Wetland Restoration – all wetlands restored to 1949 levels
  - Spatial Wetland Restoration – upper vs lower basin
  - Wetland Size Restoration – large vs small
- Wetland Drainage – all wetlands drained
  - Spatial Wetland Drainage – upper vs lower
  - Wetland Size Drainage – large vs small
- Note relatively small area of wetlands (6%) and little apparent drainage since 1949 (then 7.4%)

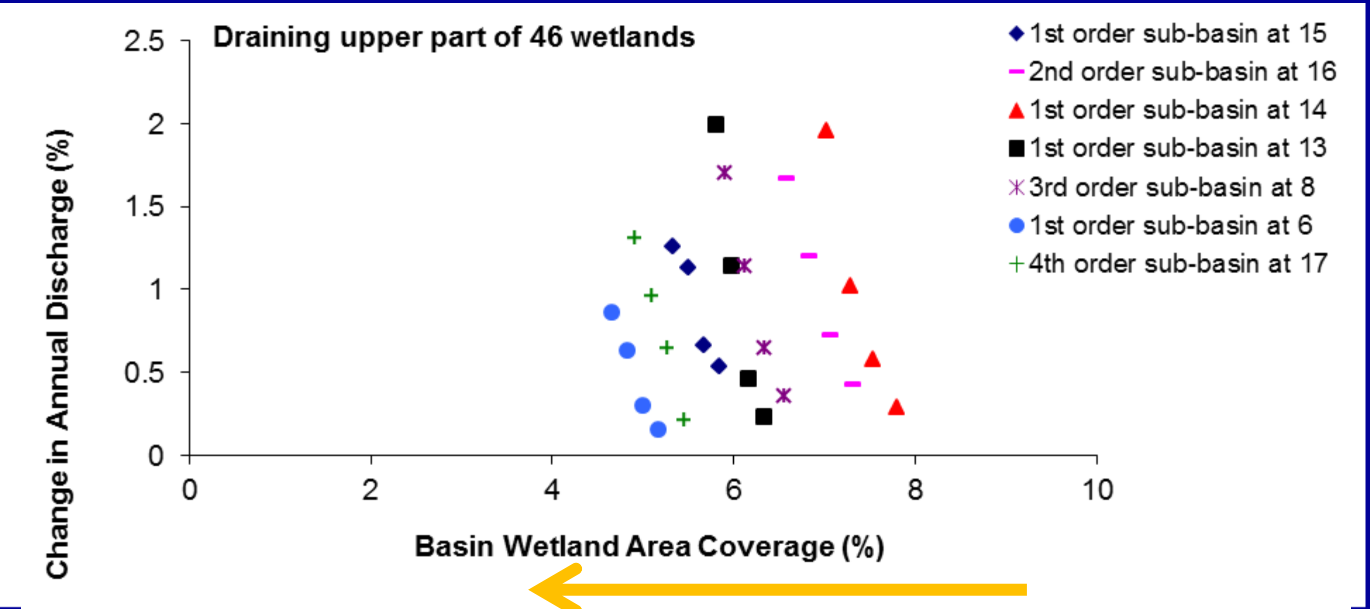
Upper vs Lower Sub-Basin Location Wetland Restoration

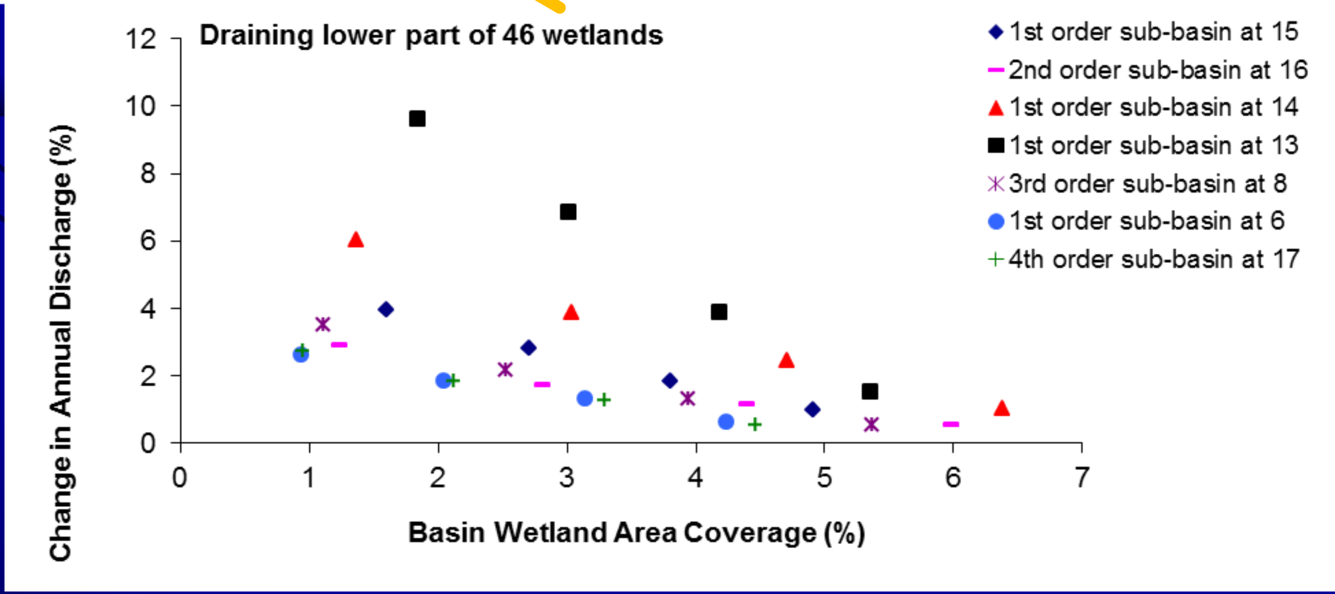


Large vs Small Size Wetland Restoration

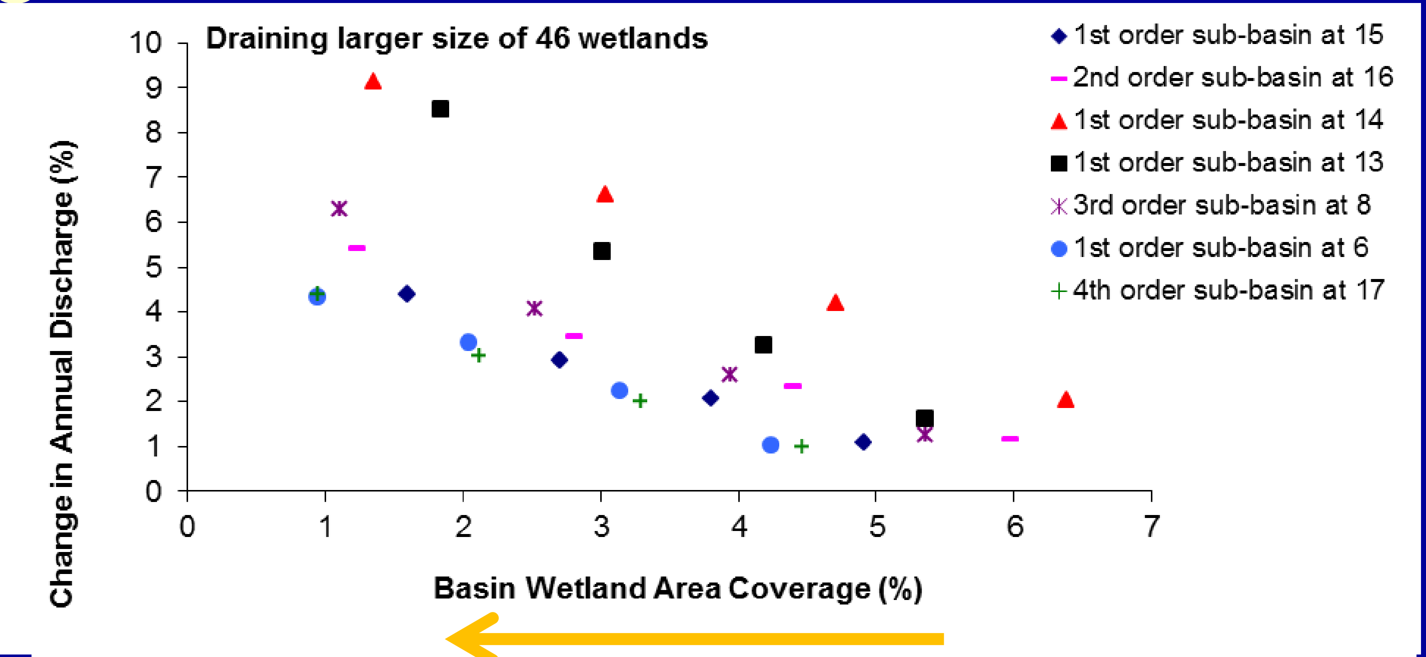


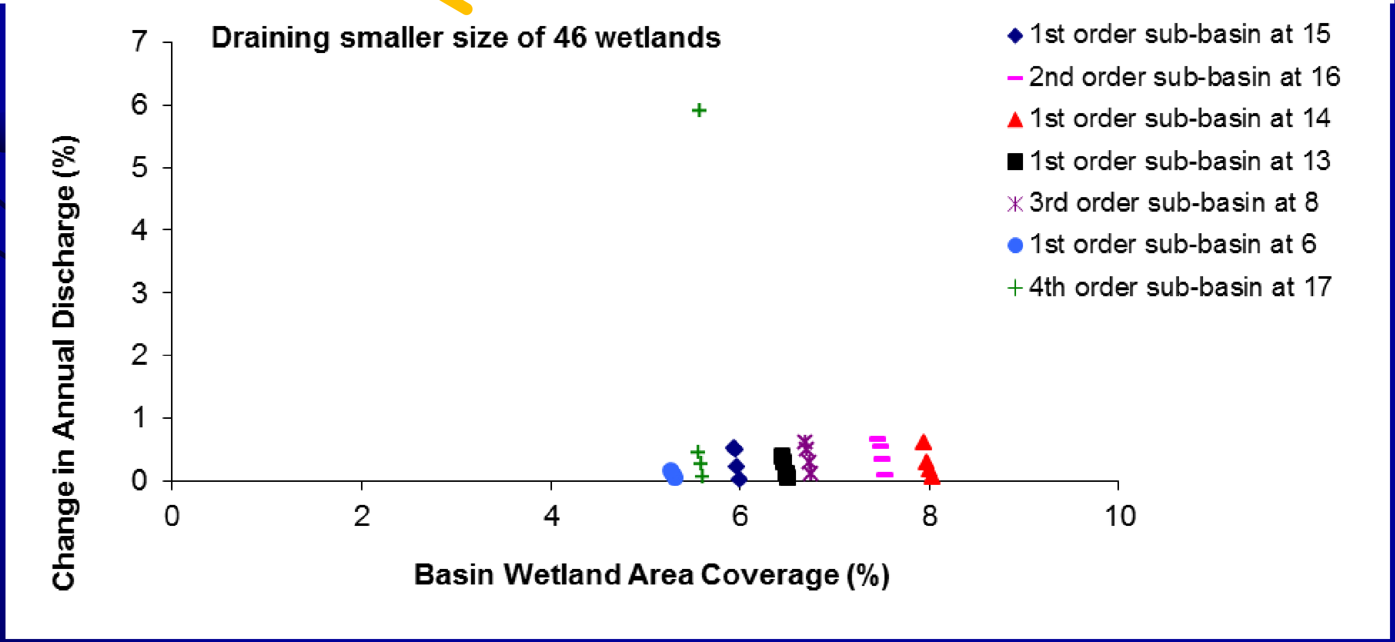
Upper vs Lower Sub-basin Location Wetland Drainage





Larger vs Smaller Wetland Drainage

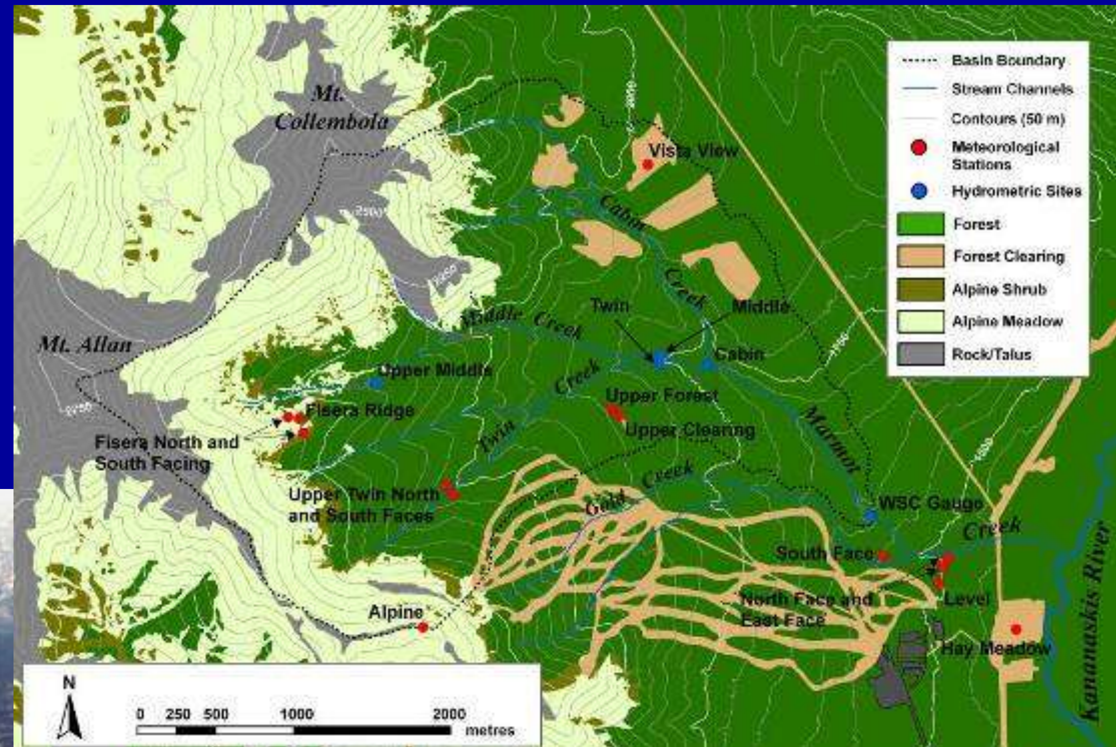


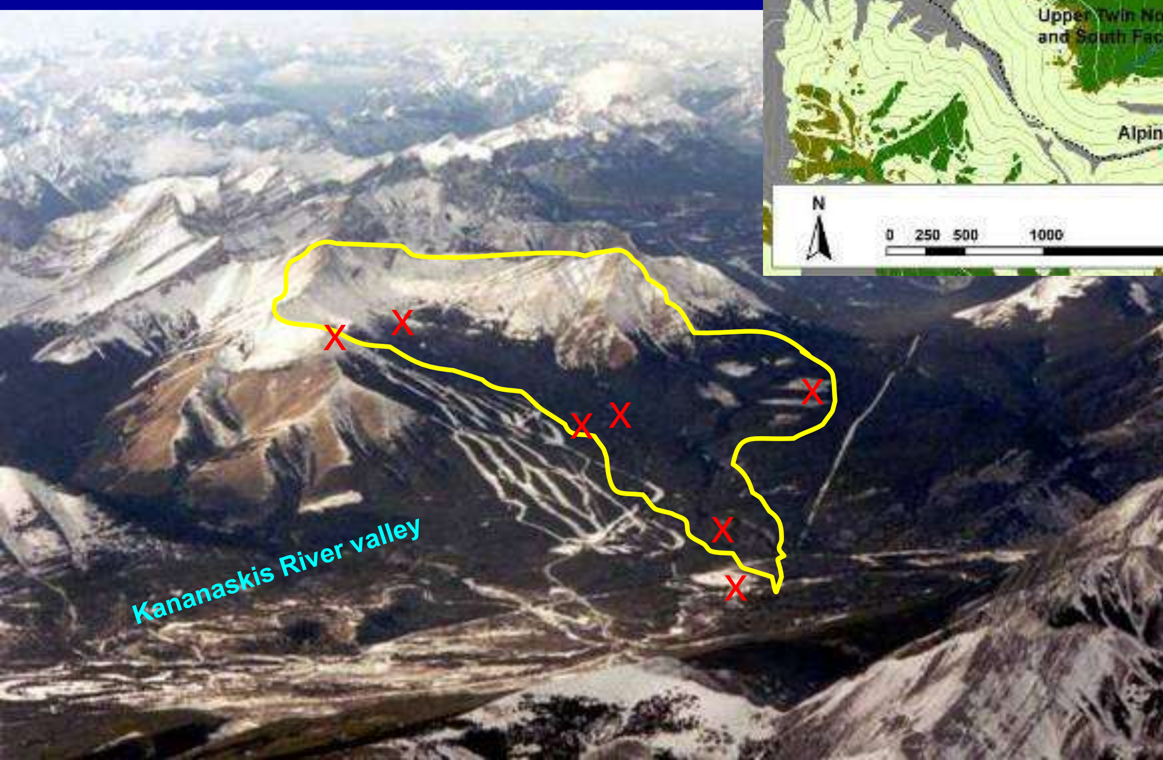


Vermilion River Basin Wetland Modelling Findings

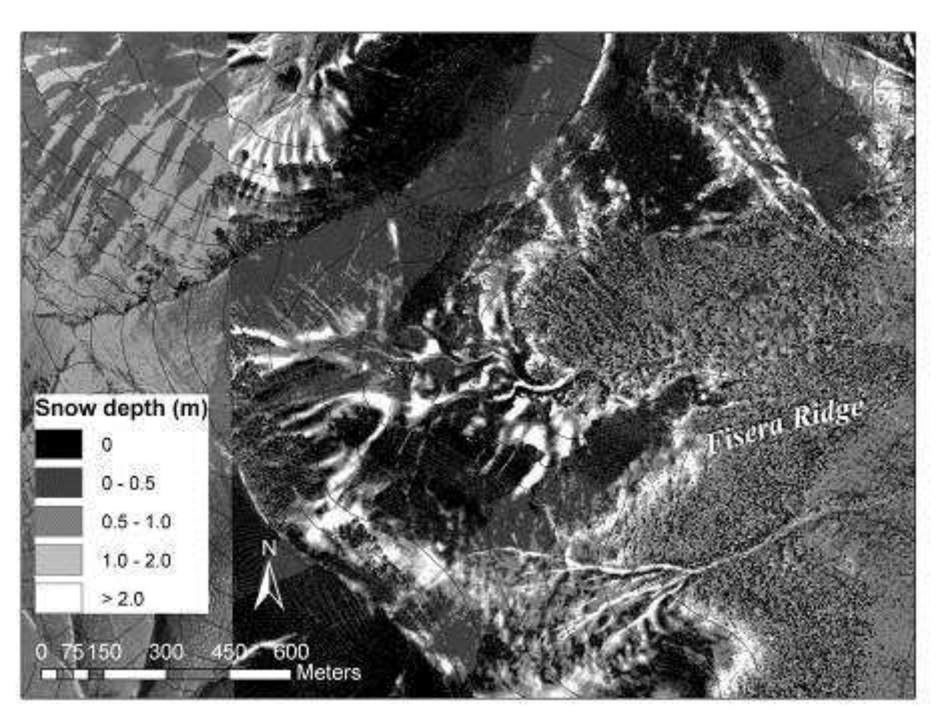
- Hysteresis affects the relationship between wetland water storage and contributing area, requiring explicit modelling of wetland dynamics in Prairie hydrology.
- Wetland restoration in the lower part of the sub-basins and for larger wetlands is most effective in reducing streamflows.
- Wetland drainage in the lower sub-basin and for larger wetlands is most effective in increasing streamflows.

Marmot Creek Research Basin

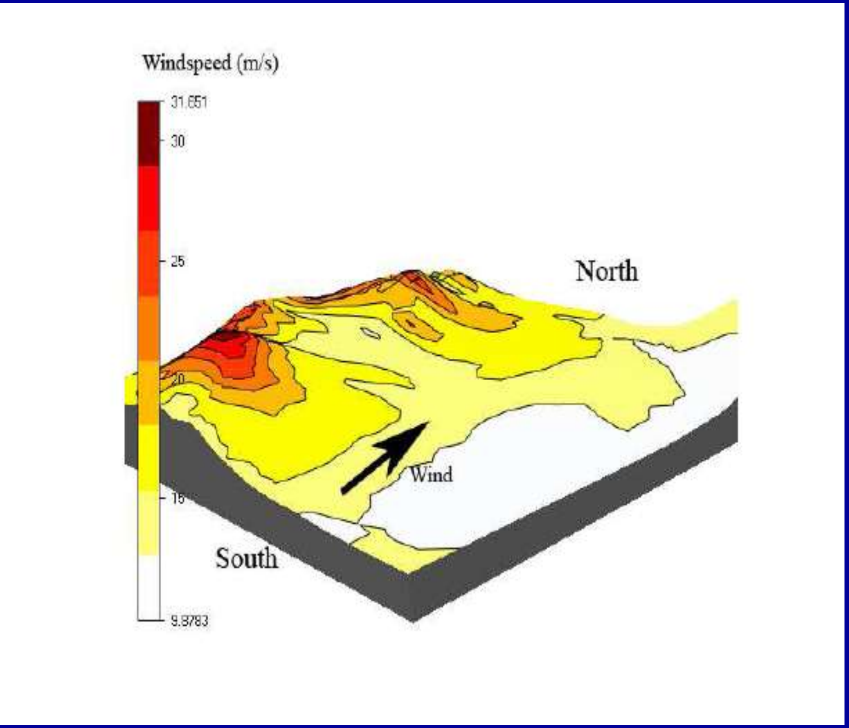




How to Determine HRU for Mountain Snow Redistribution?



LiDAR derived snow depth: subtraction of summer elevations from late winter elevations provides alpine snow depth

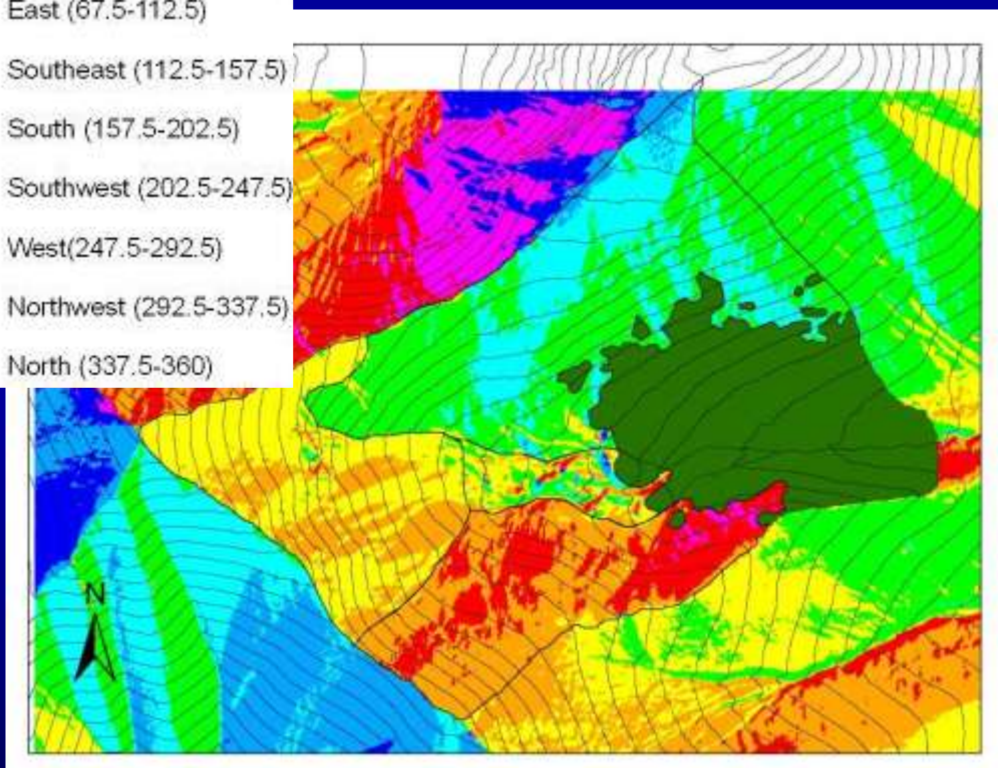


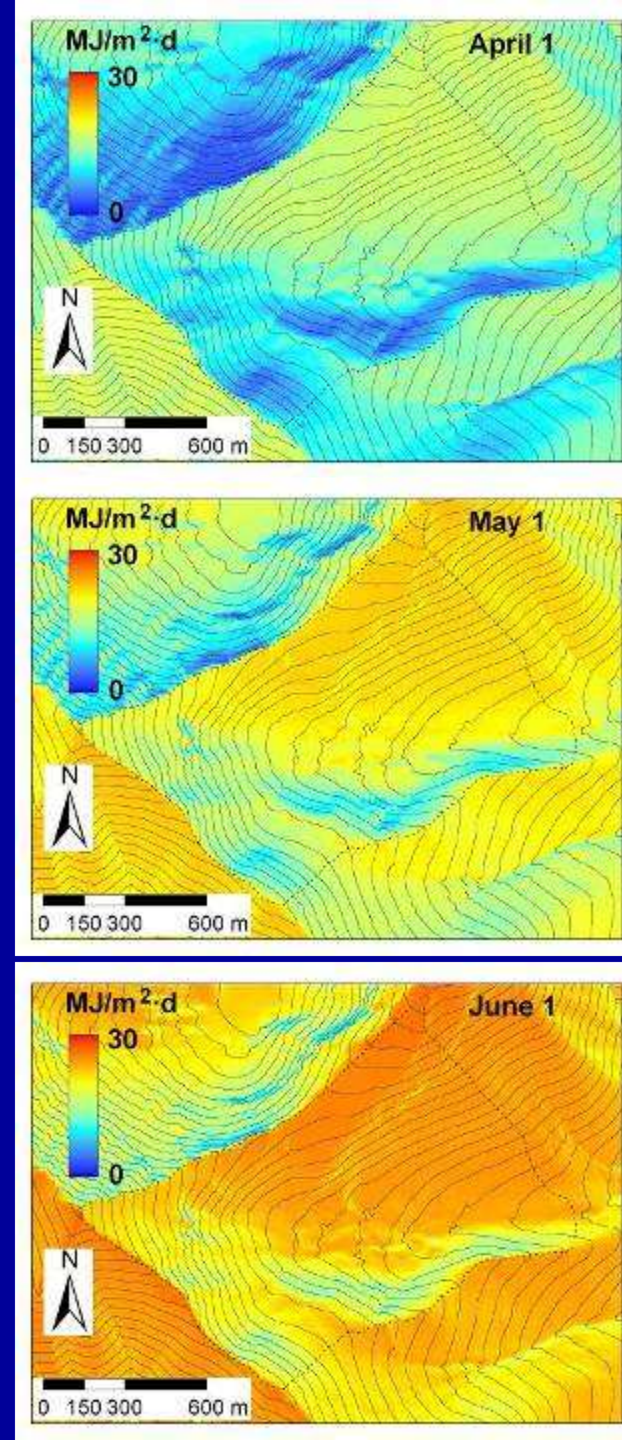
3D Reynolds averaged Navier-Stokes equations used for wind flow modelling over Marmot Creek topography (WindSim)

How to Determine HRU for Snow Melt?

Daily potential solar radiation

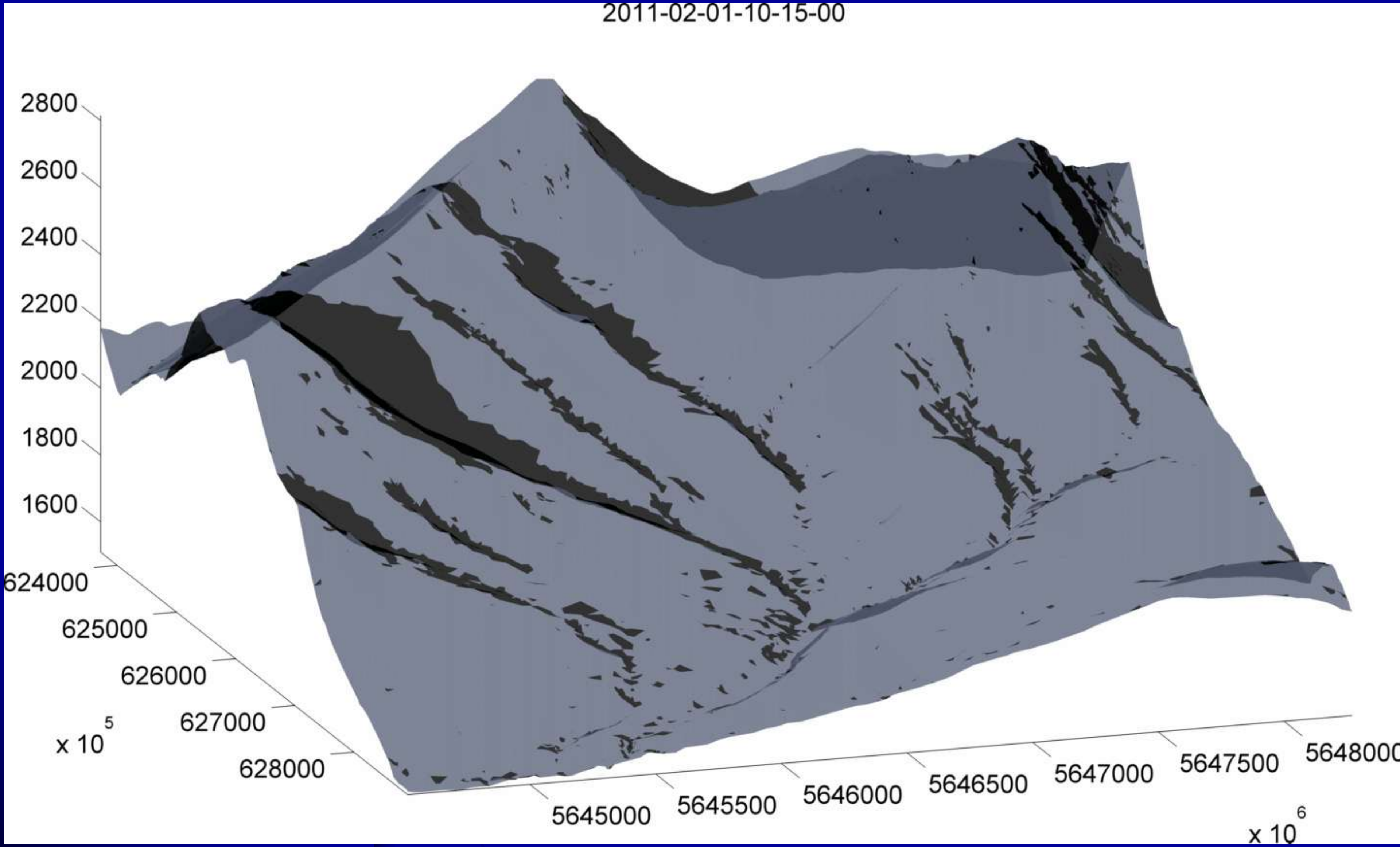
Slope and Aspect of Terrain





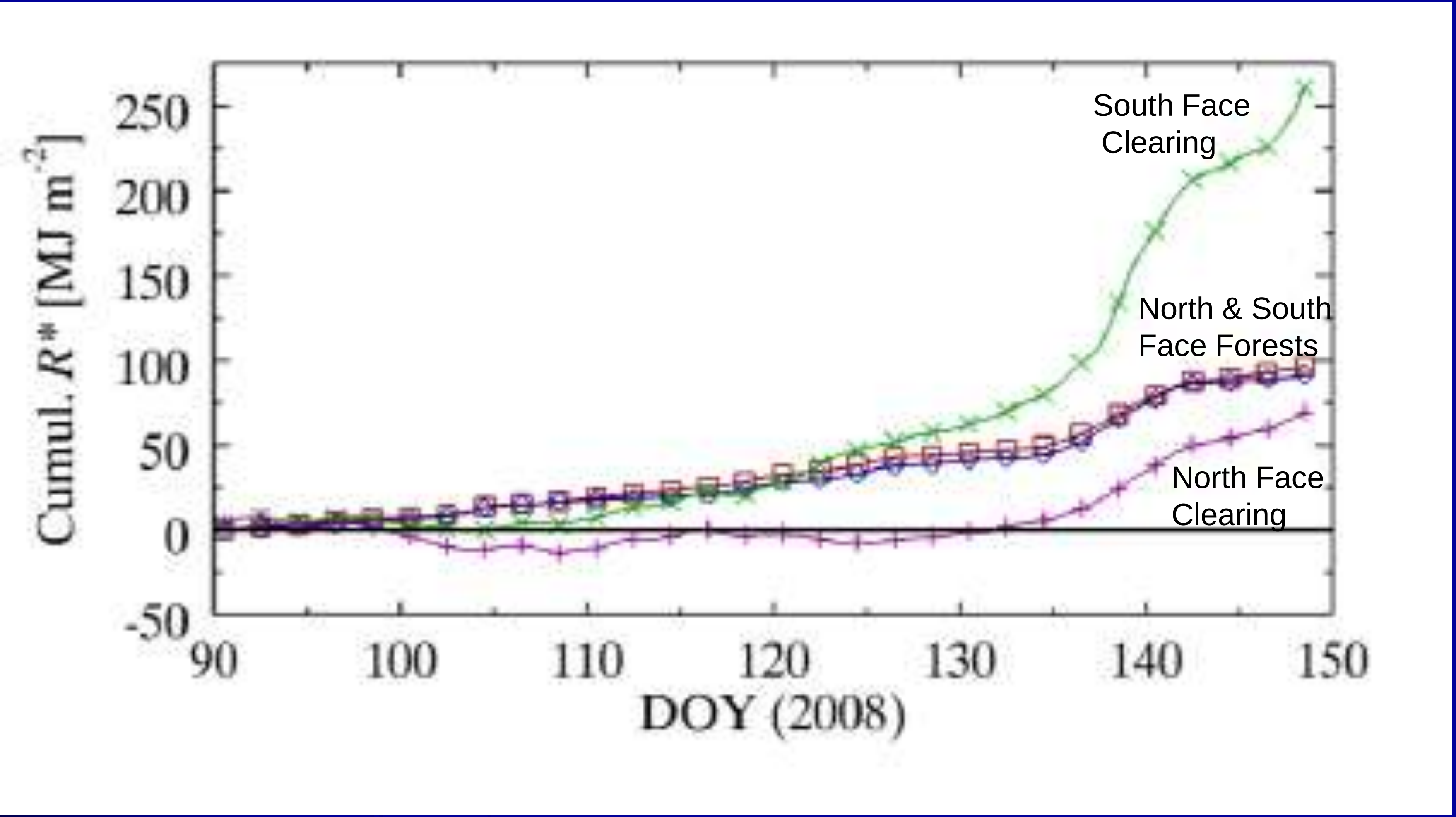
DeBeer

Shadow Migration Over a Day in Early Feb



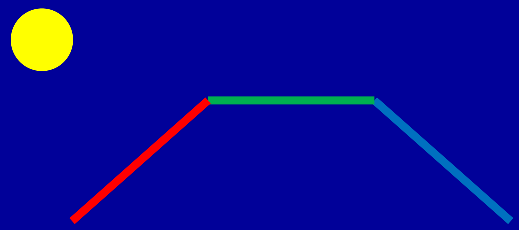
Chris Marsh, PhD

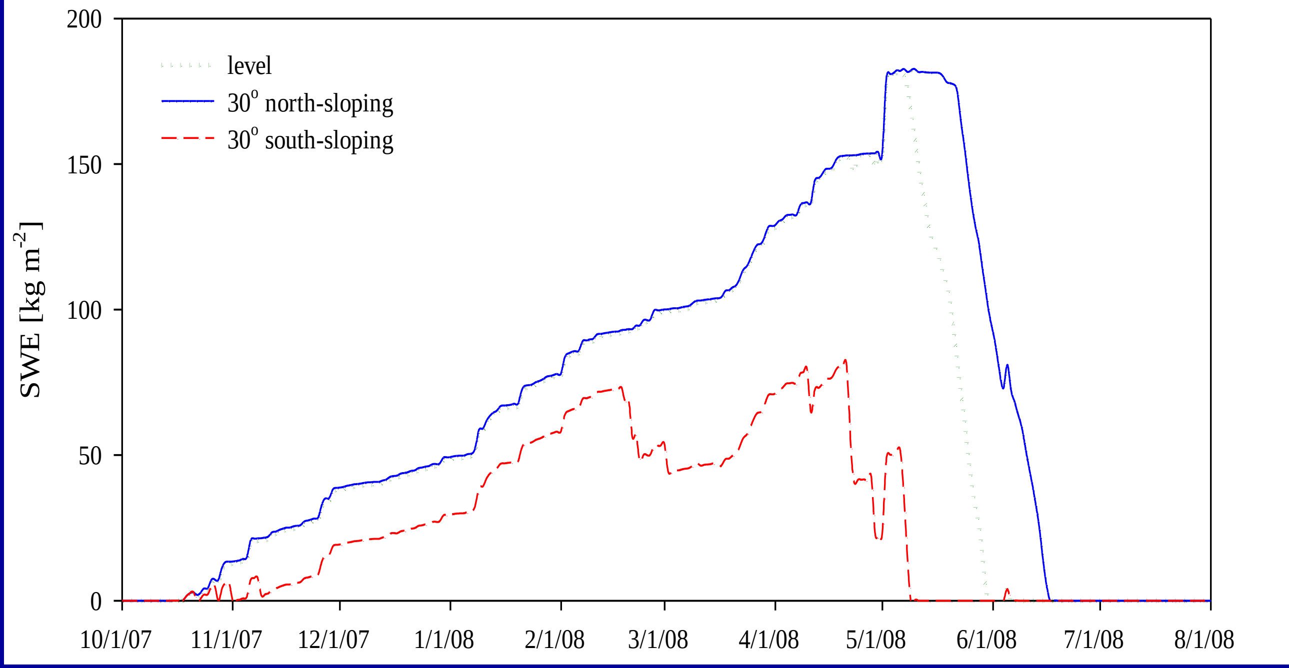
Net Radiation to Forests: Slope Effects



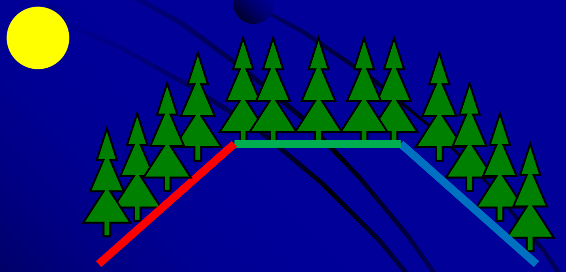
Ellis

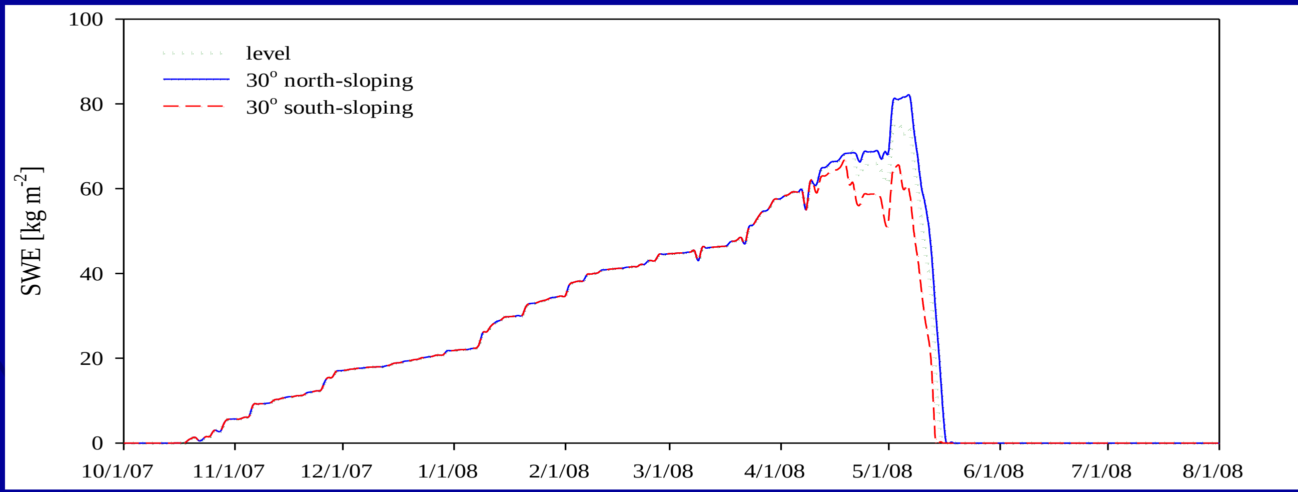
Forest Snow Regime on Slopes



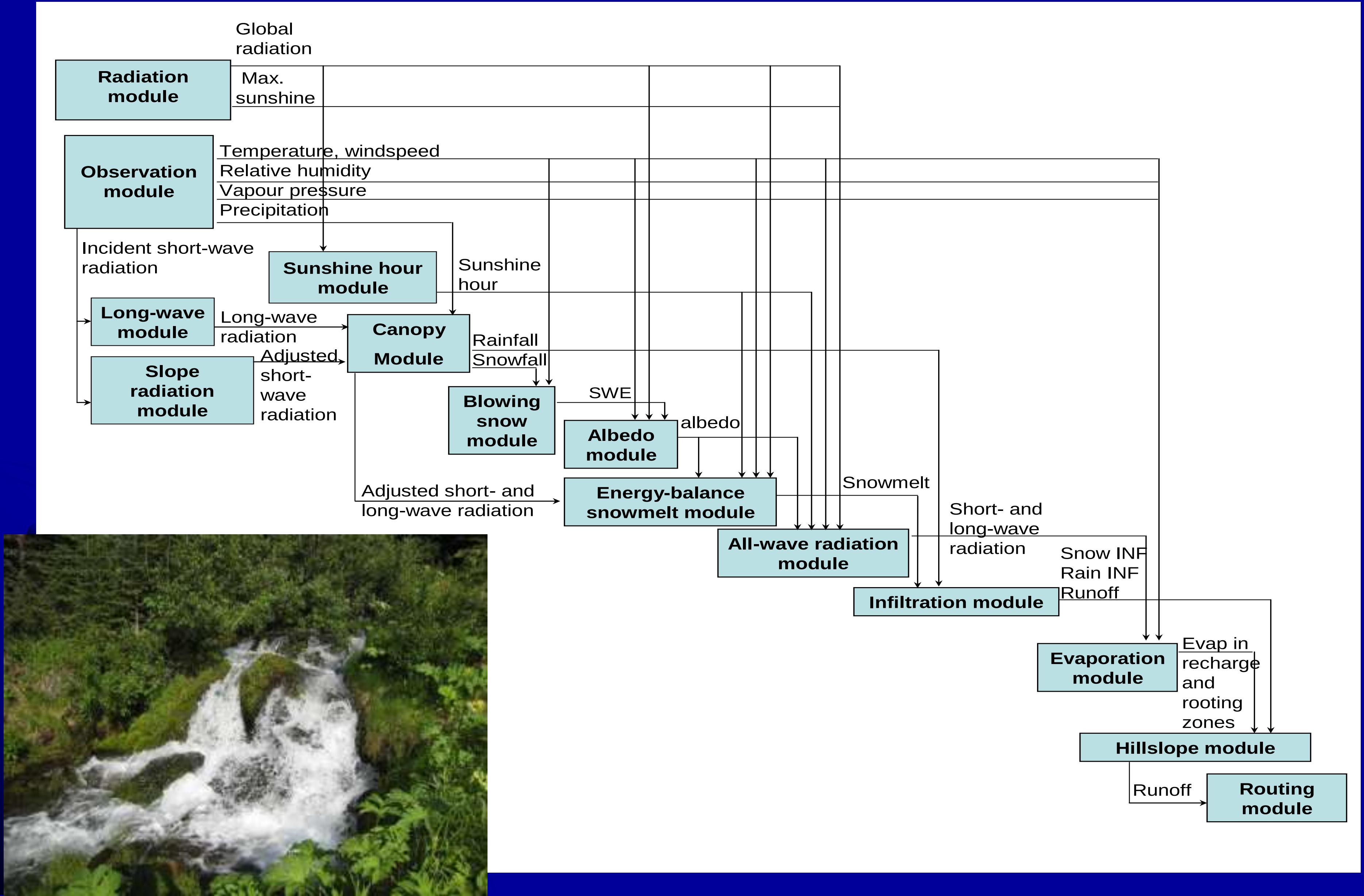


Open slopes highly sensitive to irradiation difference, forests are not

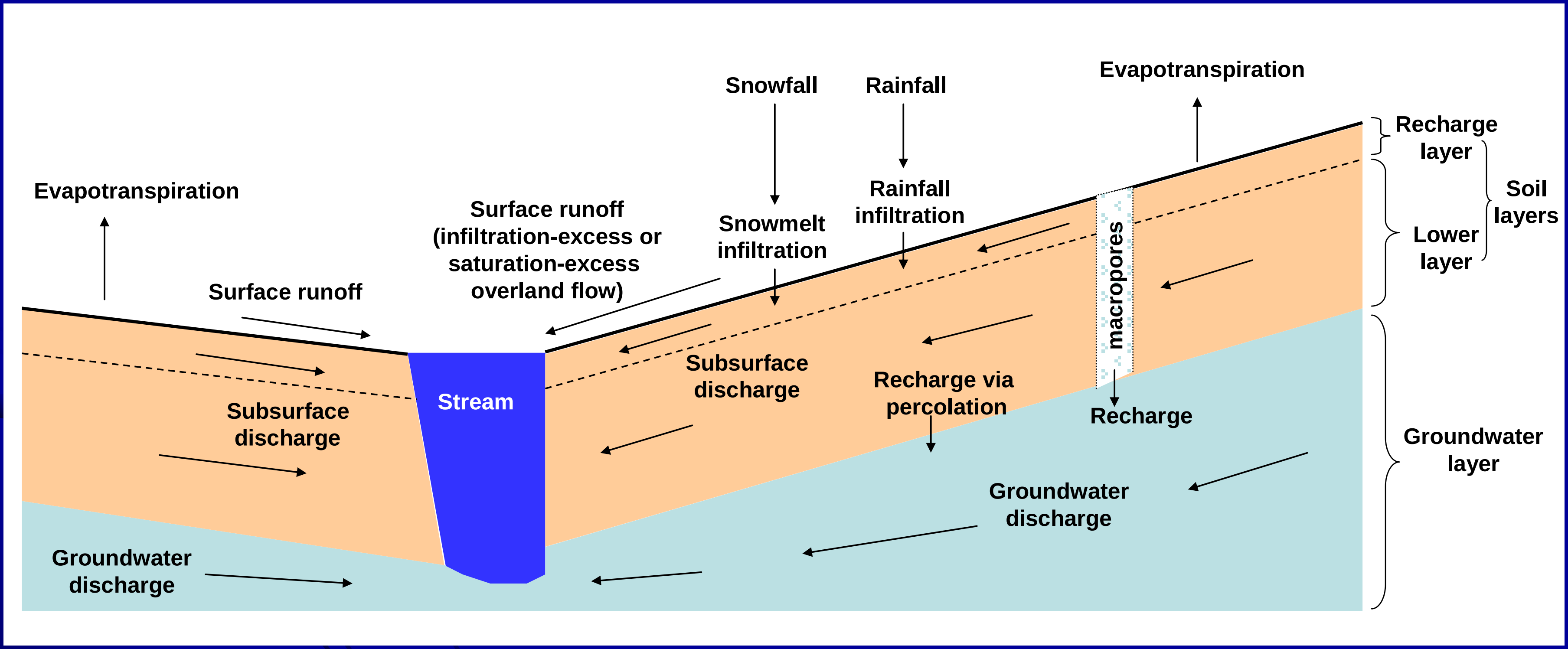




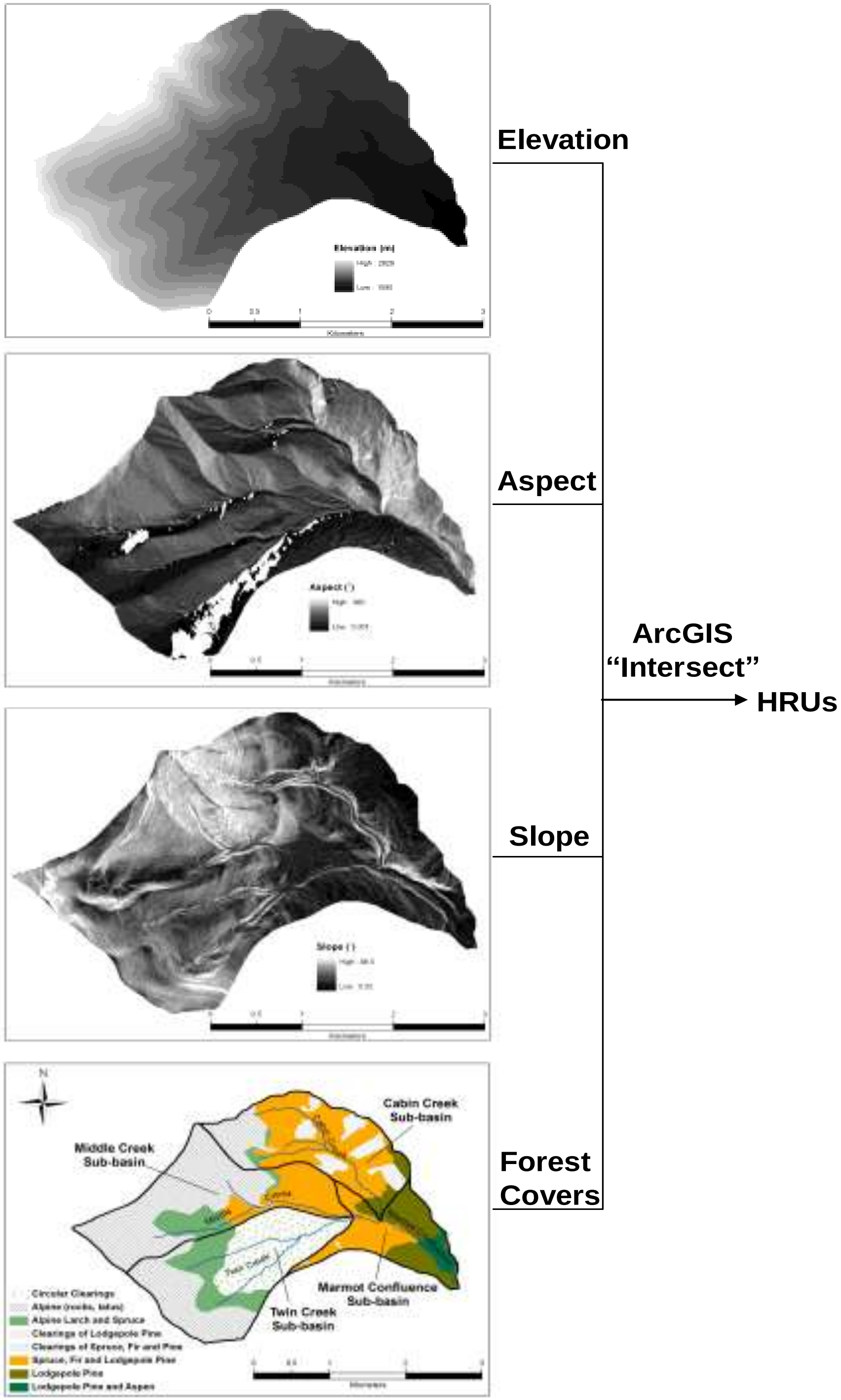
CRHM Mountain Structure



Mountain Hillslope Hydrology

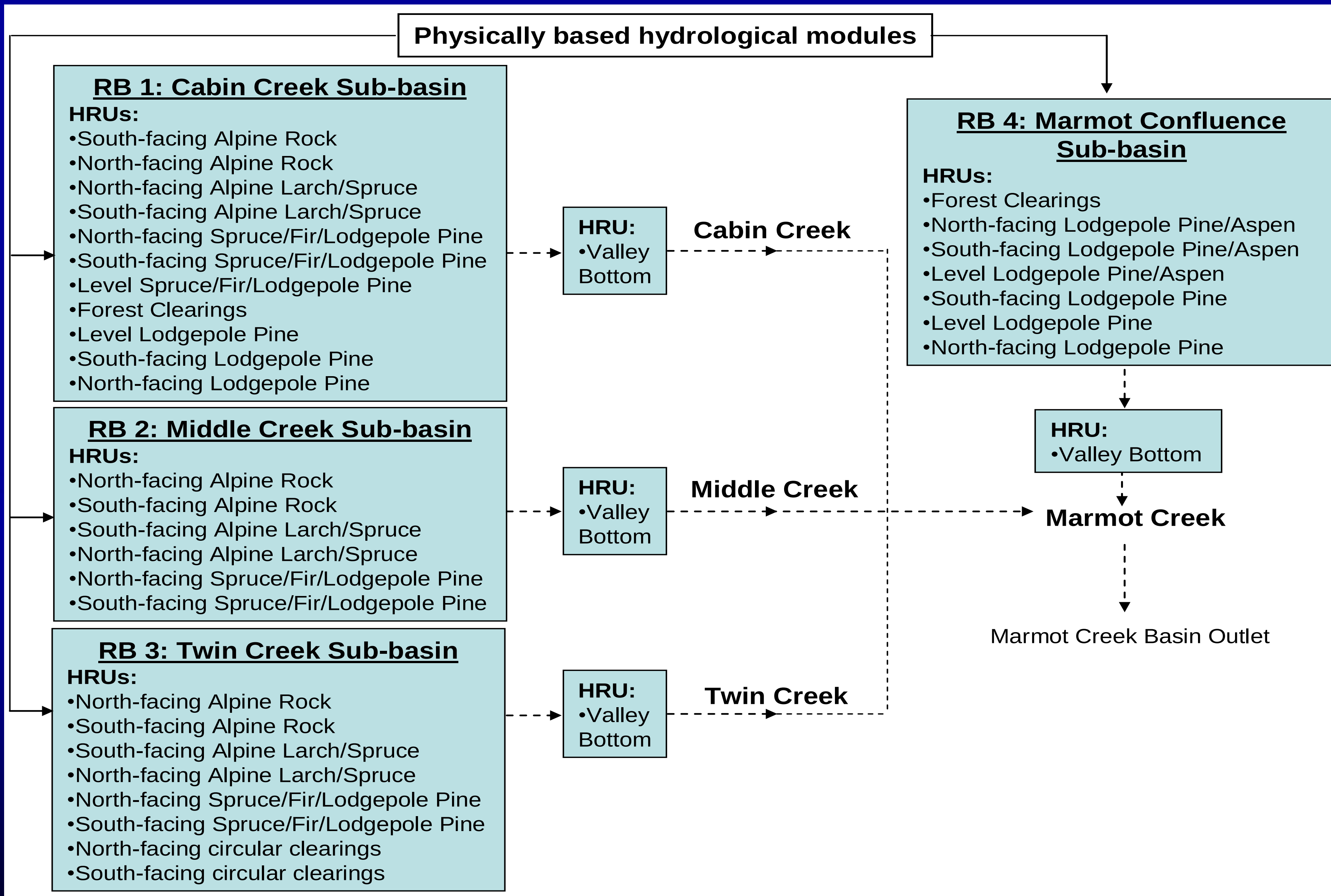


HRU Delineation

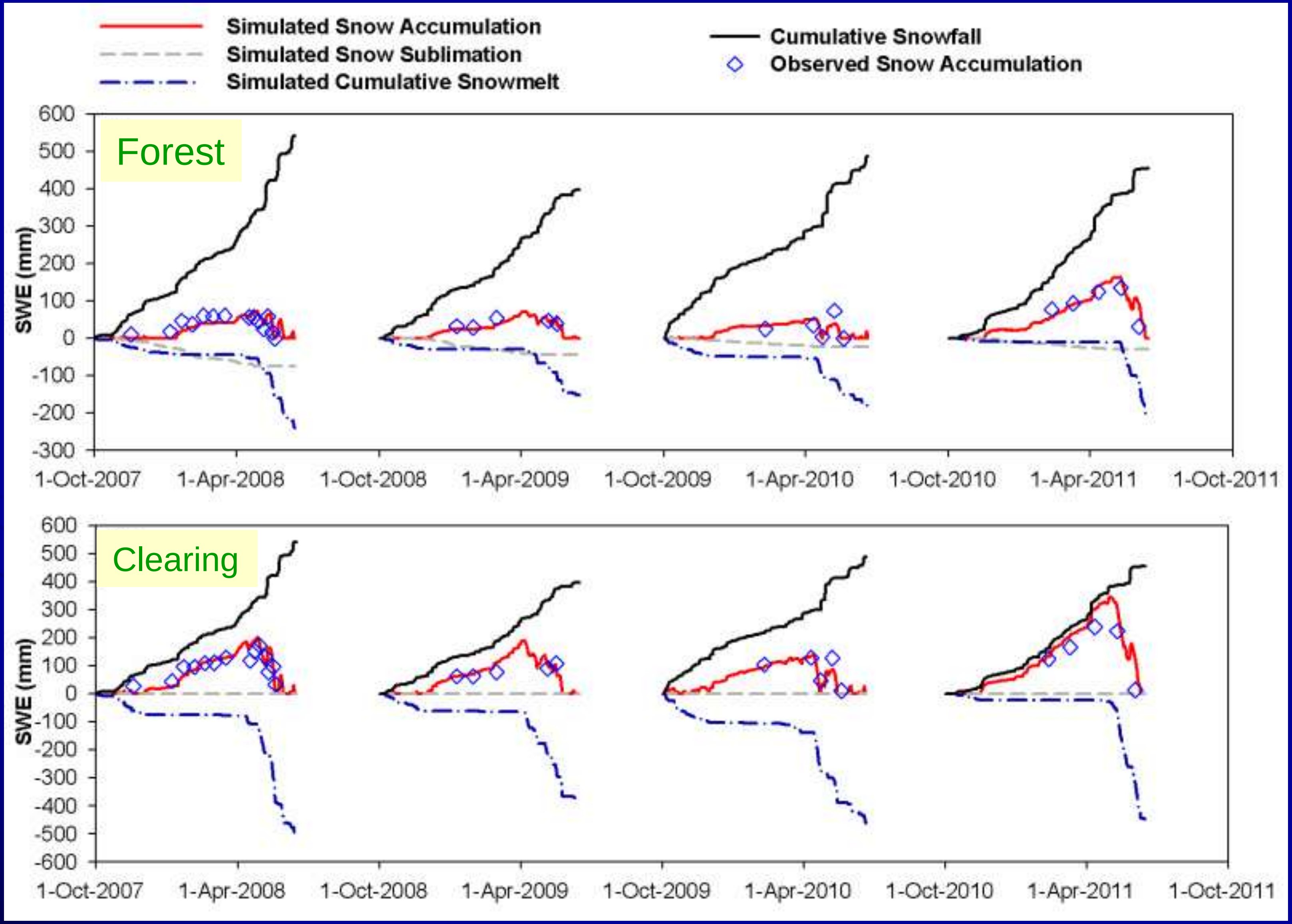


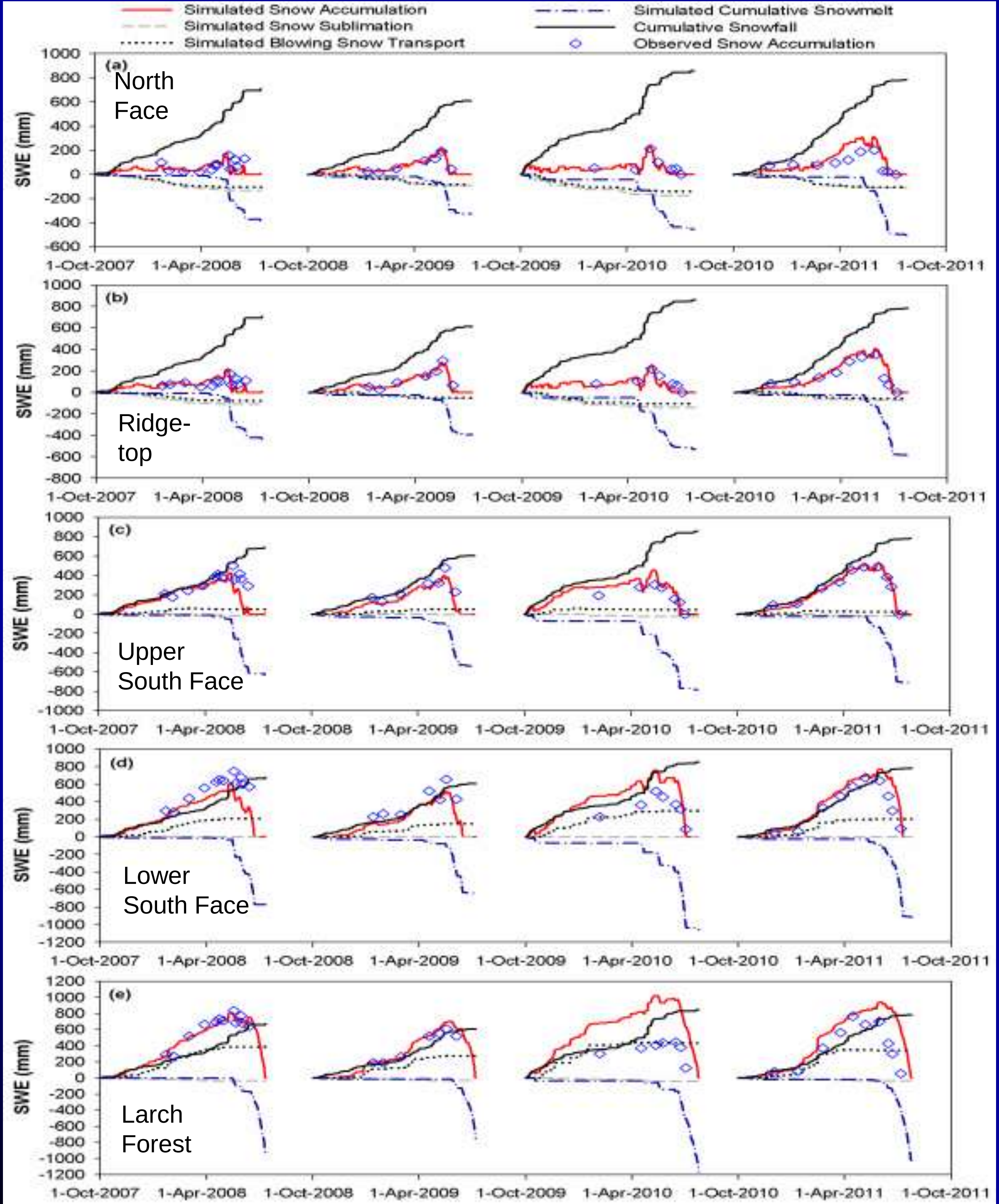
- Driving meteorology: temperature, humidity, wind speed, snowfall, rainfall, radiation
- Blowing snow, intercepted snow
- Snowmelt and evapotranspiration
- Infiltration & groundwater
- Stream network

Model Structure



Forest Snow Dynamics Simulations

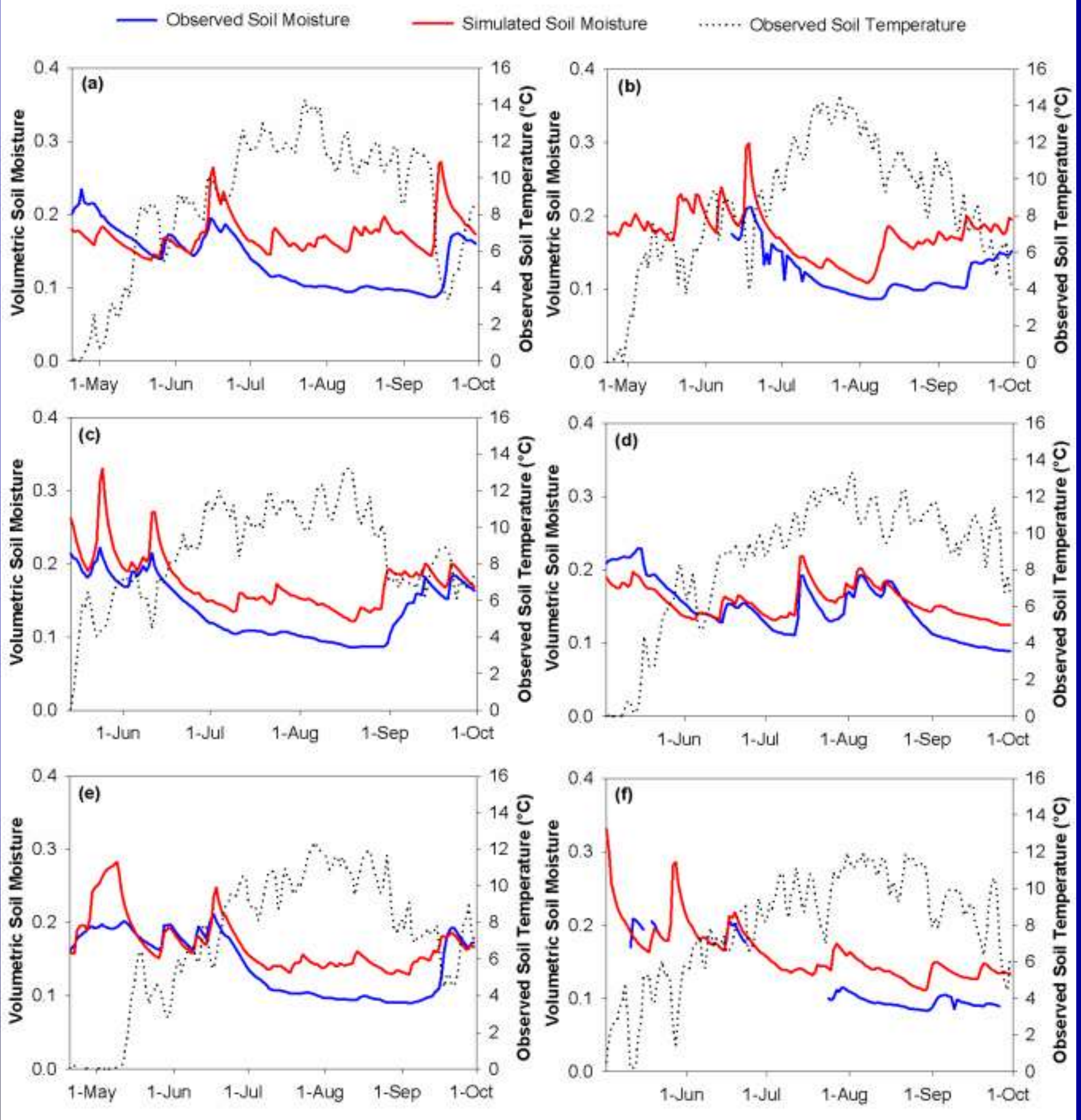




Alpine Snow Dynamics Simulations

Snow redistribution from north face and ridgetop to south face and larch forest

uncalibrated

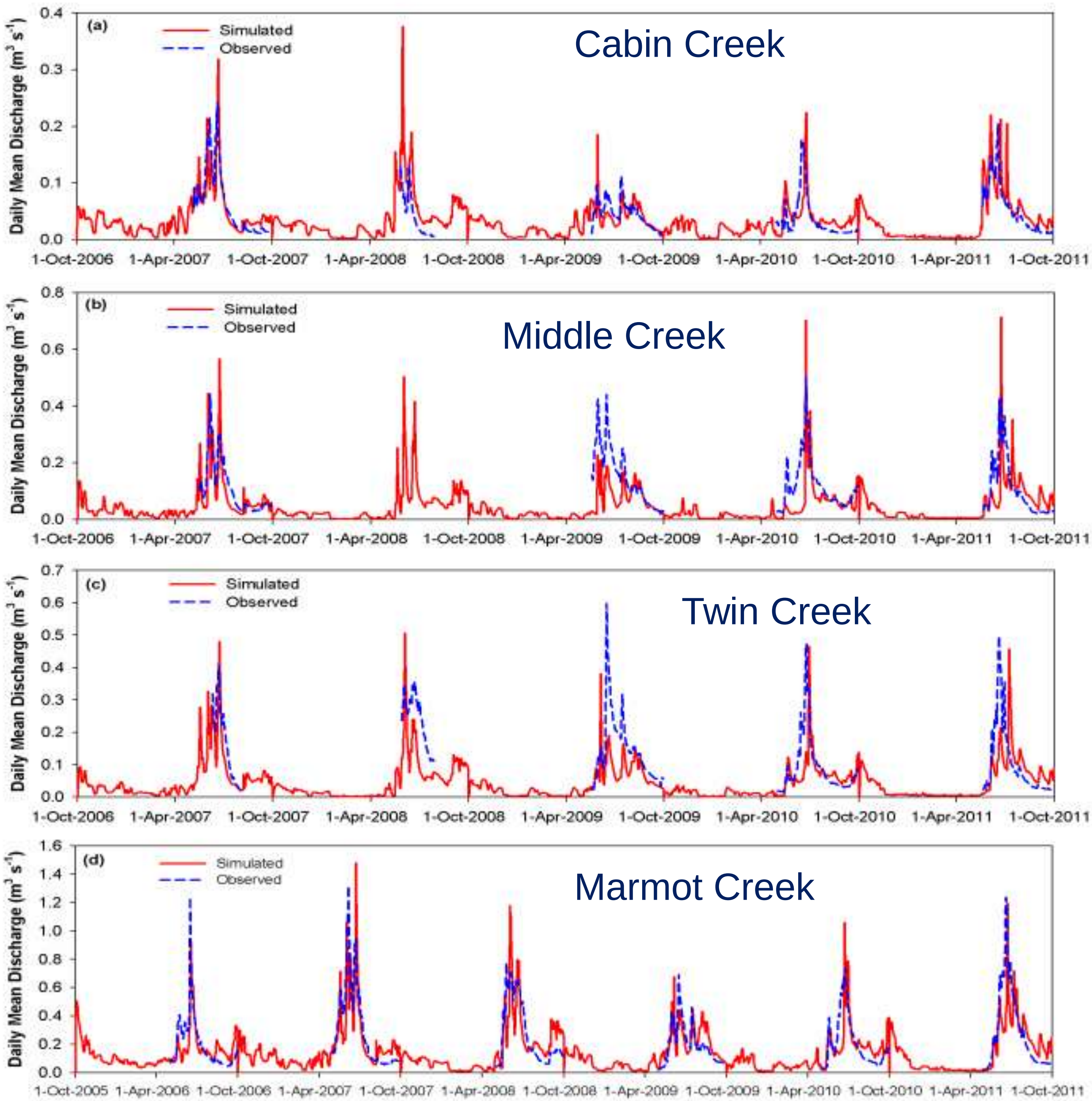


Model Tests: Soil Moisture

2006-2011

Level Forest Site

Uncalibrated



Uncalibrated Streamflow Simulation

N-S increases with basin scale to 0.58

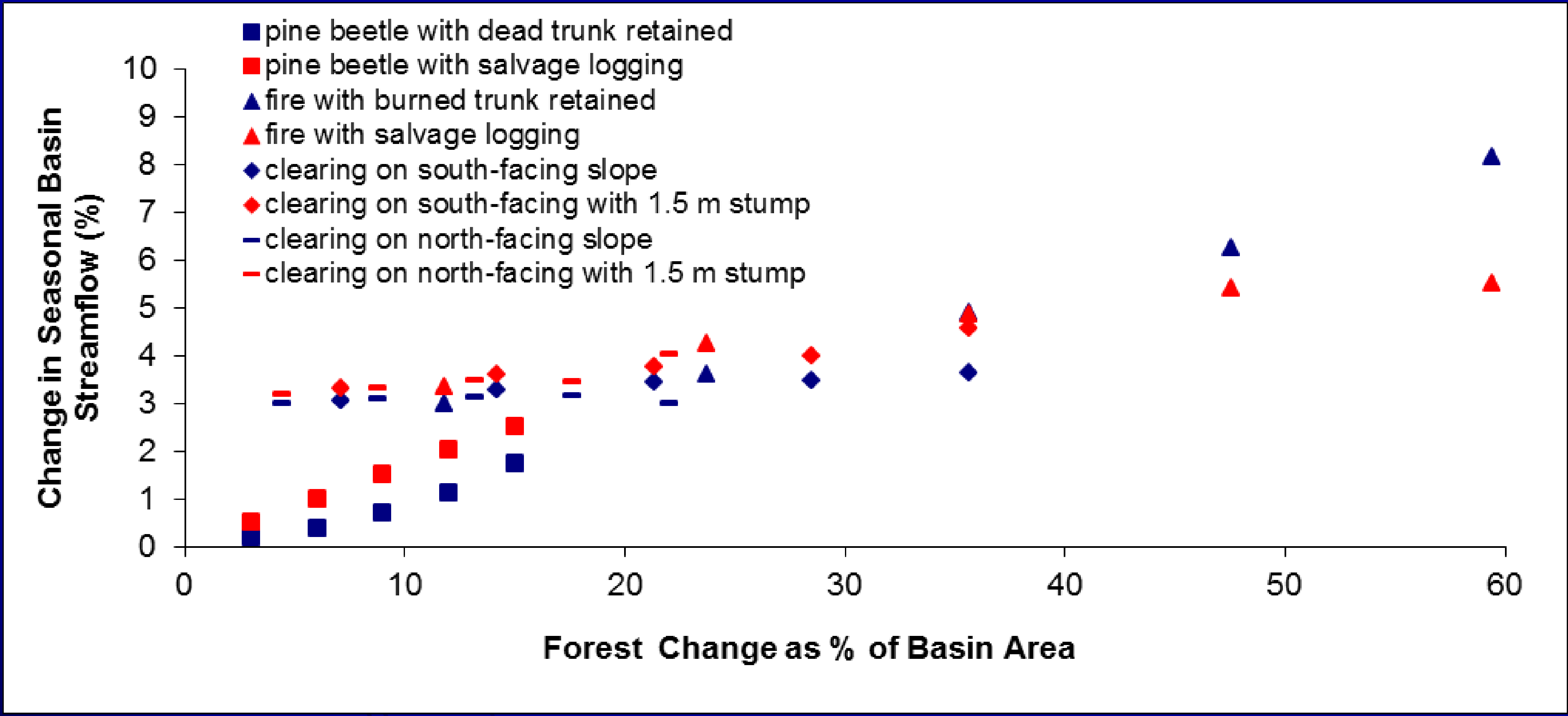
MB = 0.01 for Marmot Creek

Fang et al. HESS 2013 in review

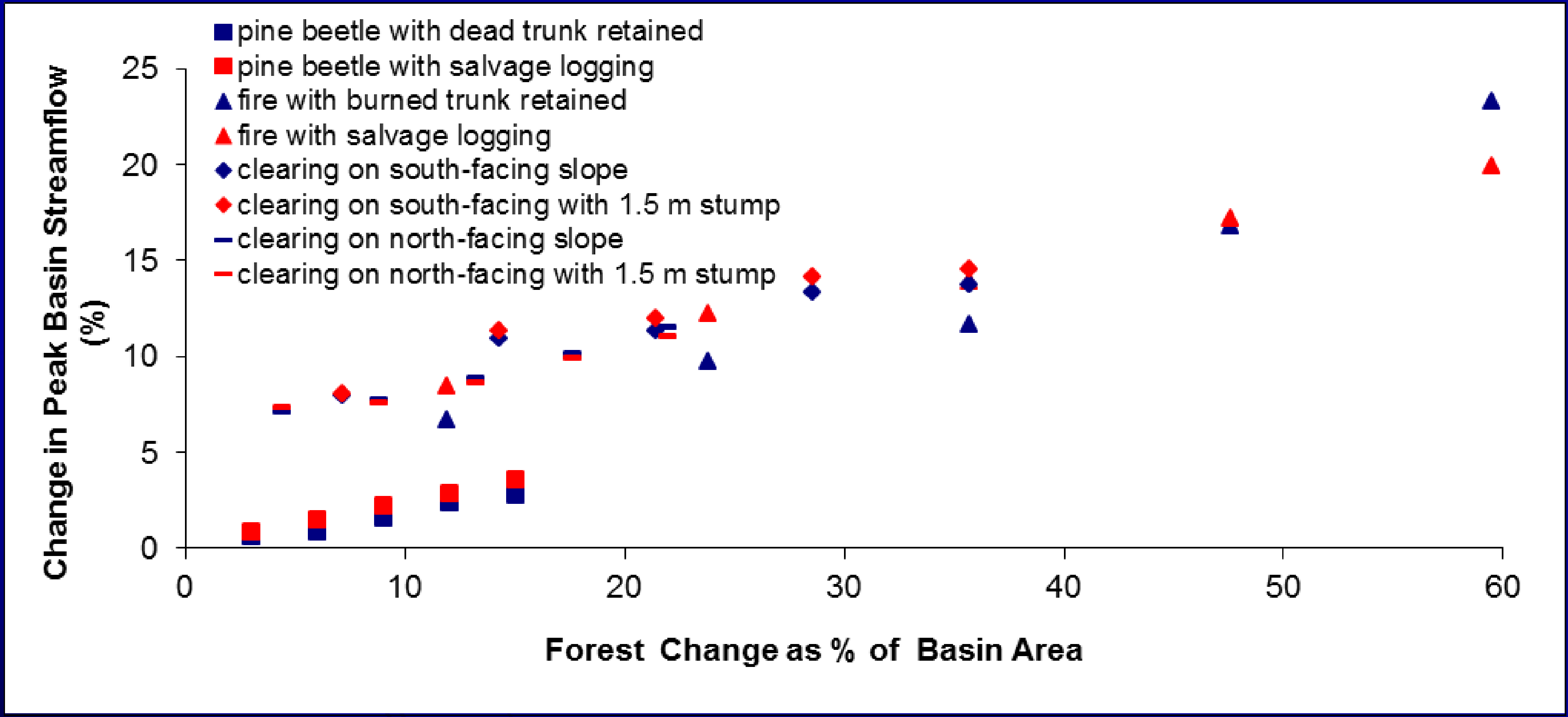
Application: Forest Cover & Climate Change

- Progressive canopy removal due to
  - Pine beetle removal of lodgepole pine canopy
  - Burning of all canopy, with and without salvage logging
  - Selective harvesting of canopy on north and south facing slopes, with and without 1.5 m trunk retention after harvesting
- Climate change: sensitivity analysis to rising air temperatures

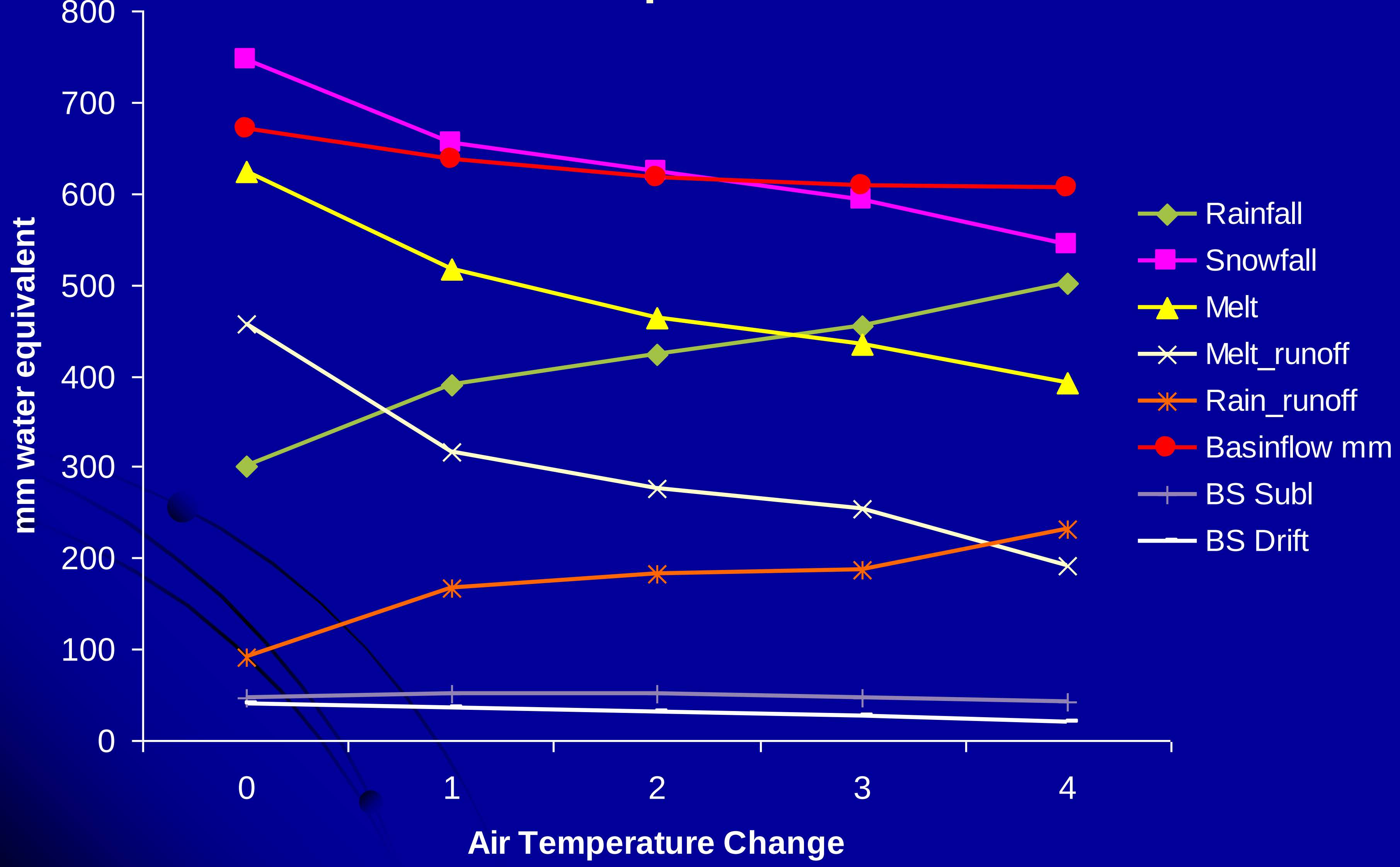
Forest Cover Disturbance Impact on Seasonal Streamflow



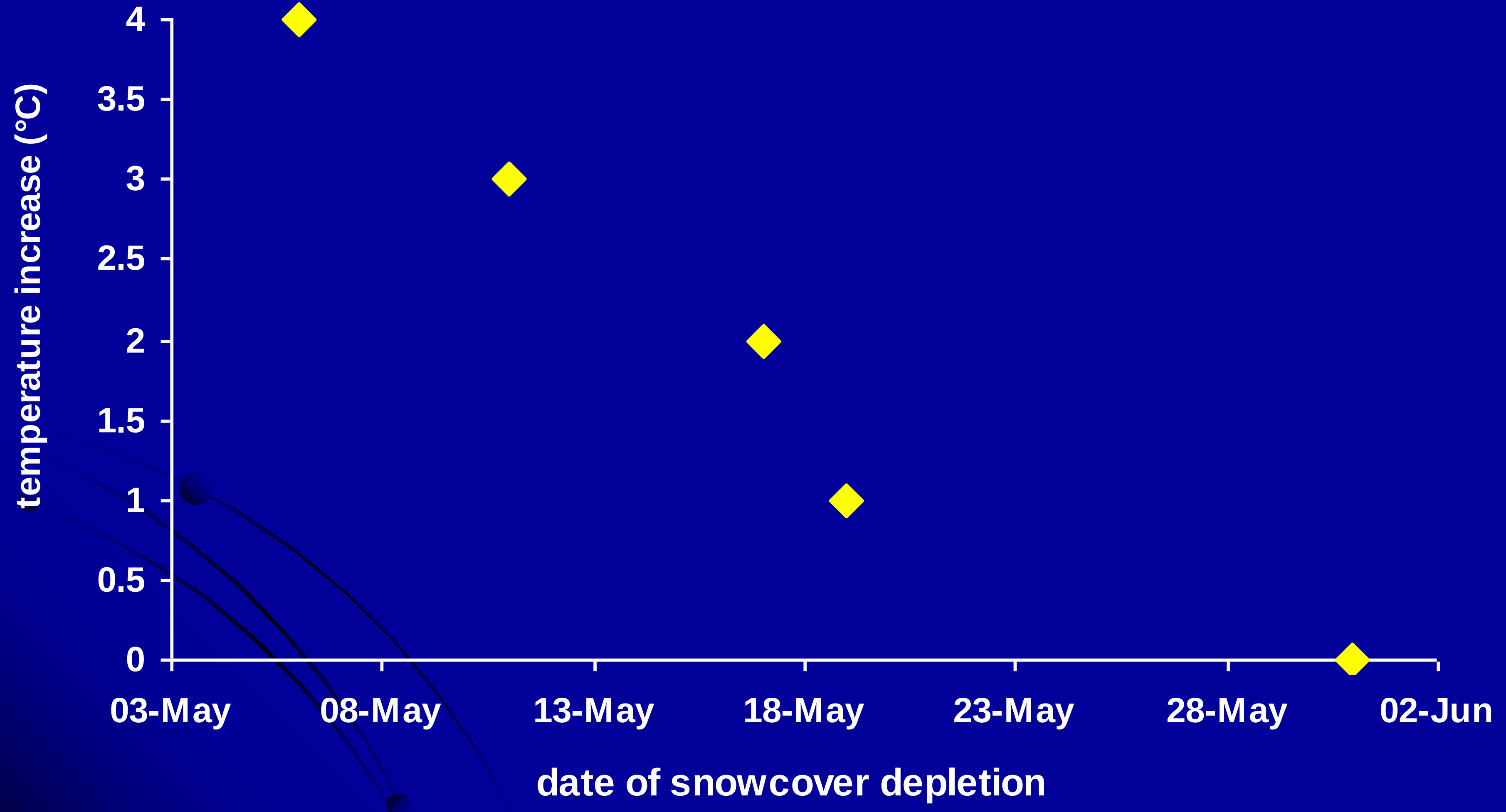
Forest Cover Disturbance Impact on Peak Streamflow



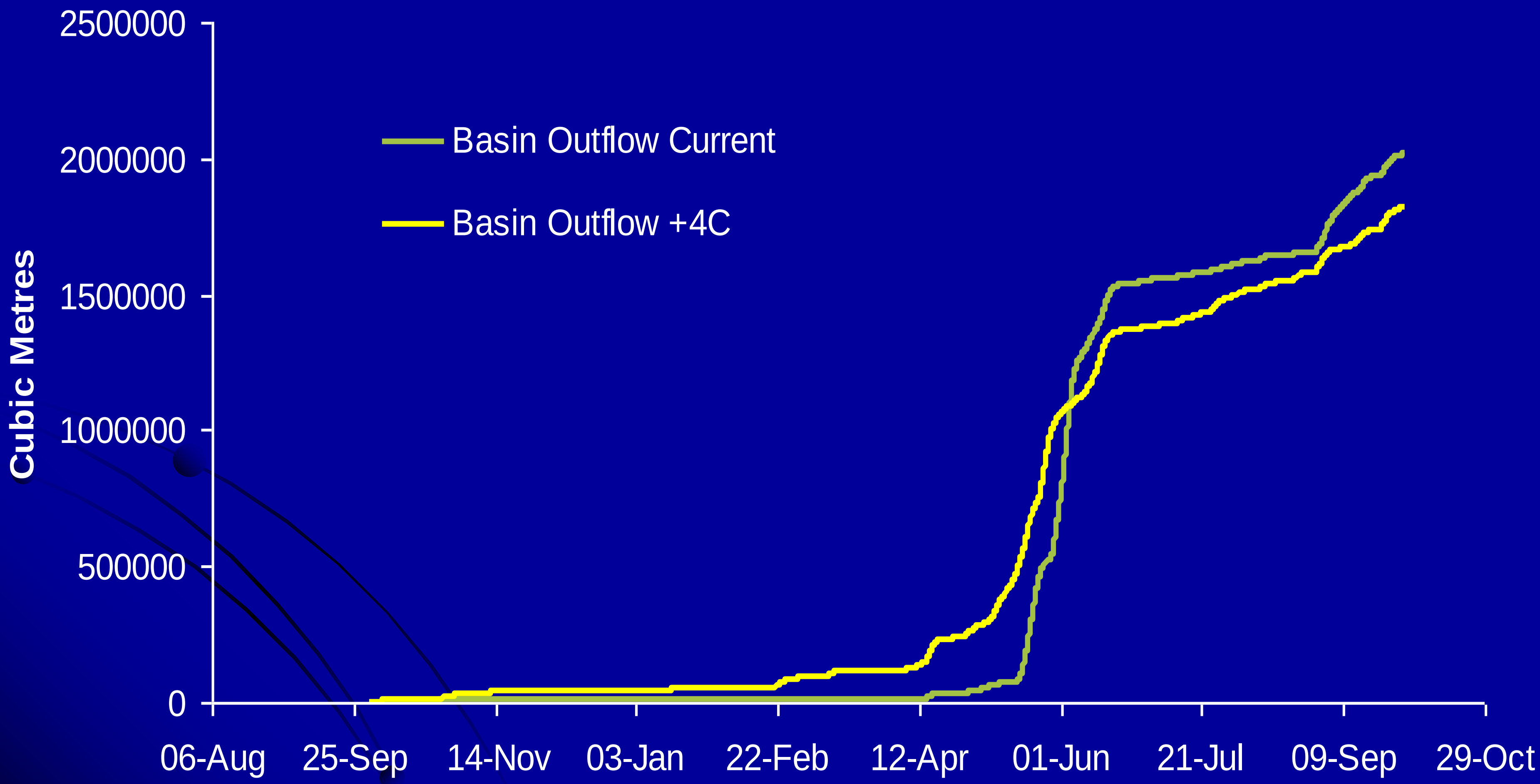
Alpine Hydrology Change with Rising Temperature



Impact of Winter Warming on Date of Snowpack Depletion



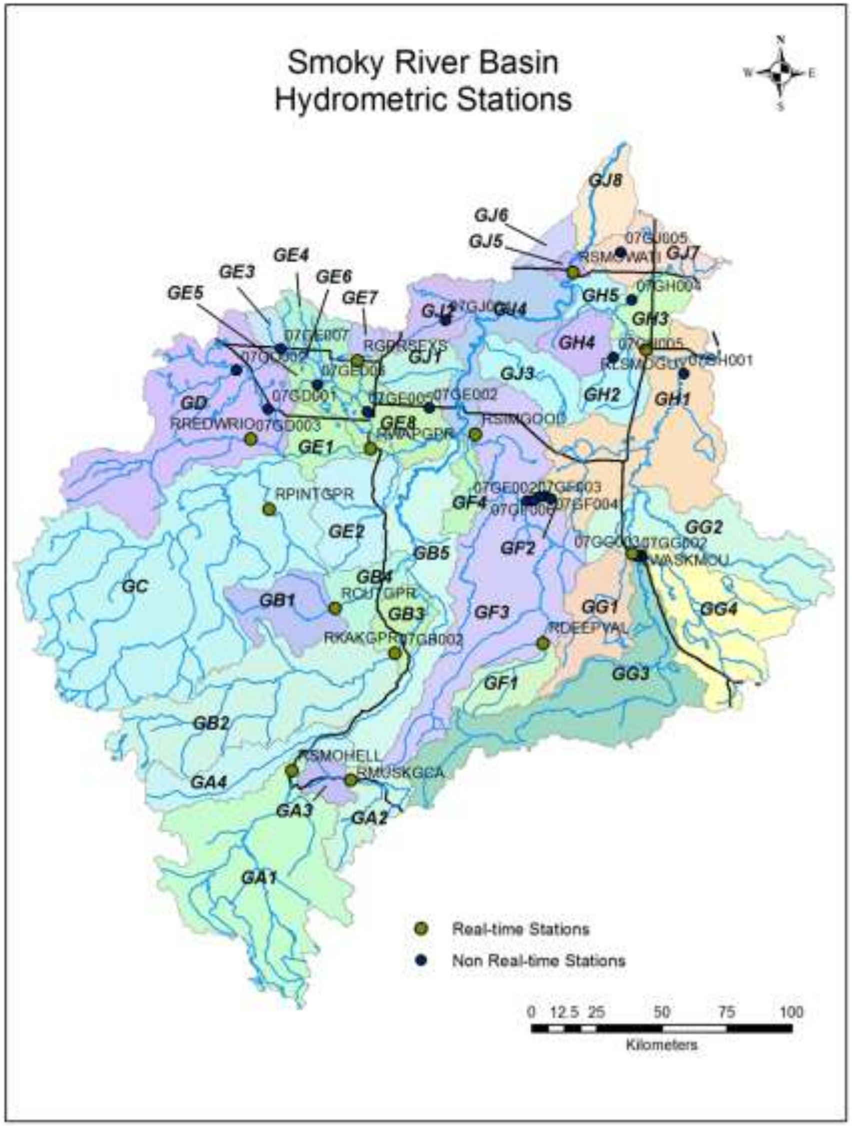
Change in Alpine Basin Discharge

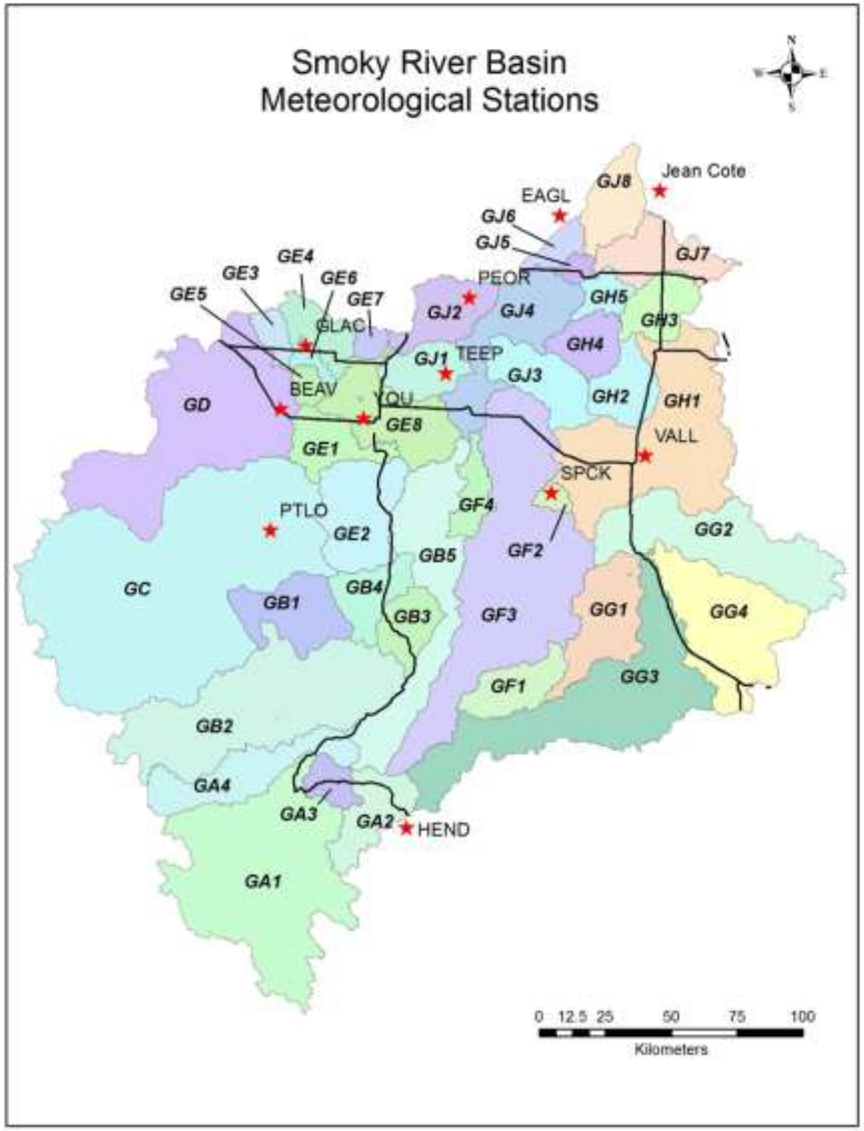


Application: Operational Forecasting of Ungauged Flows

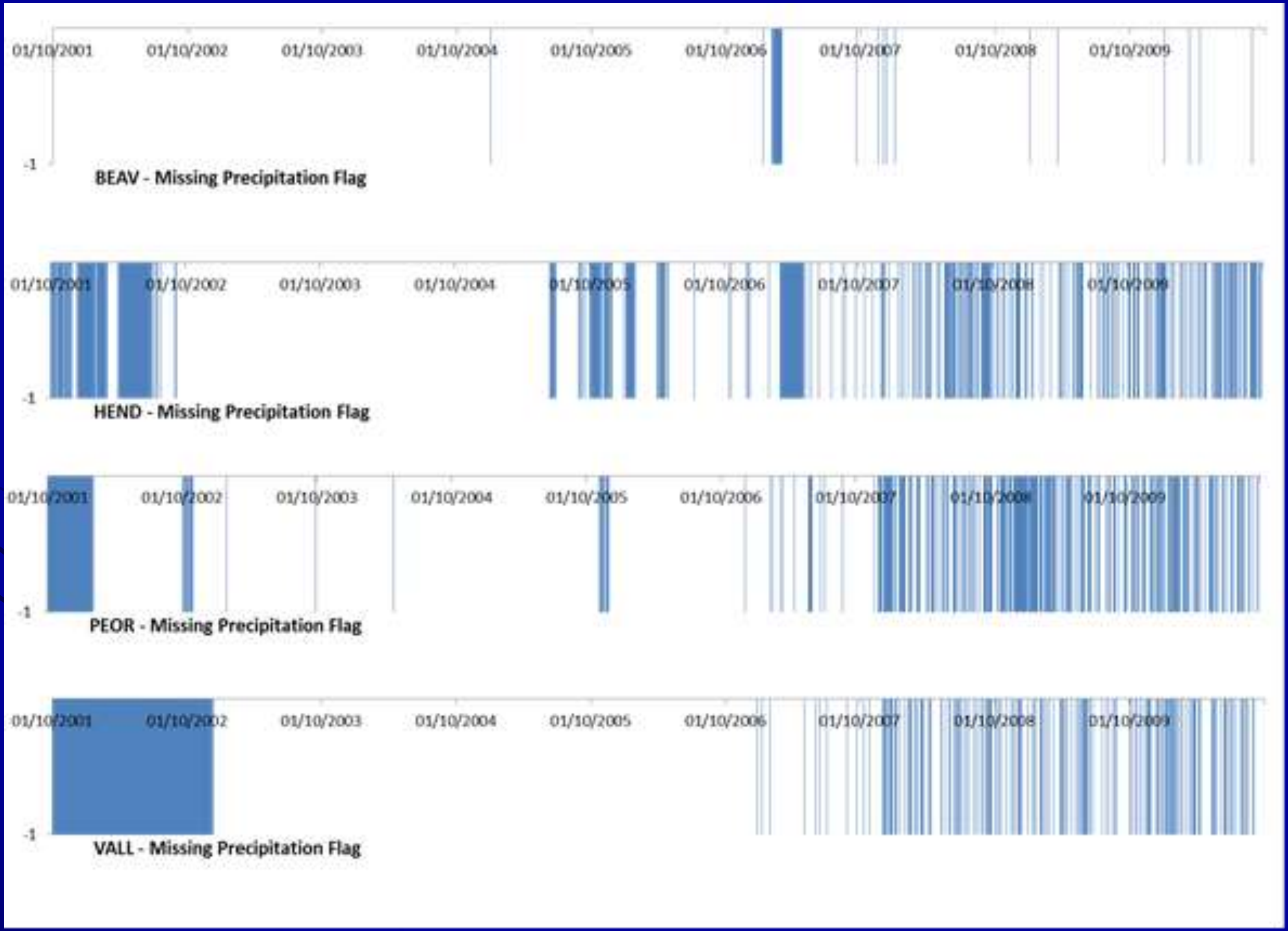
- Smoky River Basin is 46% ungauged
- Need to simulate spring streamflow from the ungauged basin area (23,769 km^2) in order to forecast Smoky River contribution to the Peace River
  - Run model on a daily basis during flood forecast period – update ungauged flows
  - Use daily updates of meteorological model forecast data to run for the future
  - Route ungauged with gauged flows for forecast

Smoky River Basin: 51,839 km^2



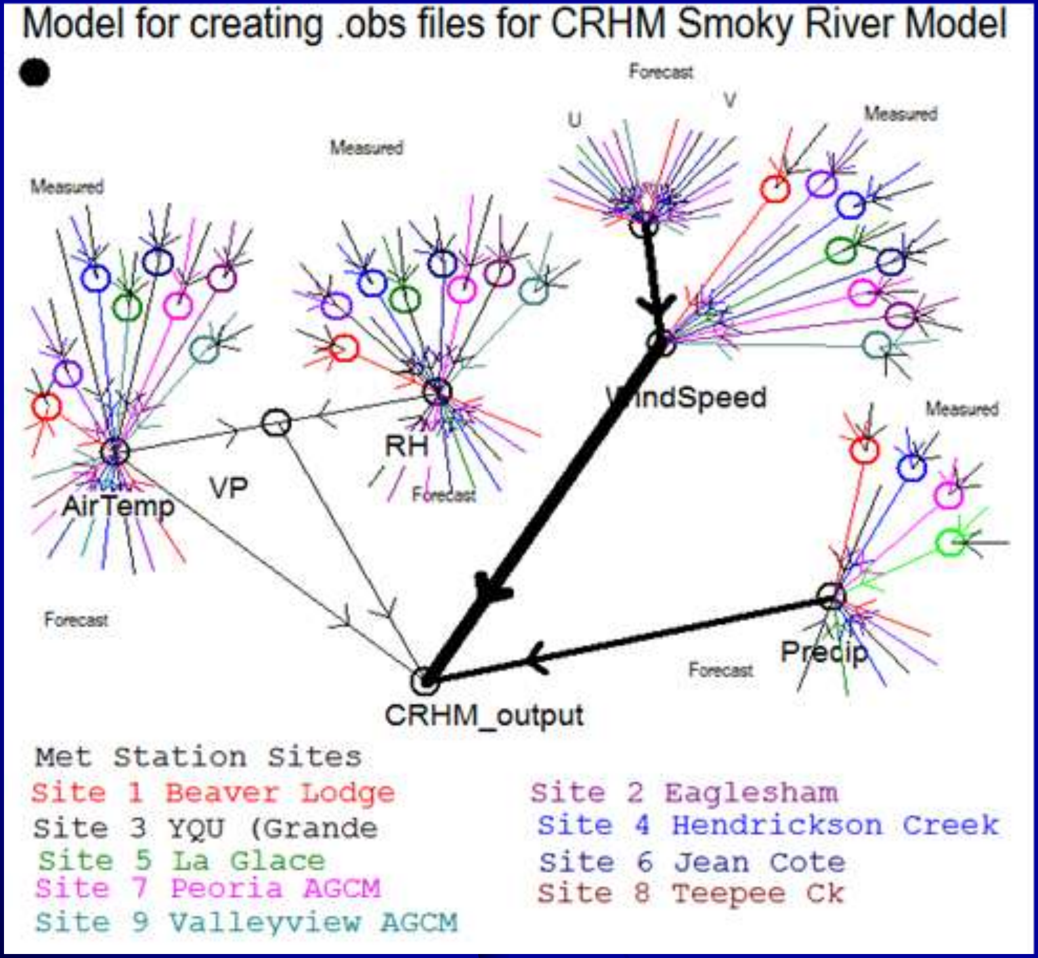


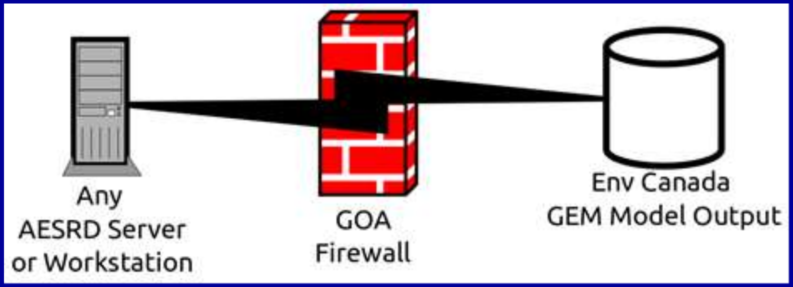
Challenge:
Reliable Meteorological Observations and Forecasts

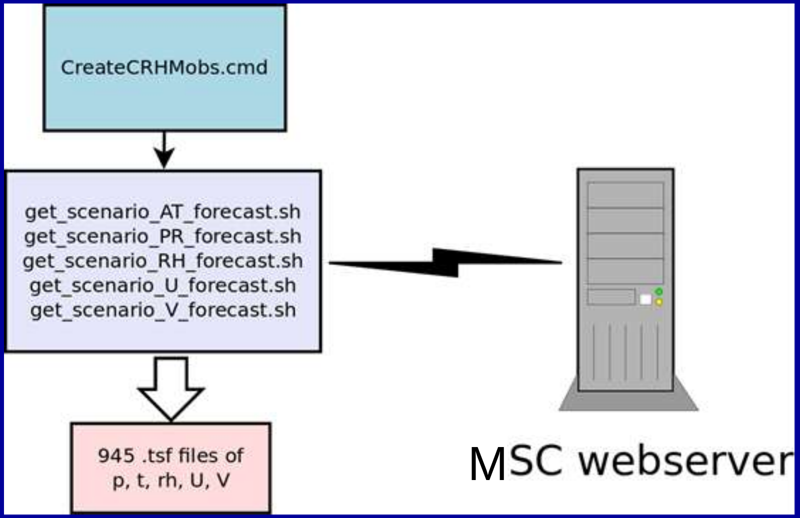


Interpolate and Predict

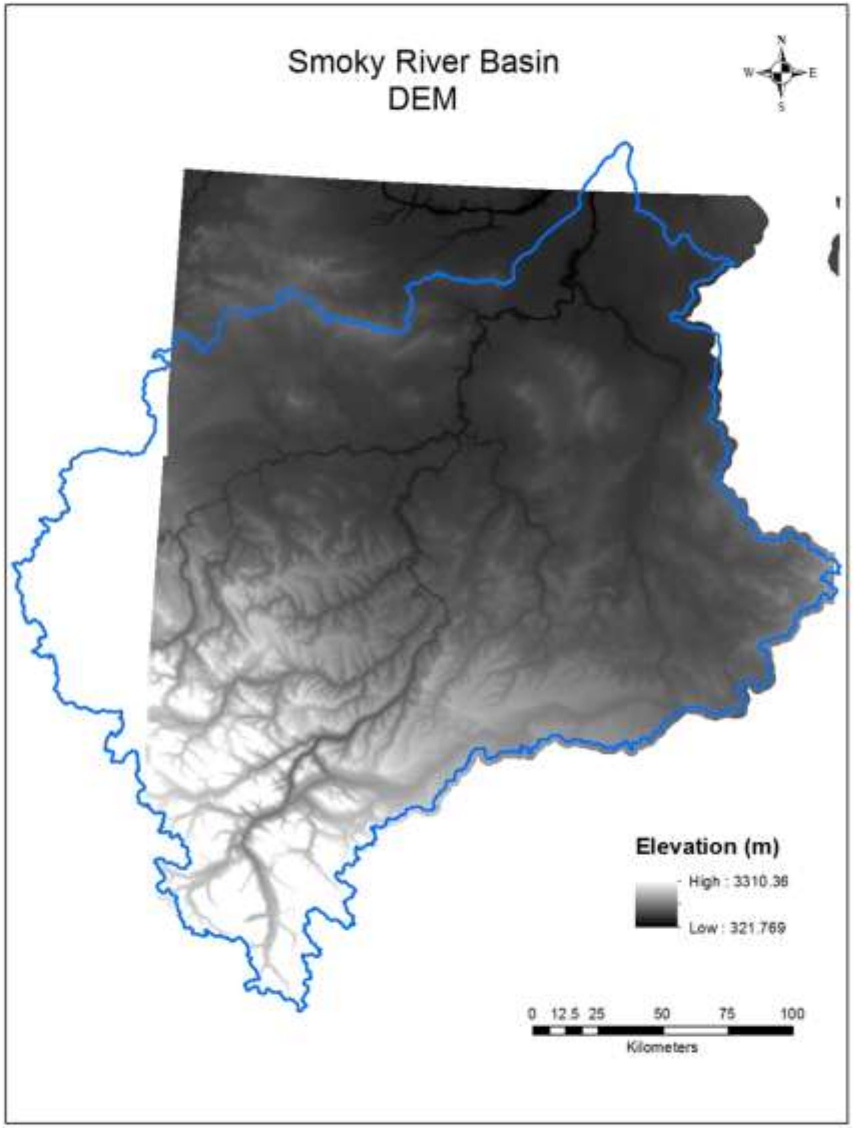
GEM-WISKI-CRHM

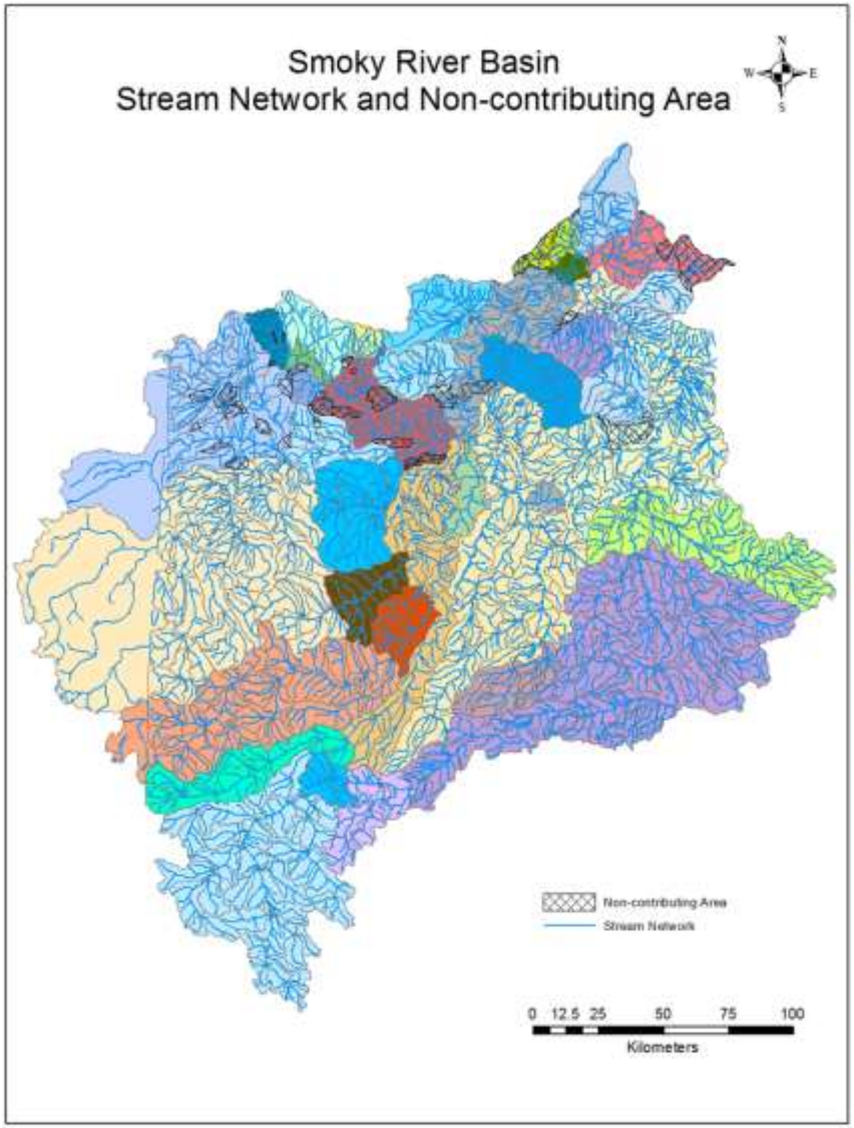




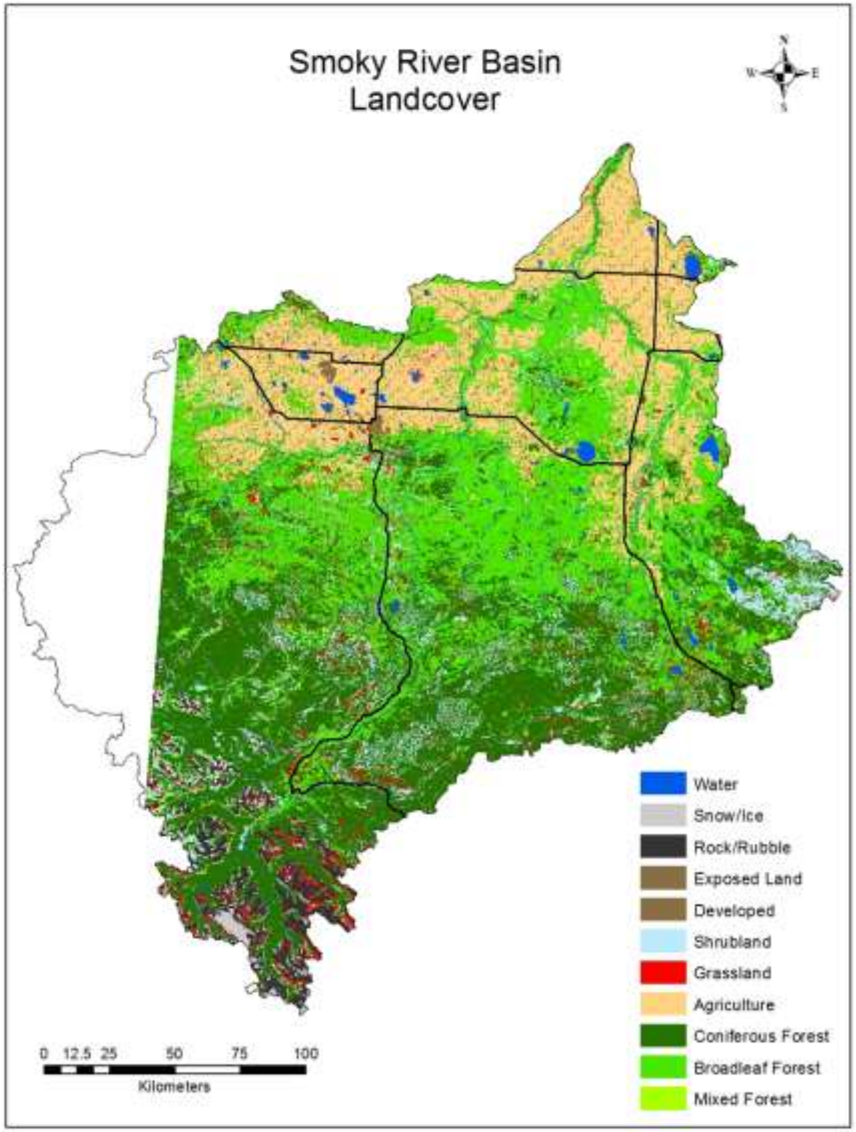


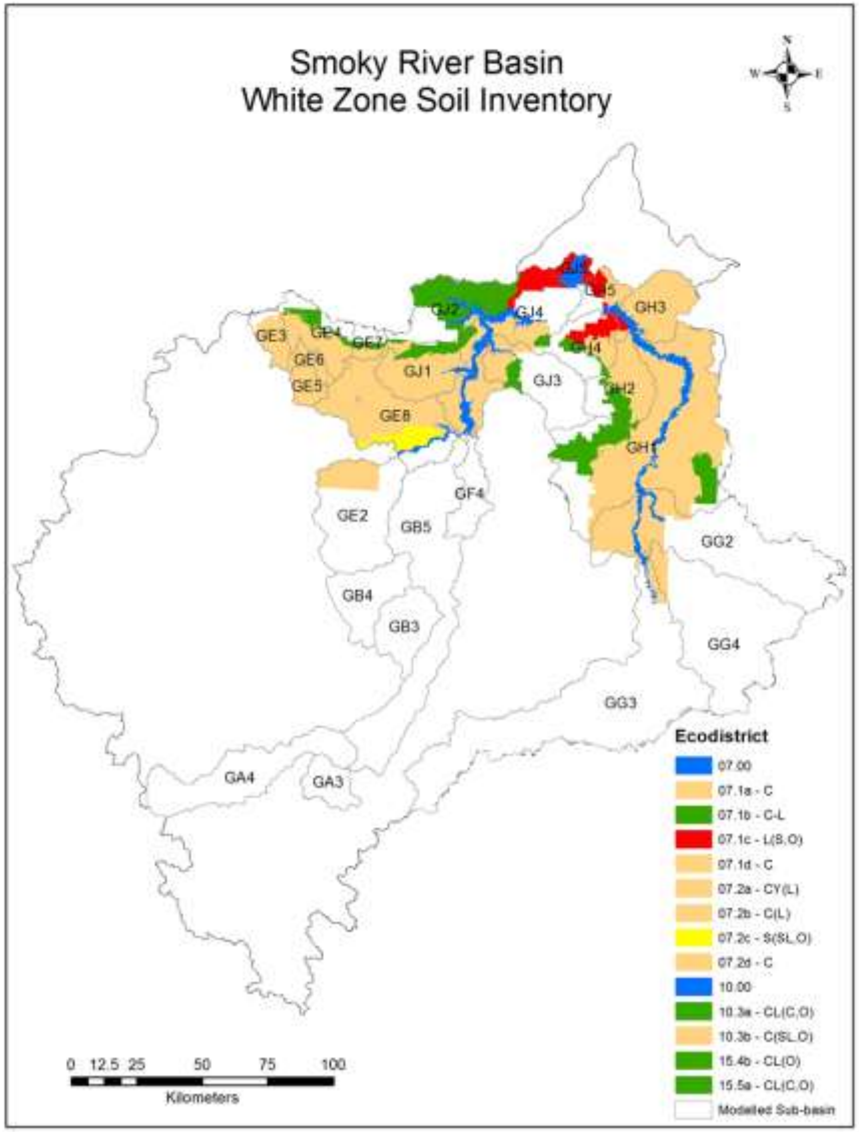
DEM and Derived Stream Network





Land Cover and Soils



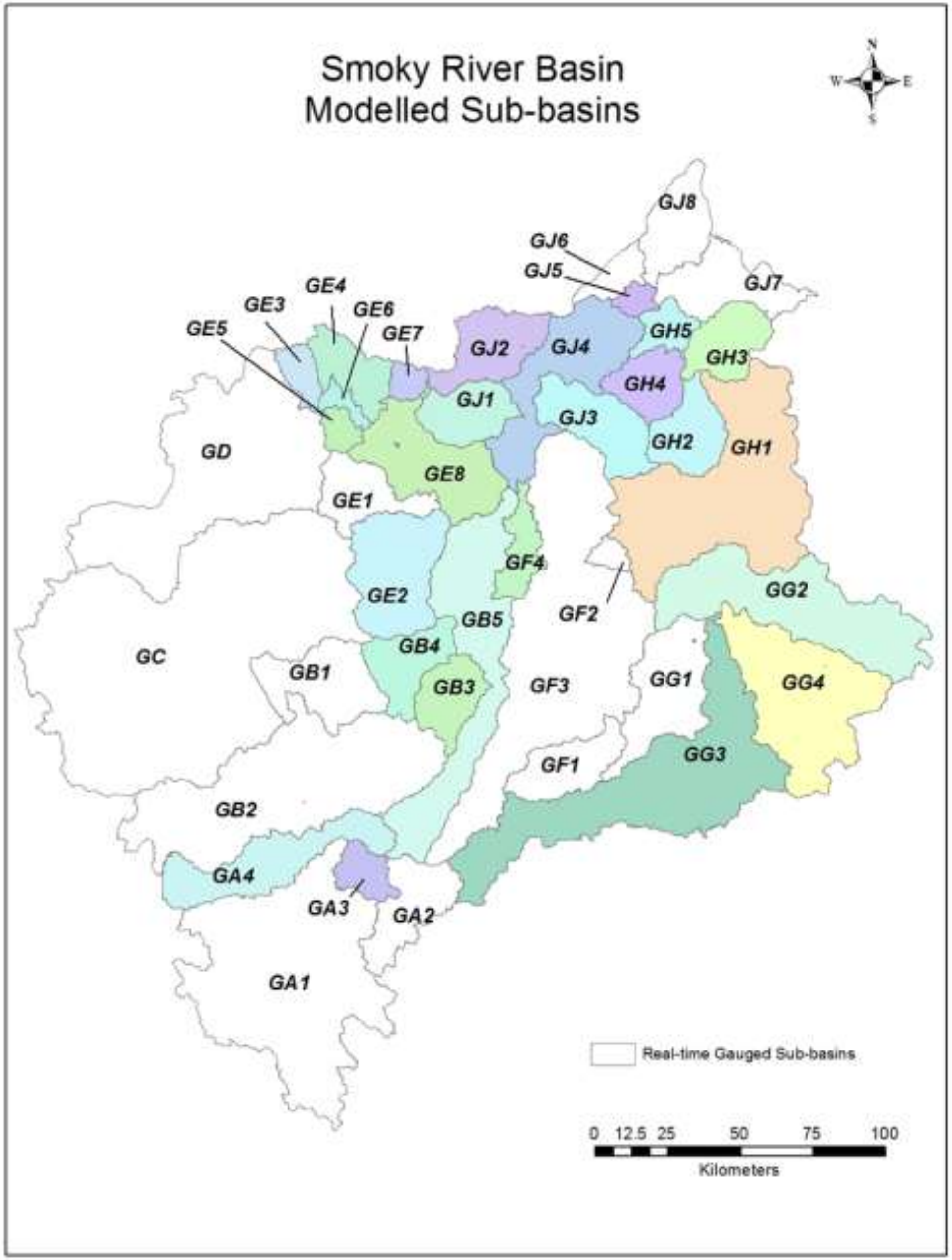


Sub-basins for Modelling

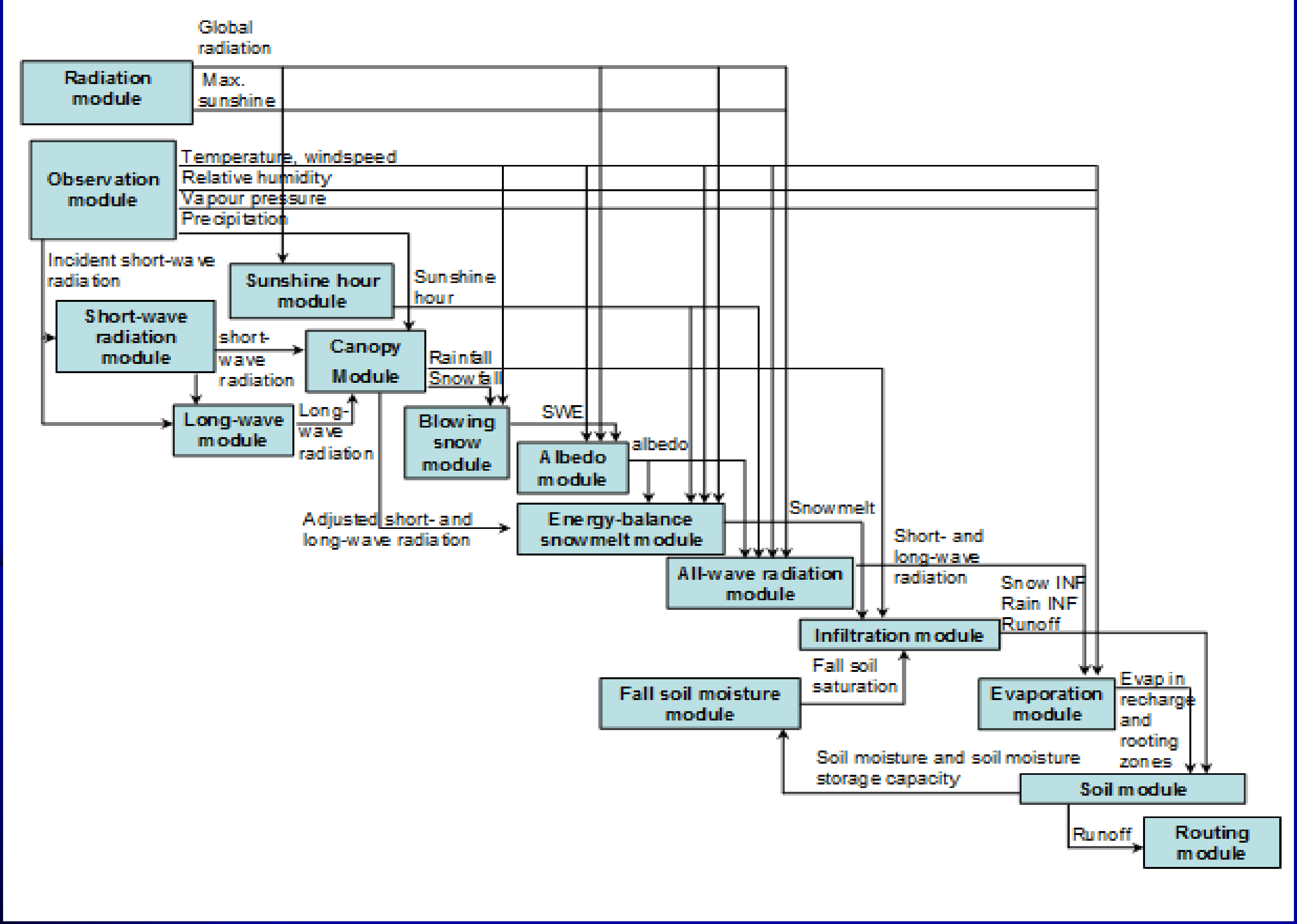
Modelled all ungauged and gauged basins without real time hydrometric stations

Sub-basins grouped into “types” based on ecoregion

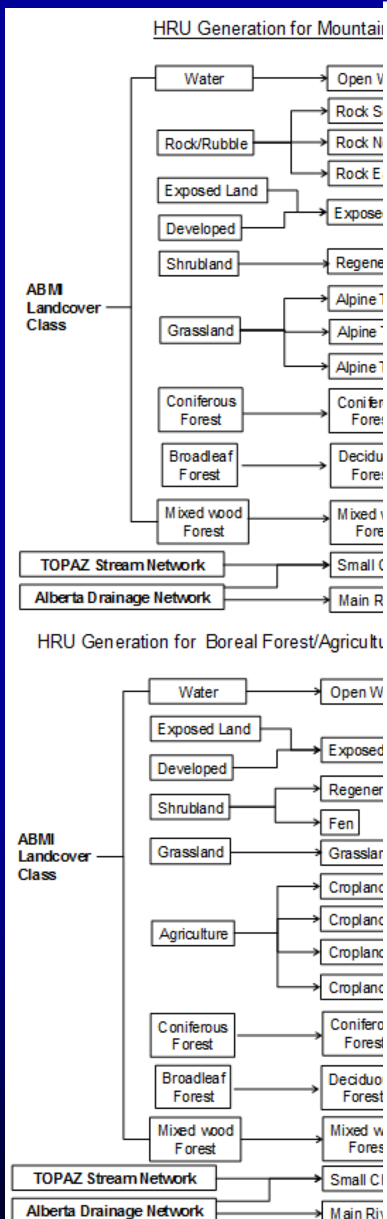
Real time gauged basins are estimated from gauge measurements and routed outside of CRHM using SSARR

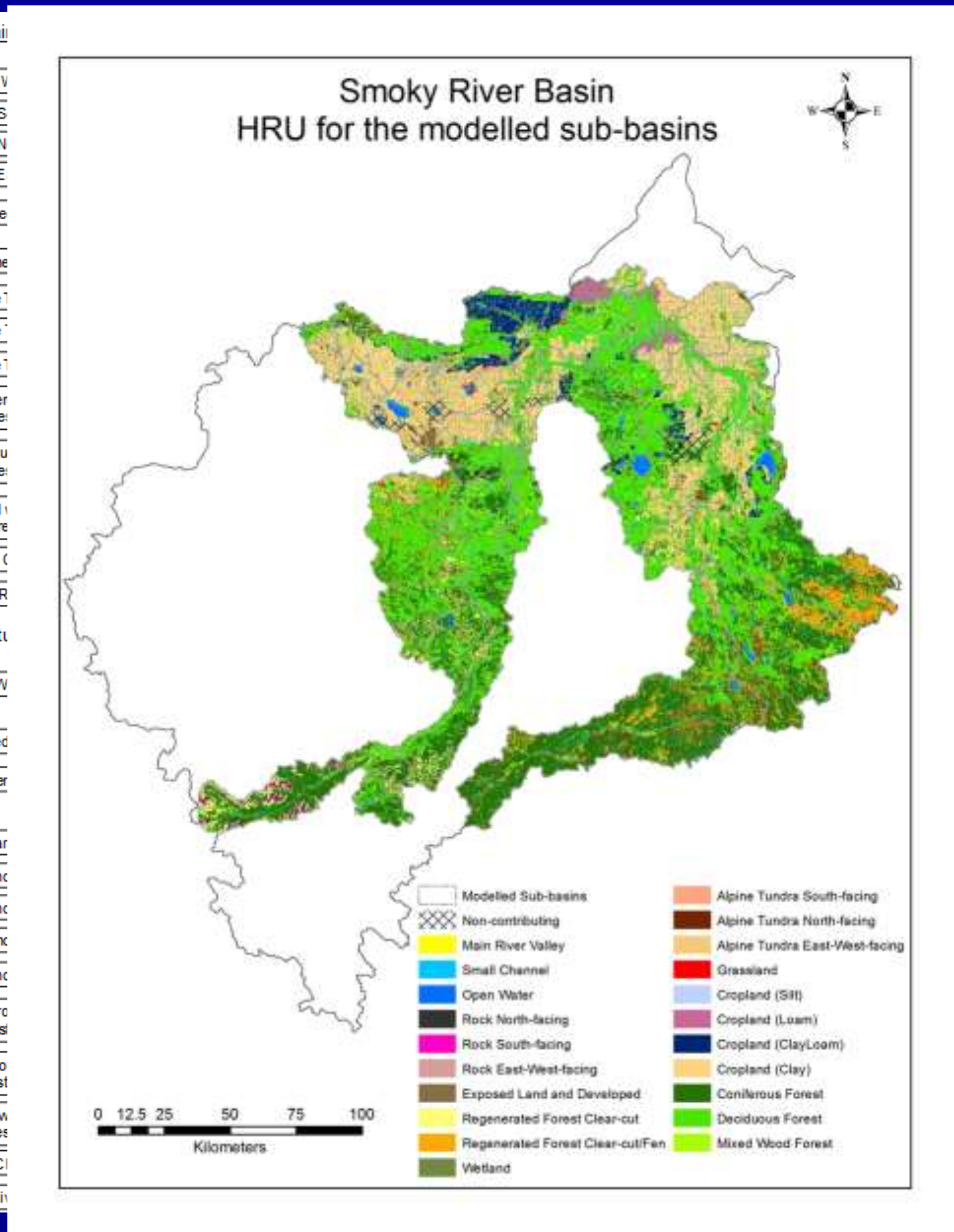


Module Structure within each HRU



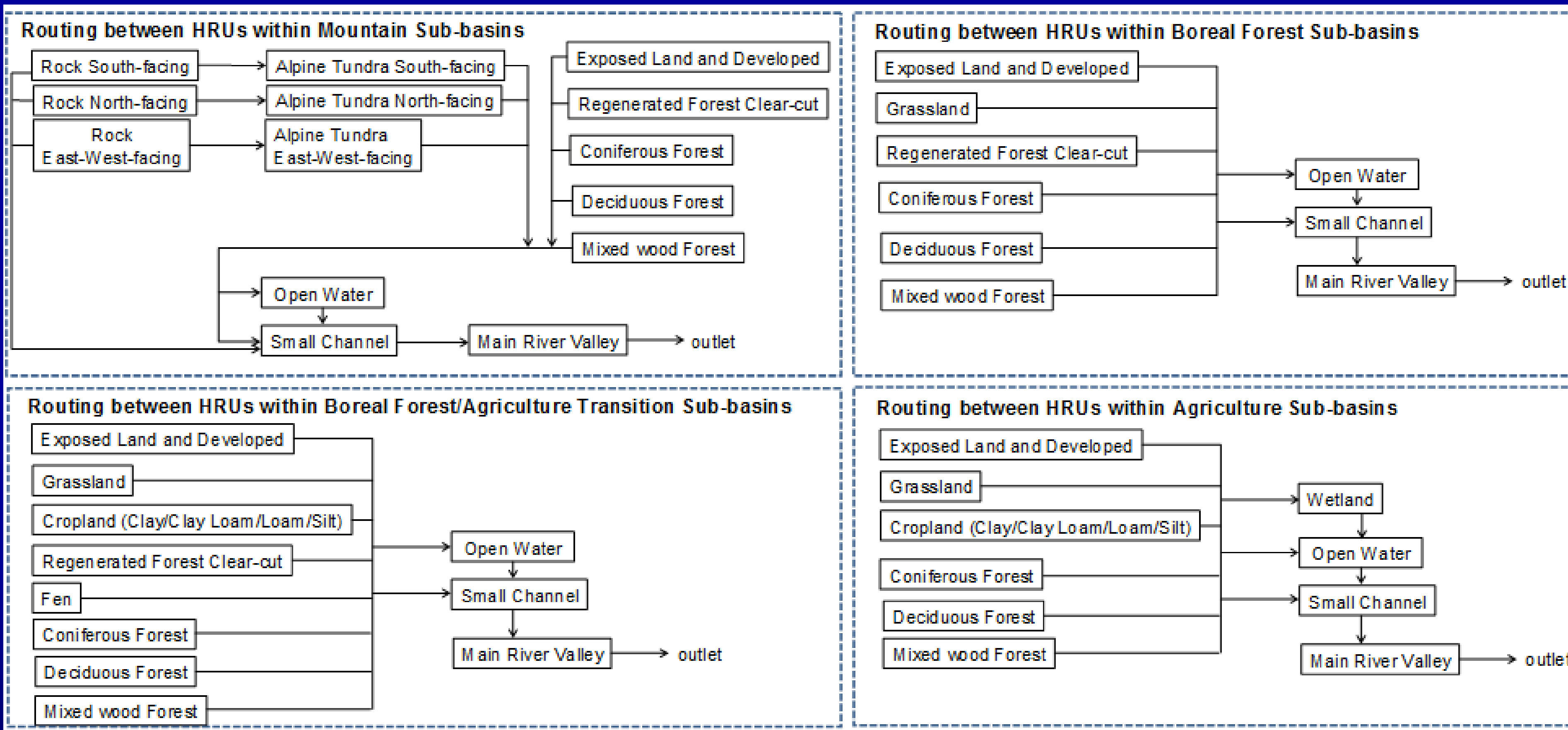
HRU Classification of Smoky Basin





HRU classification and interpretation of land cover, topography, drainage, soils to determine parameters was guided by sub-basin “type” which depended on ecoregion

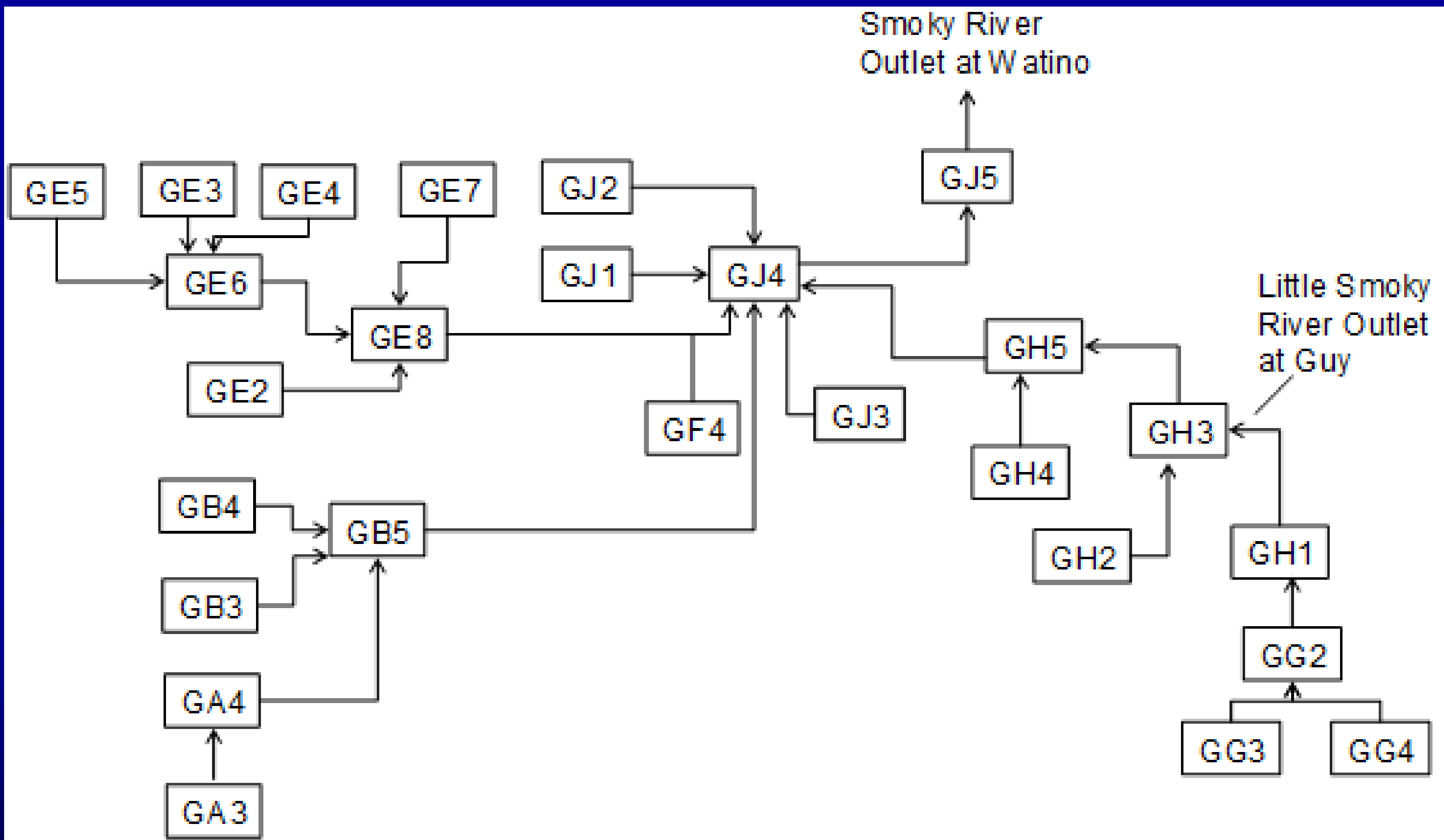
Routing between HRUs



Routing sequence depends on sub-basin type (ecoregion)

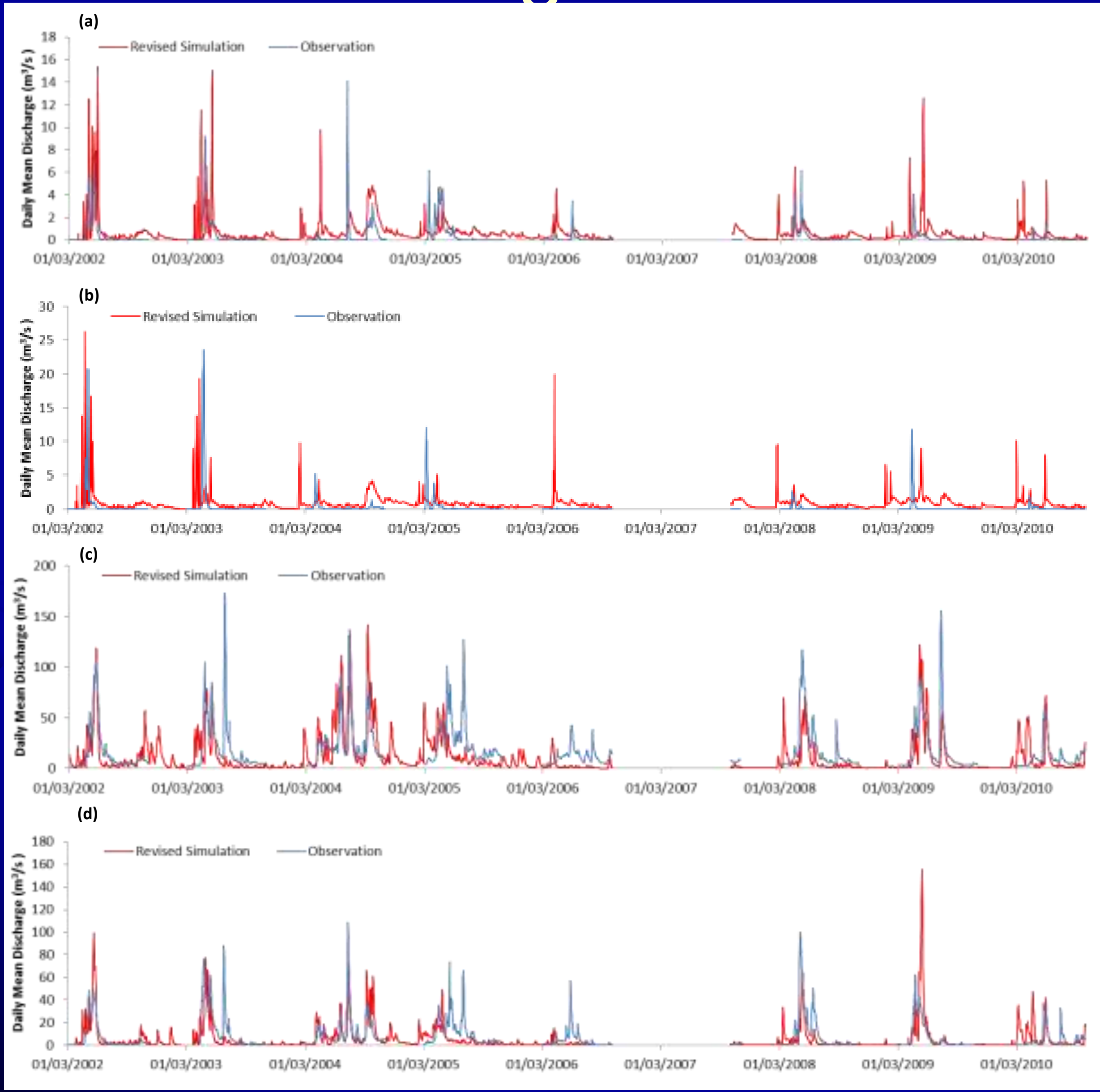
Routing between Sub-basins

Muskingum Routing used for river routing between sub-basins



Sub-basin Model Testing

Station Name	Station ID	Sub-basin
Grande Prairie Creek near Sexsmith	07GE003	GE7
Bear River near Valhalla Centre	07GE007	GE3
Little Smoky River at Little Smoky	07GG002	GG3
Iosegun River near Little Smoky	07GG003	GG4



Sub-basin

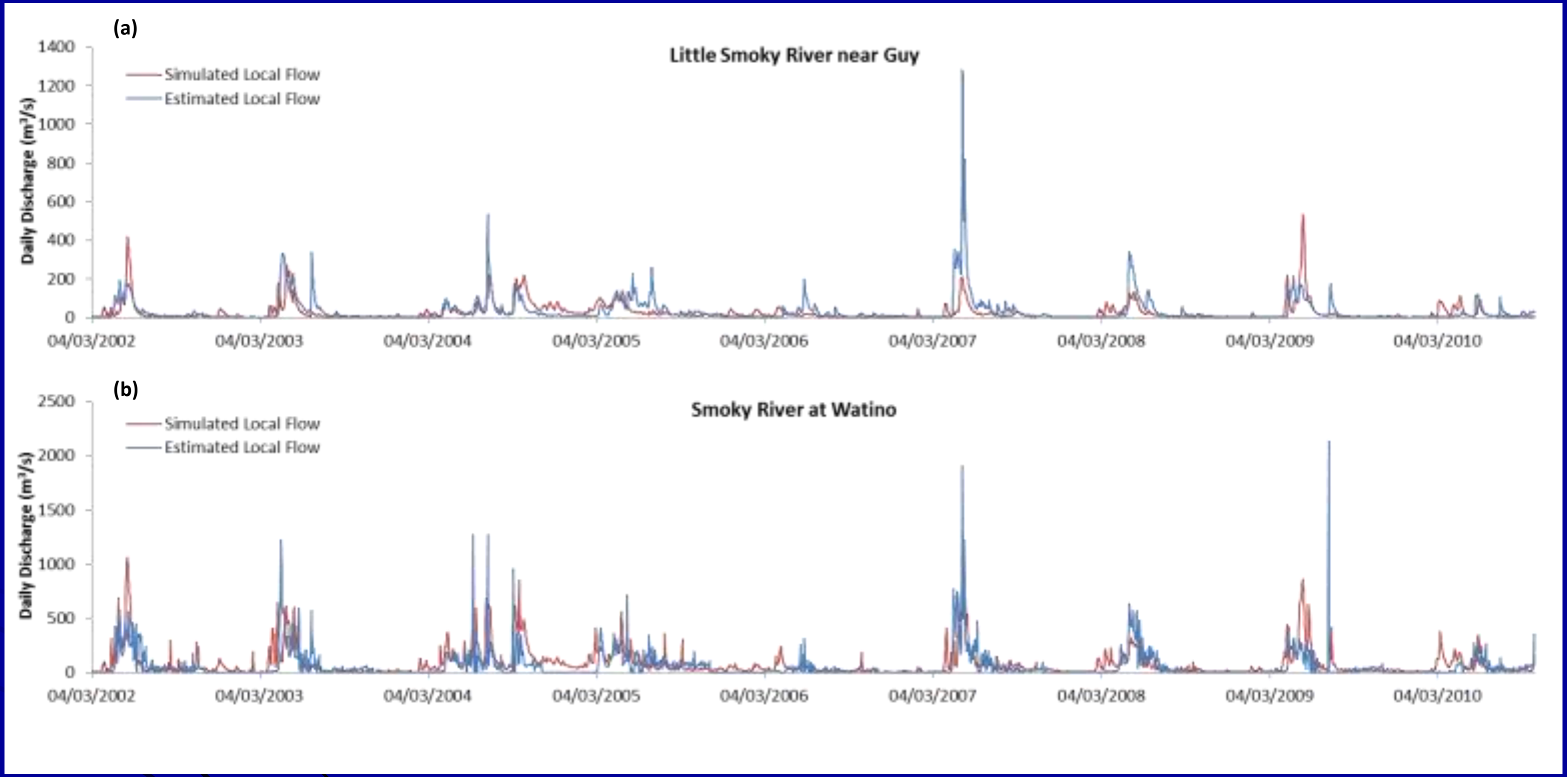
GE7

GE3

GG3

GG4

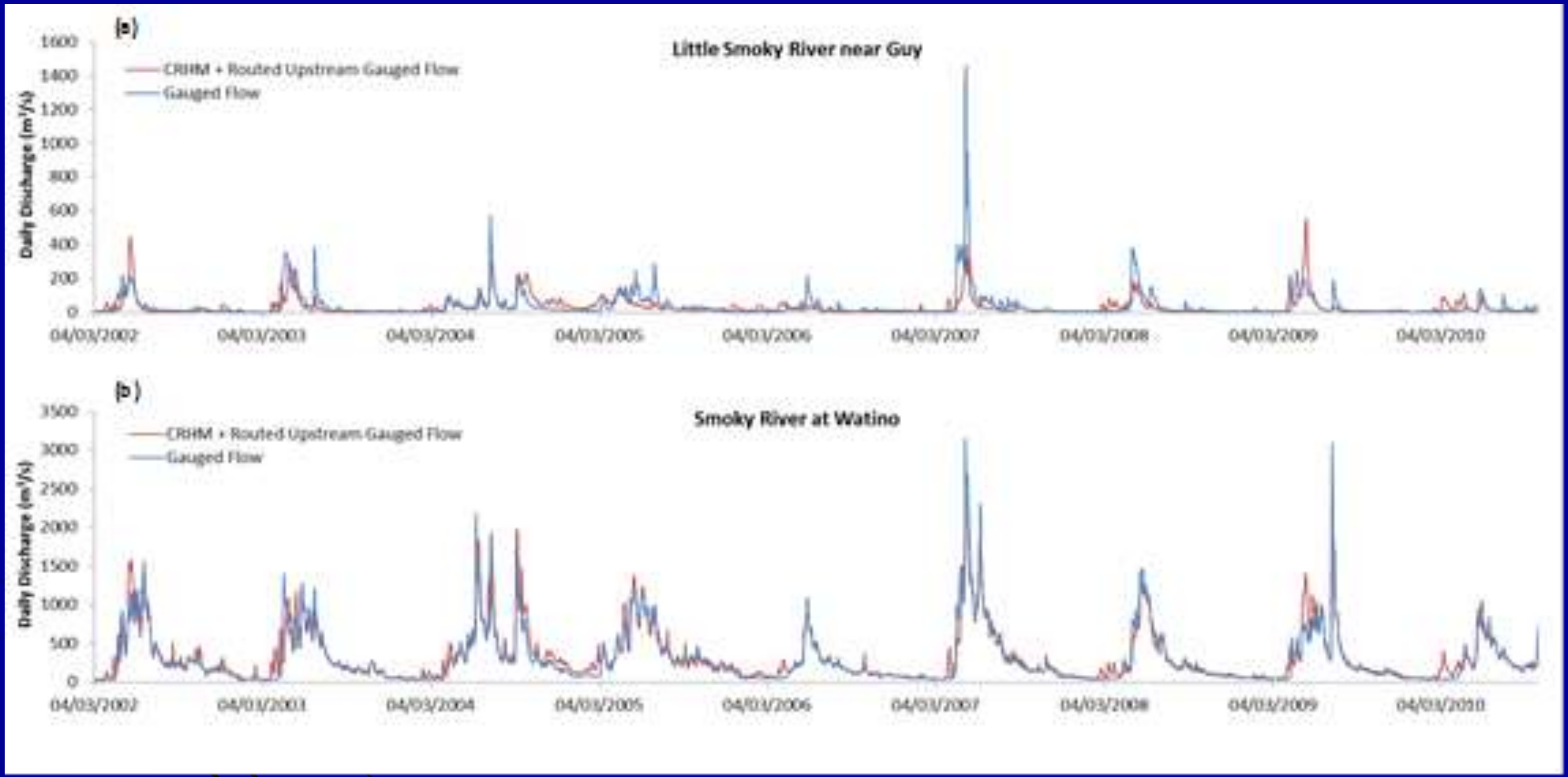
Basin Scale Local Inflow Evaluation



-Simulated local flows are only from CRHM hydrographs.

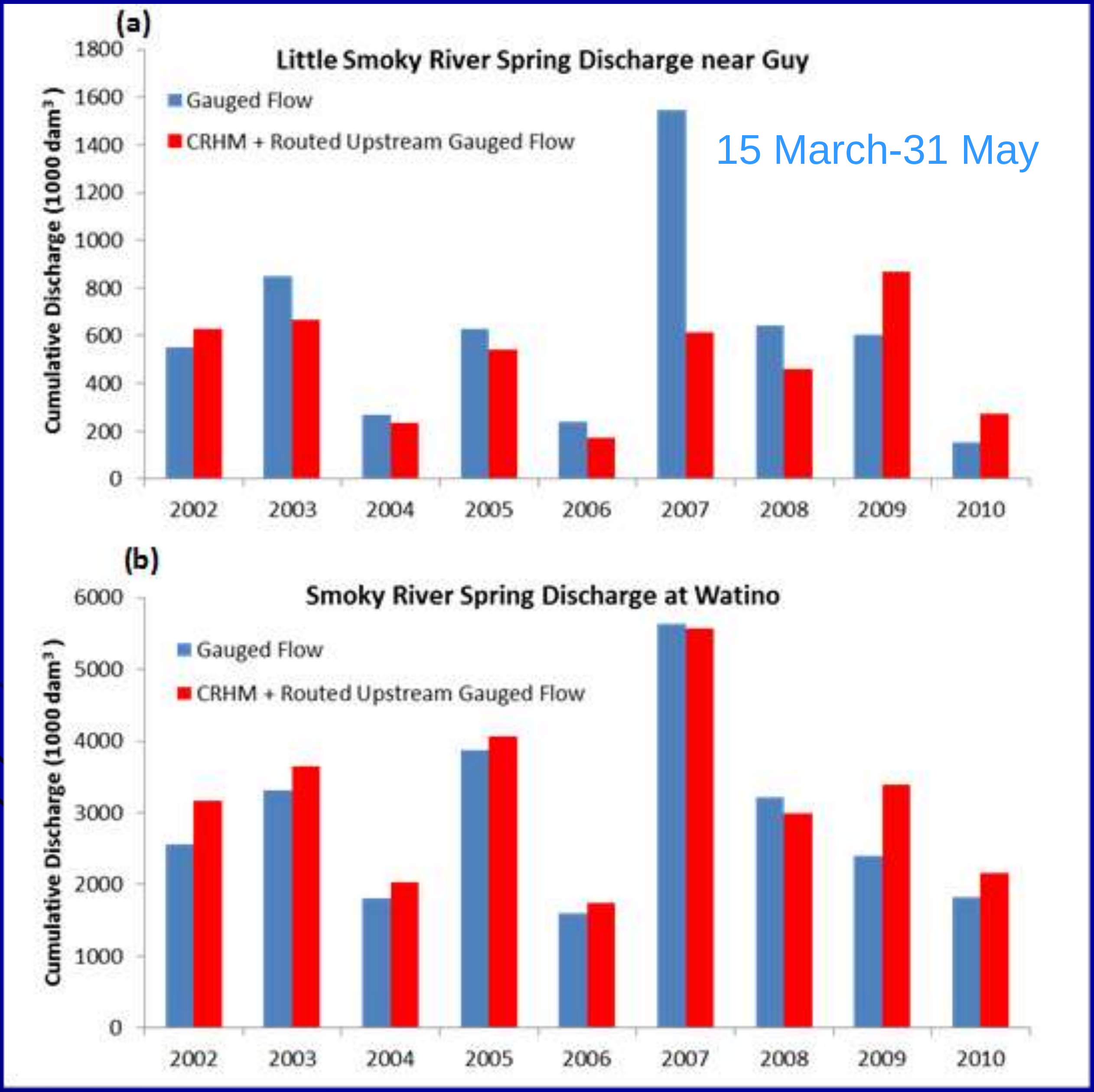
-Estimated local flows are gauged hydrographs minus routed upstream gauged hydrographs.

Basin-scale Prediction Evaluation

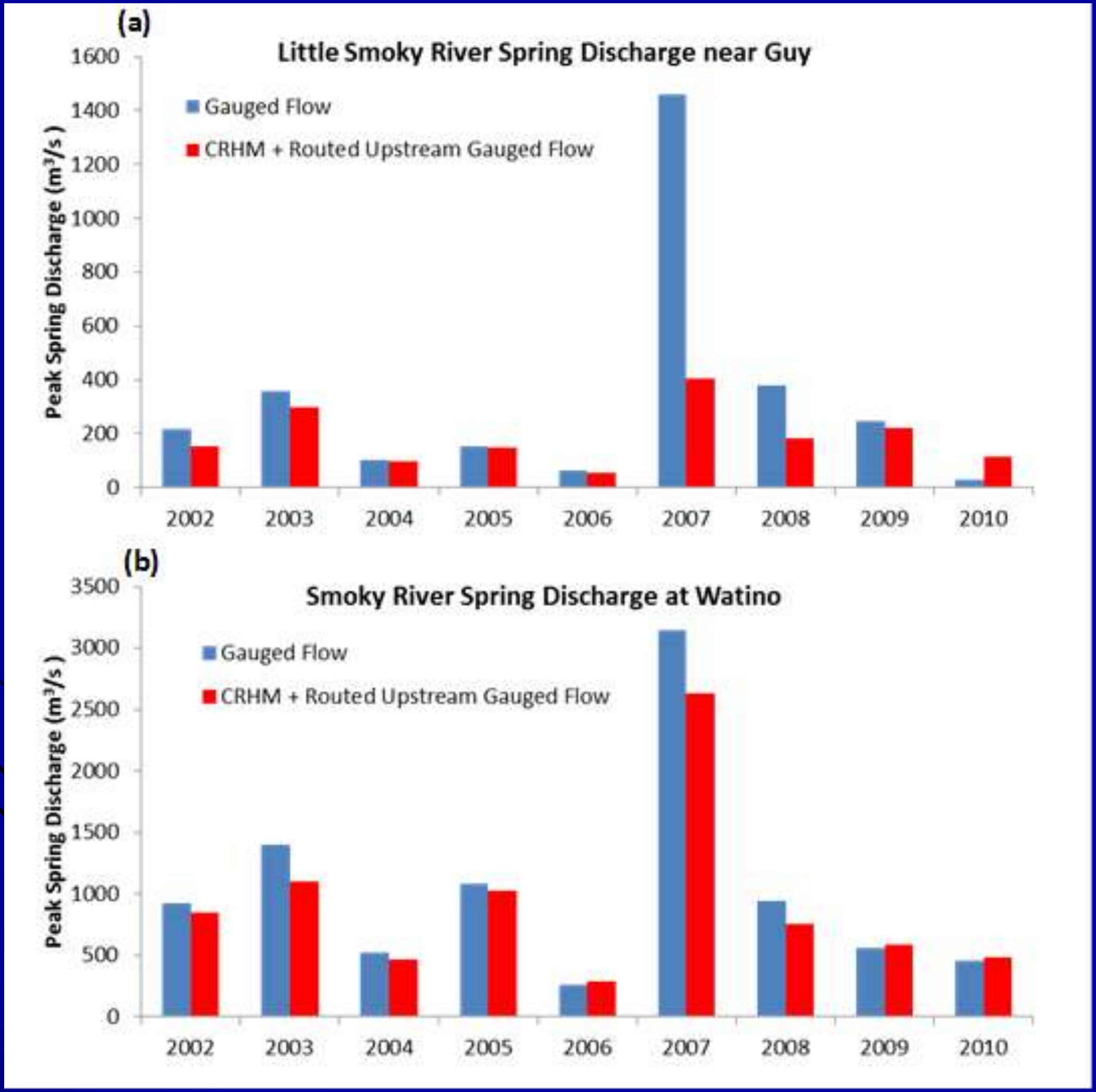


Predicted flows, Nash-Sutcliff Statistic: 0.41 (Little Smoky) and 0.87 (Smoky)

Predicted Spring Discharge



Predicted Spring Peak Discharge



Conclusions

- Better understanding of processes by intensive field study and detailed distributed modelling in research basins can be the basis for more realistic models and confident parameterisation.
- Using the results and understanding from research basins It is possible to simulate multiple hydrological states and fluxes in Alberta's mountains and prairies without extensive calibration from streamflow observations.
- These models can be used to reliably show the sensitivity of Alberta's river basins to climate change, drainage and land use change and provide new insights because of their strong physical basis.