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A Physically-Based Modelling Approach to Assess the Impact of Climate Change on Surface and Groundwater Resources within the Grand River Watershed, Ontario, Canada

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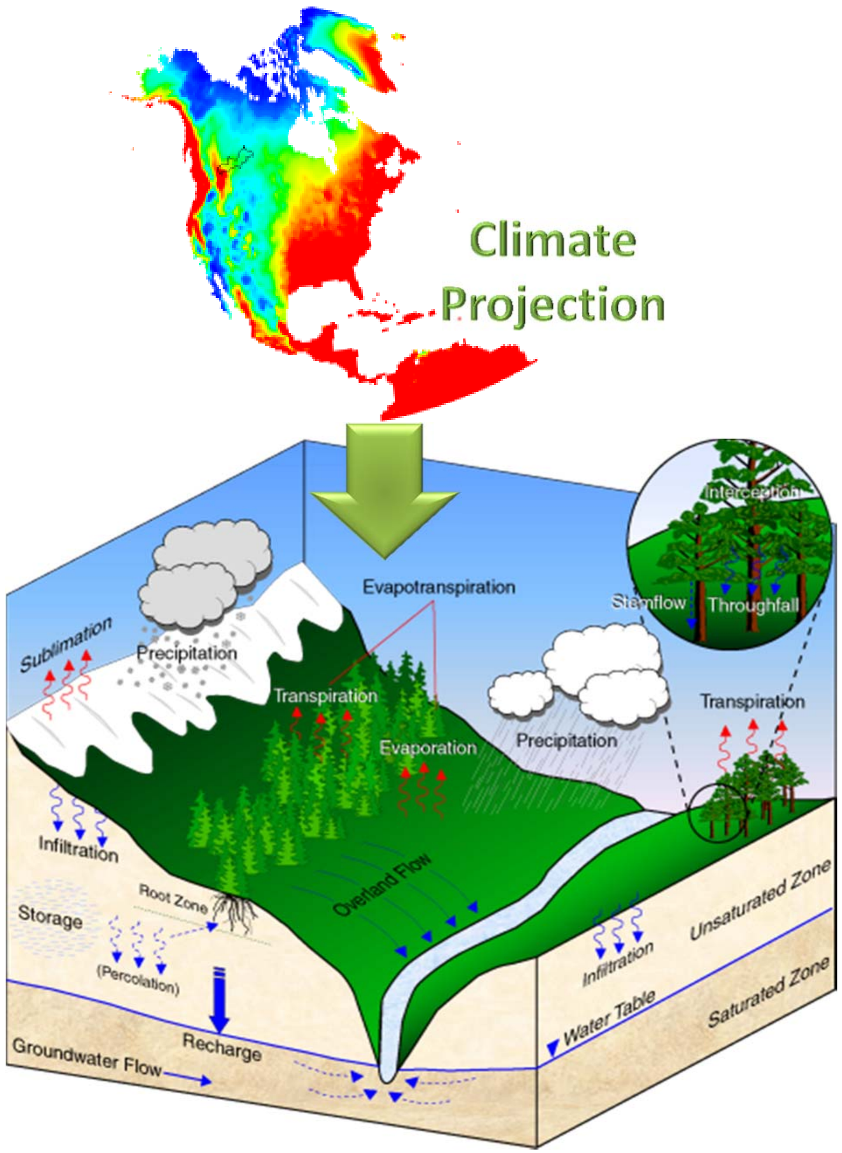
Need for a Community Model Inter-Comparison: Complexity *versus* Simplicity

- Many models – some comprehensive, some less so
- Some physics-based (i.e., coupled PDE’s), some “lumped”
- Some structured, some “cobbled” together
- Some flexible, some “rigid”
- Disparate data needs
- Avoid “model wars”

A community model inter-comparison…

- Could use well-characterized data-rich watersheds as a platform
- Include models ranging from comprehensive (complex?) to simple (parsimonious?)
- Water quantity, water quality
- Not a competition to define winners and losers
- Serves the entire hydrologic community (scientific, consulting, government, regulatory, policy sectors)

HydroGeoSphere Philosophy



HGS™ SIMULATION

- Fully-coupled 3D model based on PDEs to capture interactions between surface and subsurface water flow, solute and energy transport
- Can be “simplified” to consider only individual water cycle components

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Examples of Coupled Surface-Subsurface Models

Earliest known coupled surface/subsurface flow model:
Freeze, R.A. and R.L. Harlon, Blueprint for a physically-based, digitally-simulated hydrologic response model, *J. Hydrol.,* 9, 237-258, 1969.

Some Existing *"Integrated"* Models:

- InHm
- HydroGeoSphere
- MODHMS
- Parflow
- OpenGeoSys
- CATHY
- PIHM
- …

Seems to be a growing area of model development, but do we need more models, or more applications centered on resolving key societal concerns & scientific questions ?

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Overview of “HydroGeoSphere” Model Features

- 2D overland/stream flow (Diffusion-wave equation), including stream/surface drainage network genesis;
- 3D variably-saturated flow (Richards’ equation + ET) in porous medium;
- 3D variably-saturated flow in macropores, fractures and karst conduits (dual-porosity, dual-permeability or discrete fractures);
- Advective-dispersive, reactive solute/thermal transport in all continua, snow accumulation/melting, soil freeze/thaw;
- Groundwater age, life expectancy
- Allows for complex topography, irregular surface & subsurface properties, density-dependent flow, subgridding & subtiming
- Fully-coupled, simultaneous solution of surface/subsurface flow and transport via Control-Volume Finite Element or Finite Difference Methods.

Grand River Watershed Background

- 7000 km^2
- Population of ~900,000
- Intensive Agriculture
  - 93% rural/agricultural land use
  - 290,000 head of cattle
  - 500,000 thousand swine
  - 8.8 million poultry
- 900 mm of precipitation/year
- Heavy Dependence on Groundwater for Municipal Water Supply
- Well Instrumented
- Long Term Records

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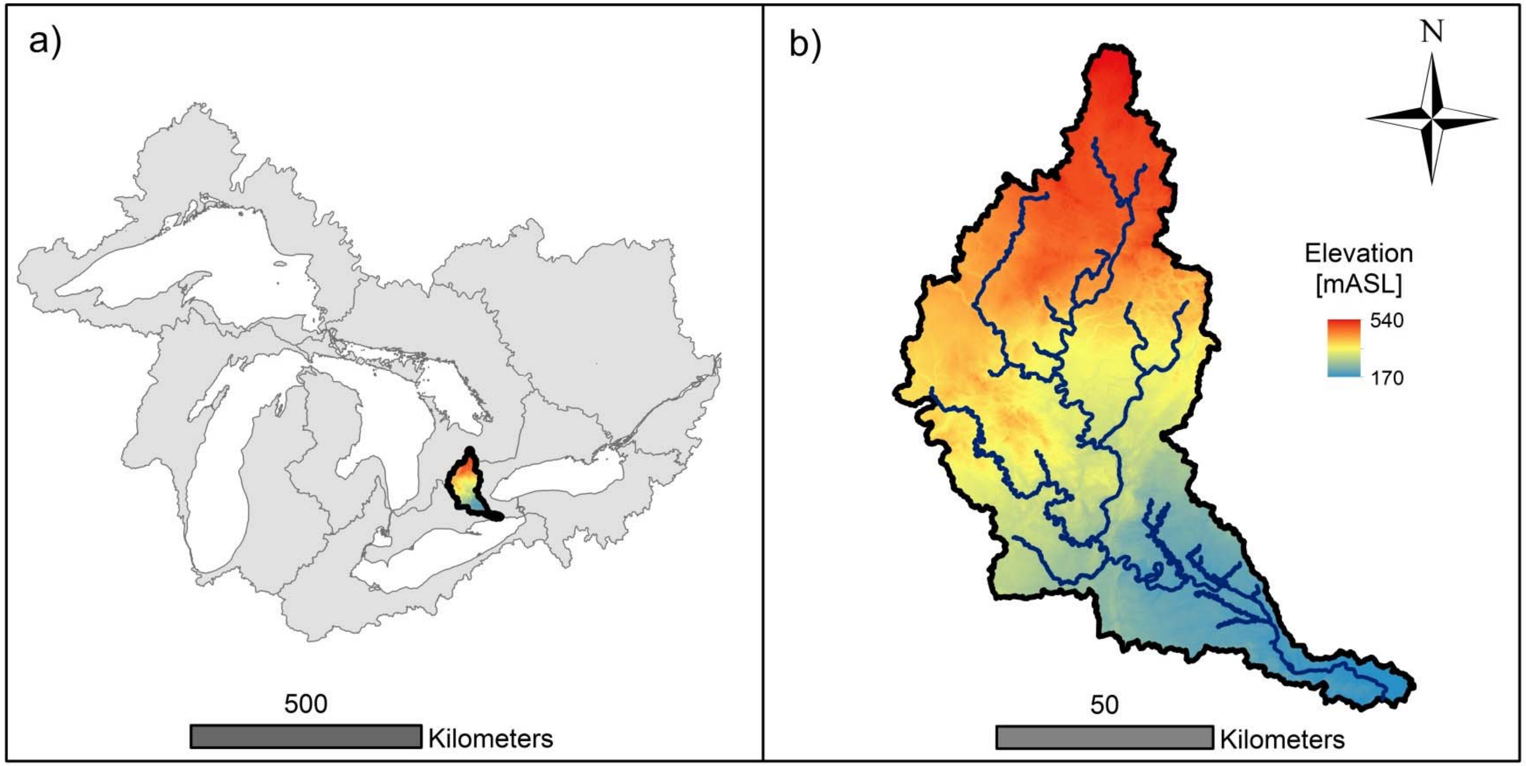
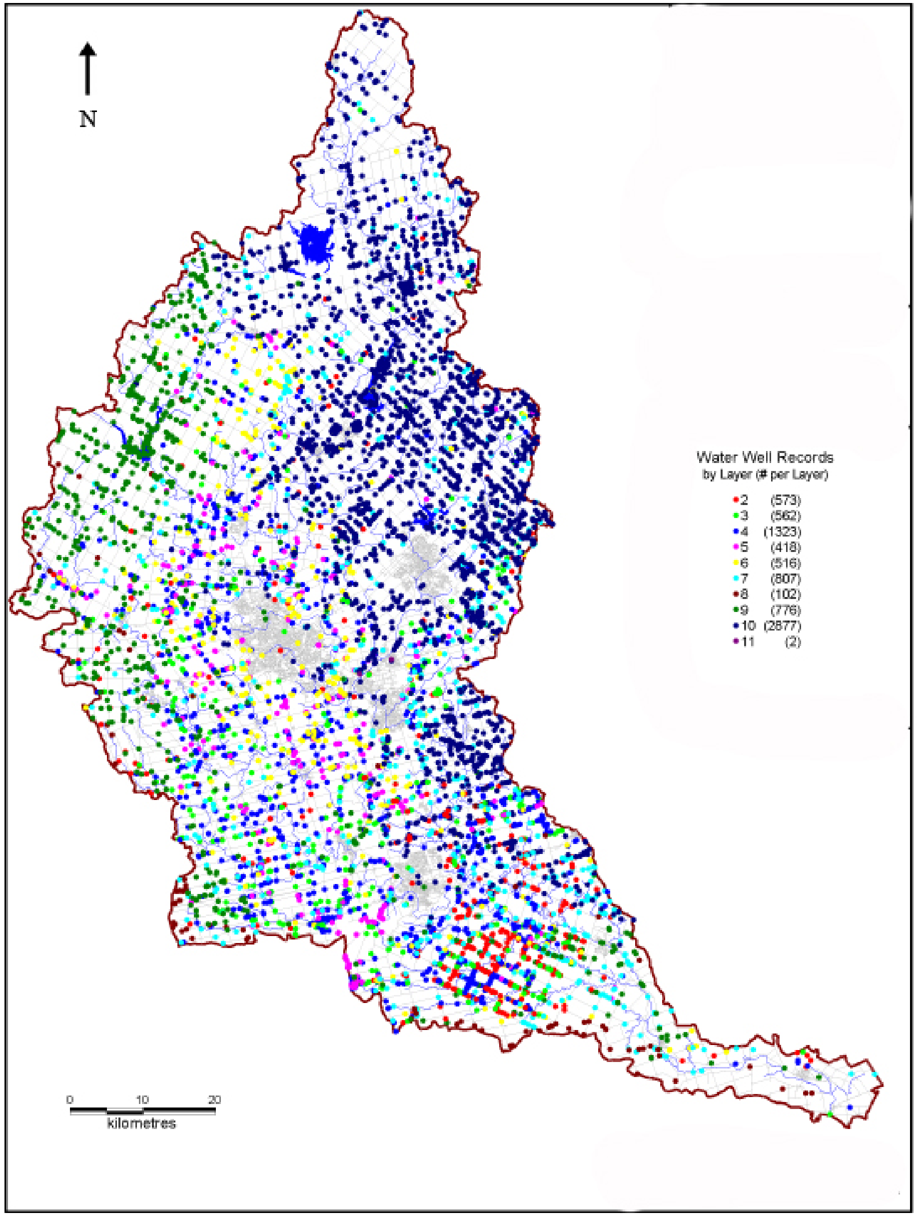
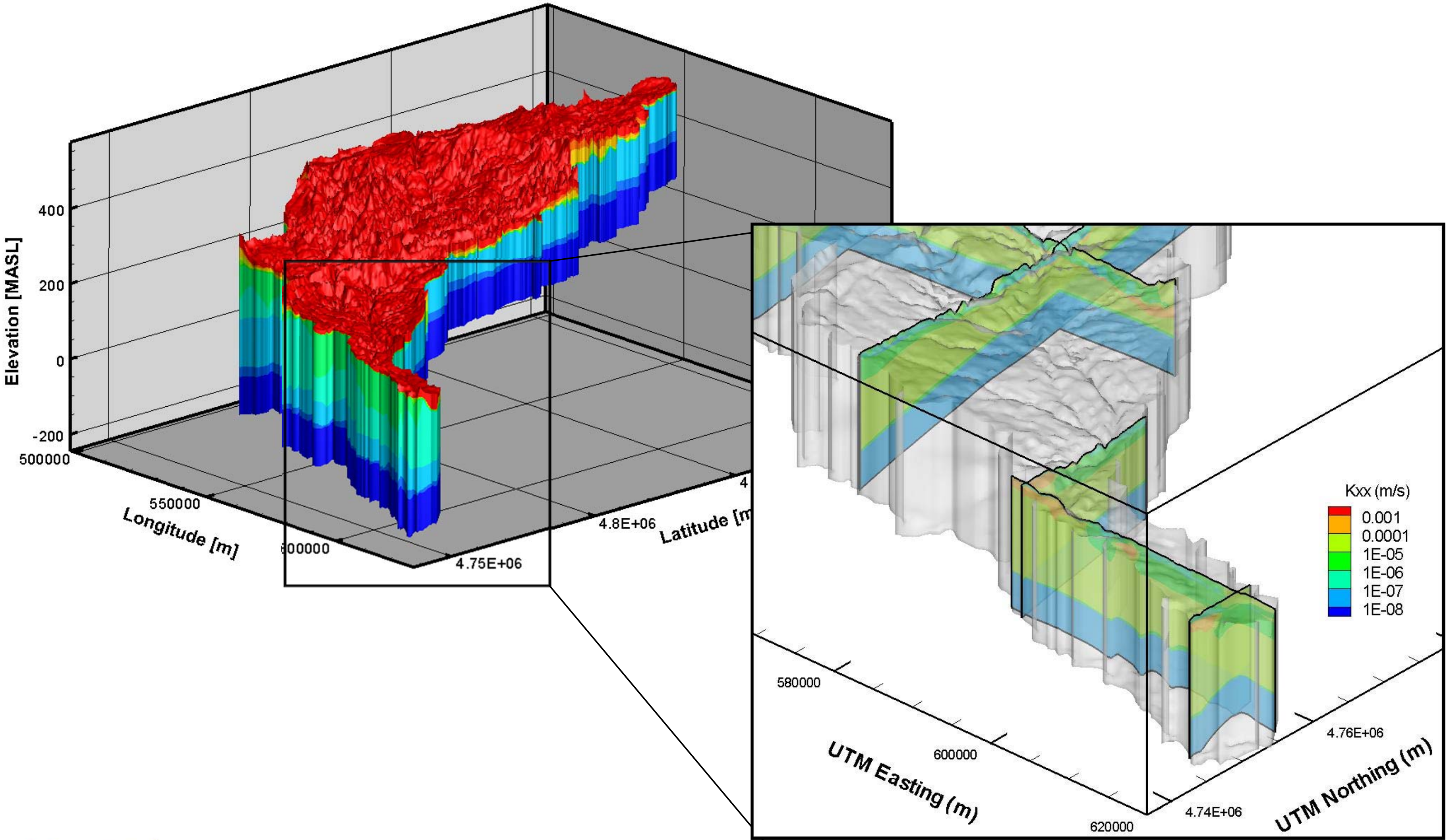
Location Within Great Lakes Basin



Drilling and Water Well Records



3D Geological Model



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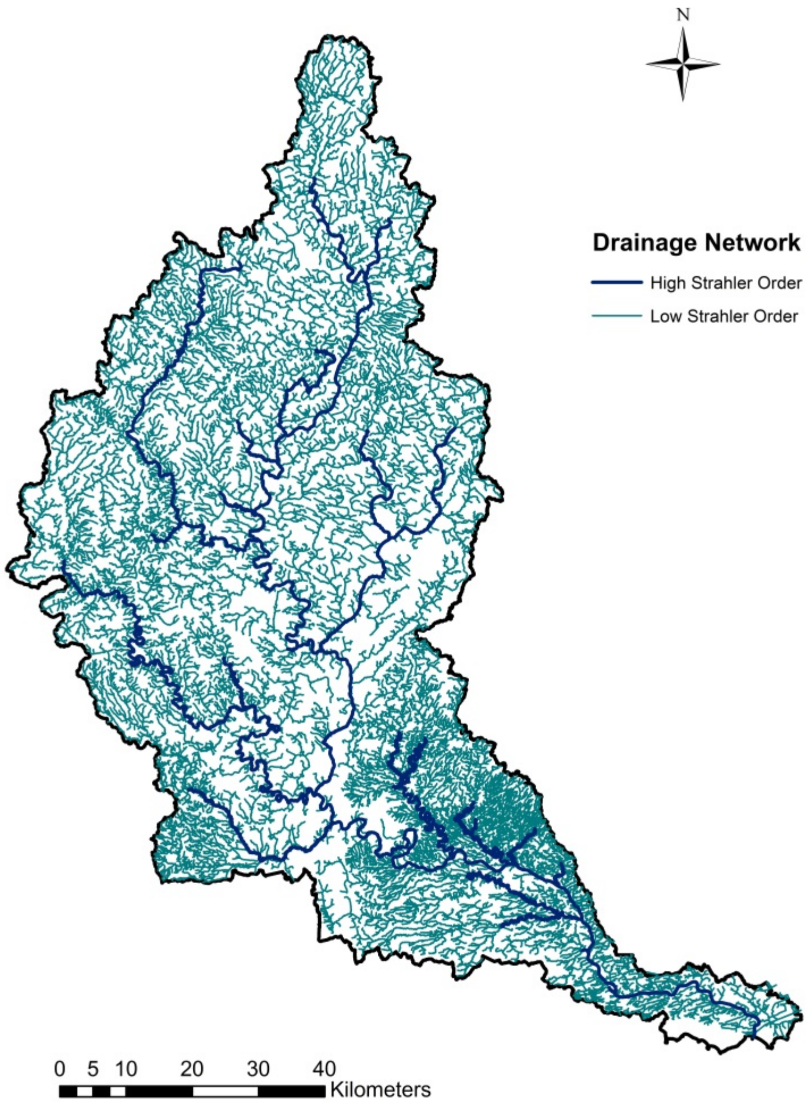
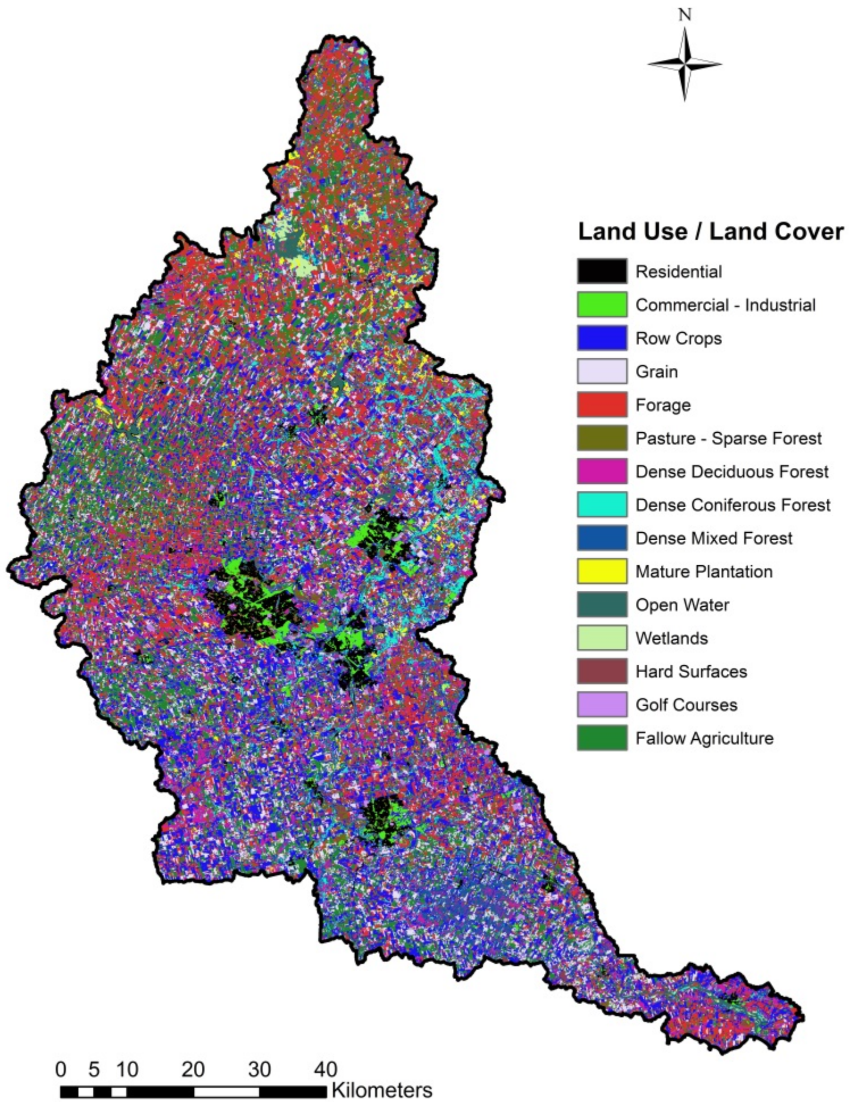
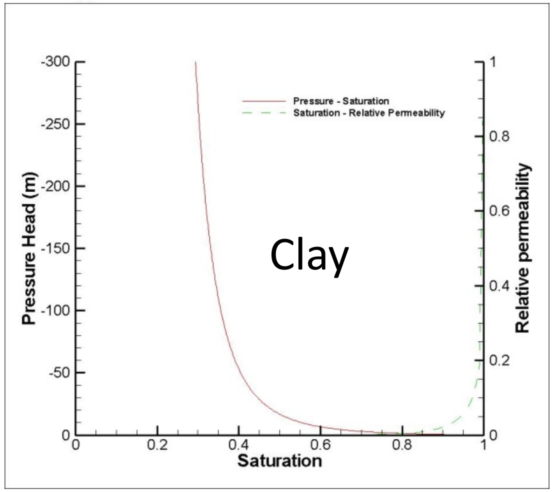
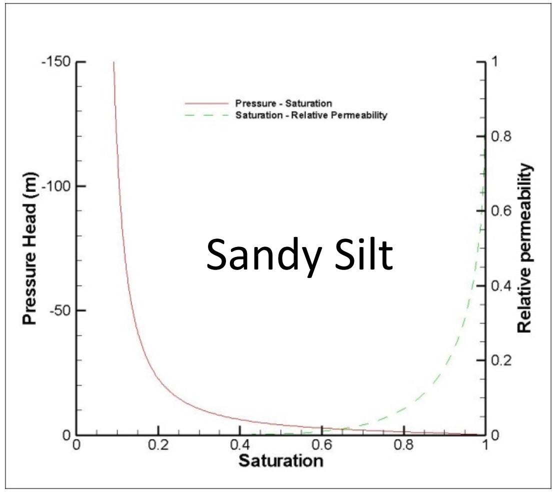
Extensively Characterized

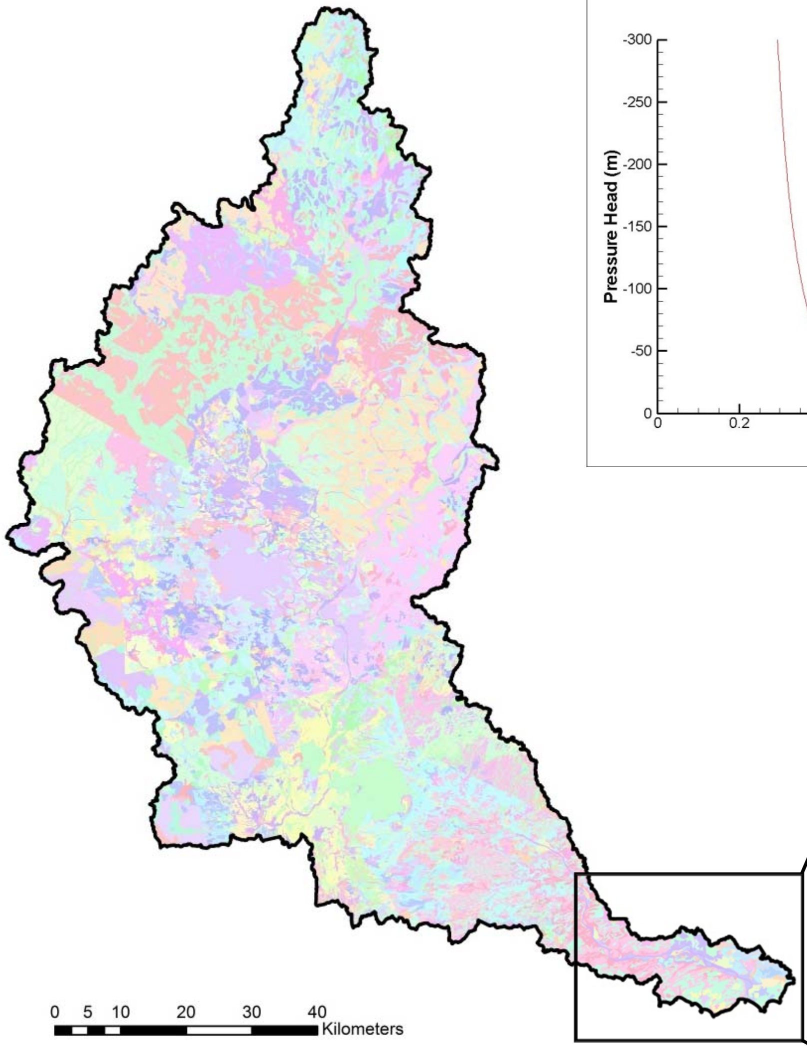


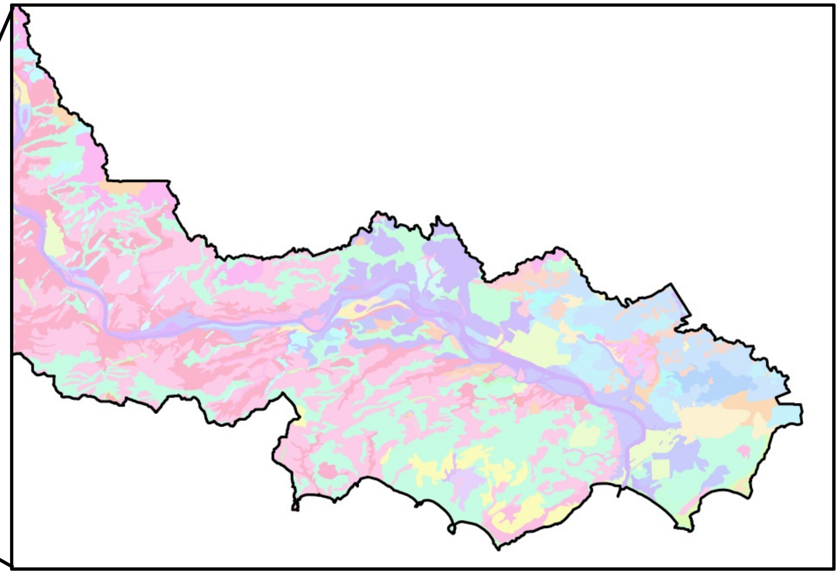


Well Defined Soil Type Distributions









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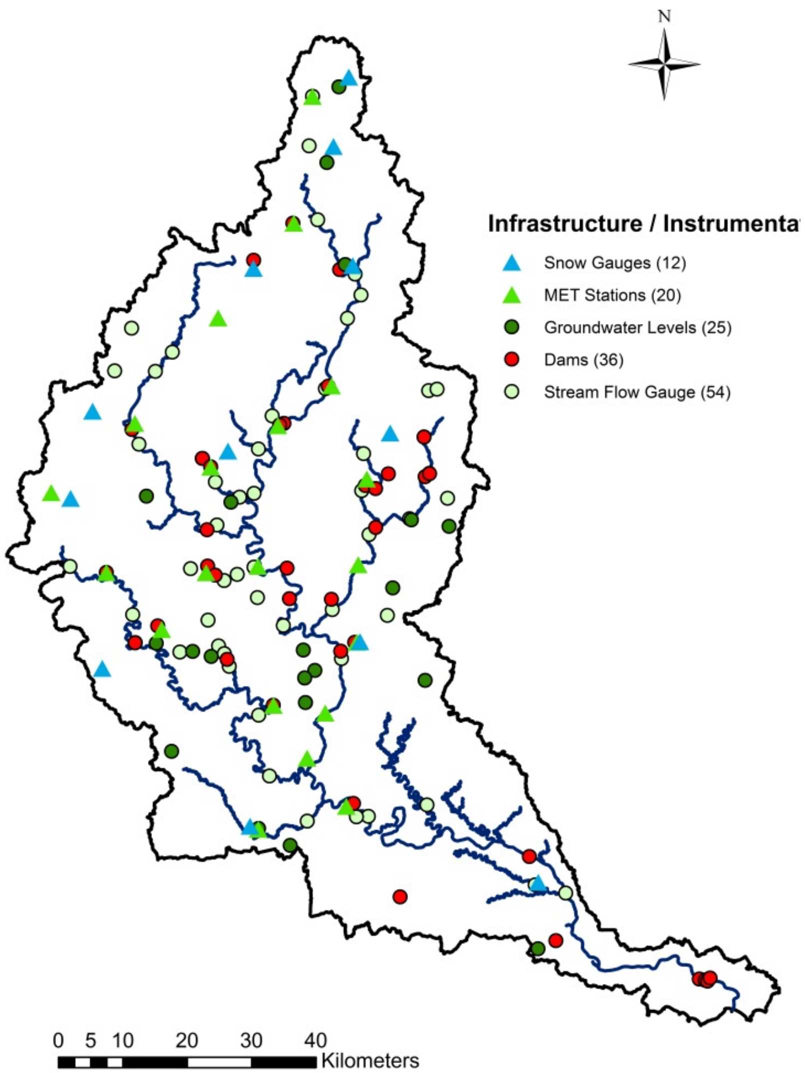
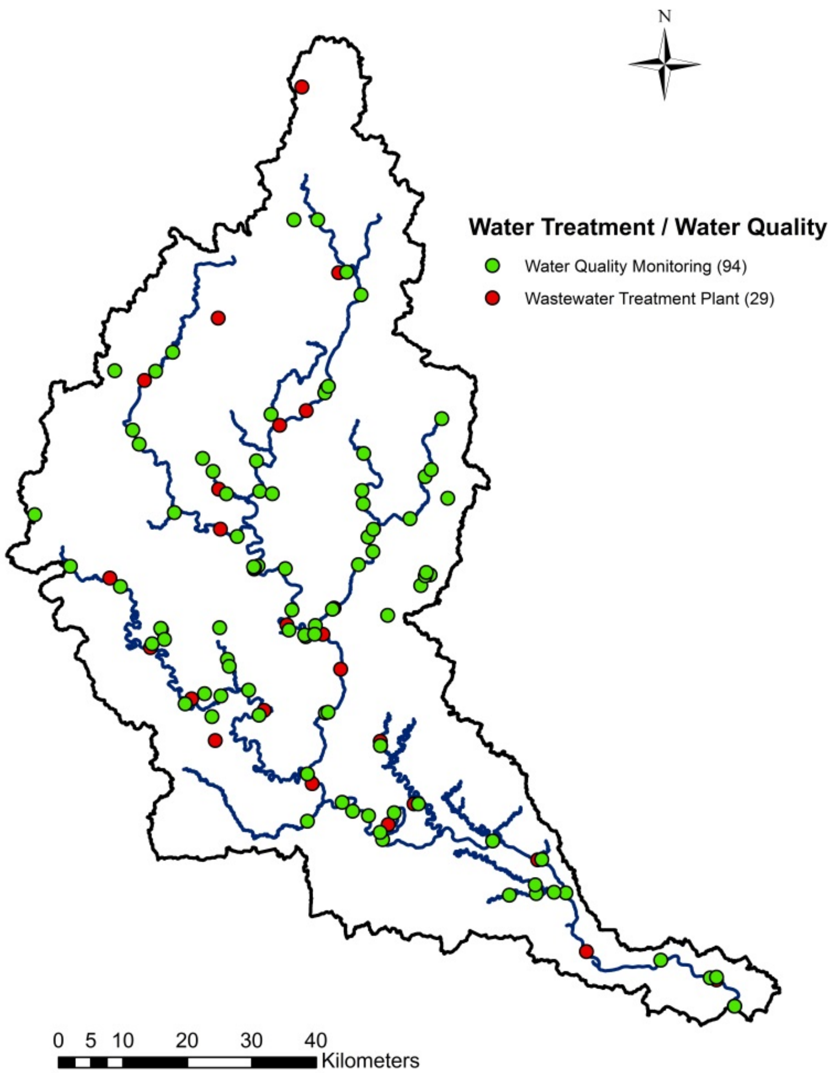
Extensively Monitored





Water Budget

Water Budget Parameter	Value (mm/year)
Precipitation	930
Evapotranspiration	605
Surface Flow Out of GRW	313.5
Infiltration	465
Exfiltration	170
Recharge	186
Groundwater Flow Out of GRW	0
Groundwater Pumping	11.5

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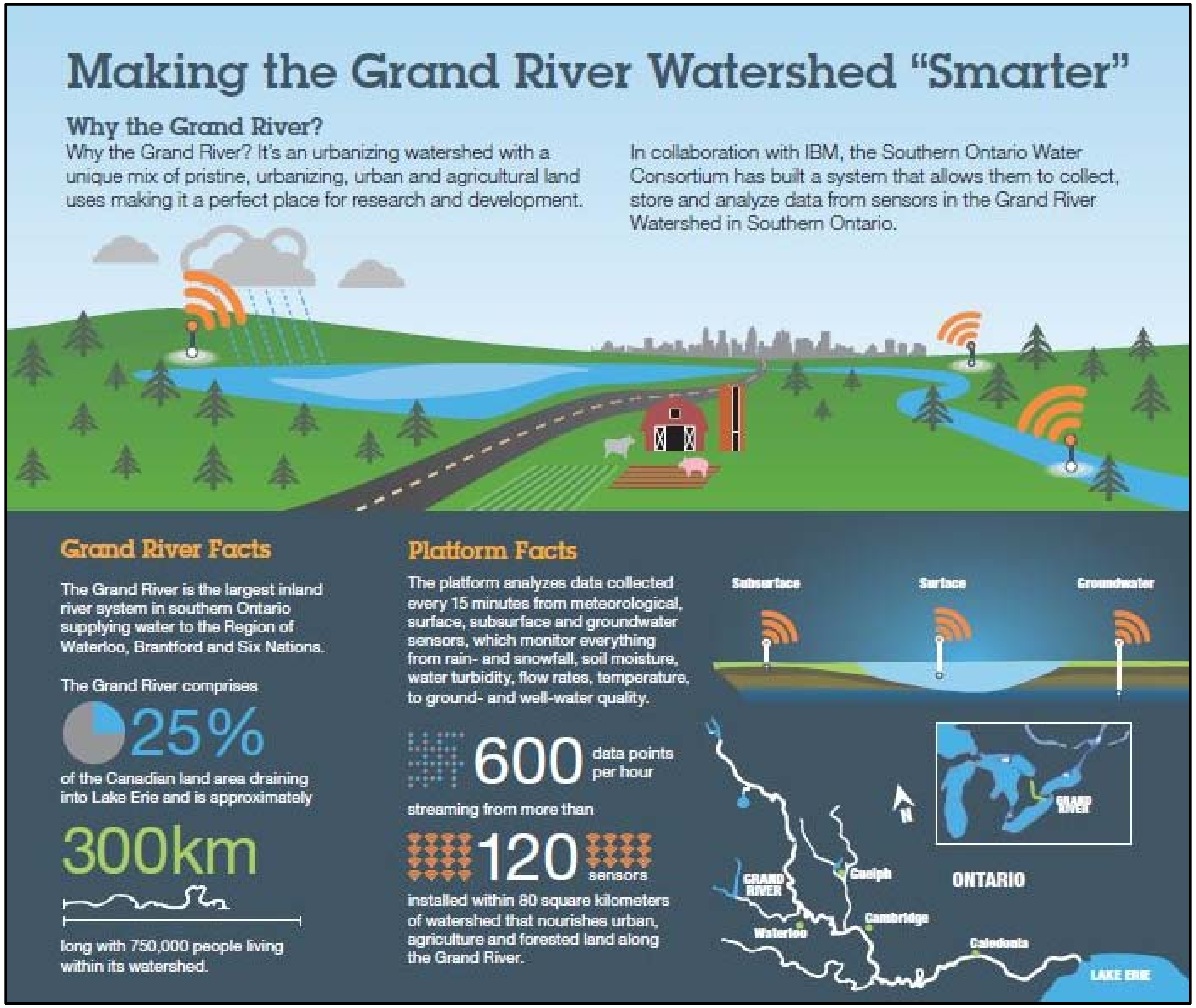
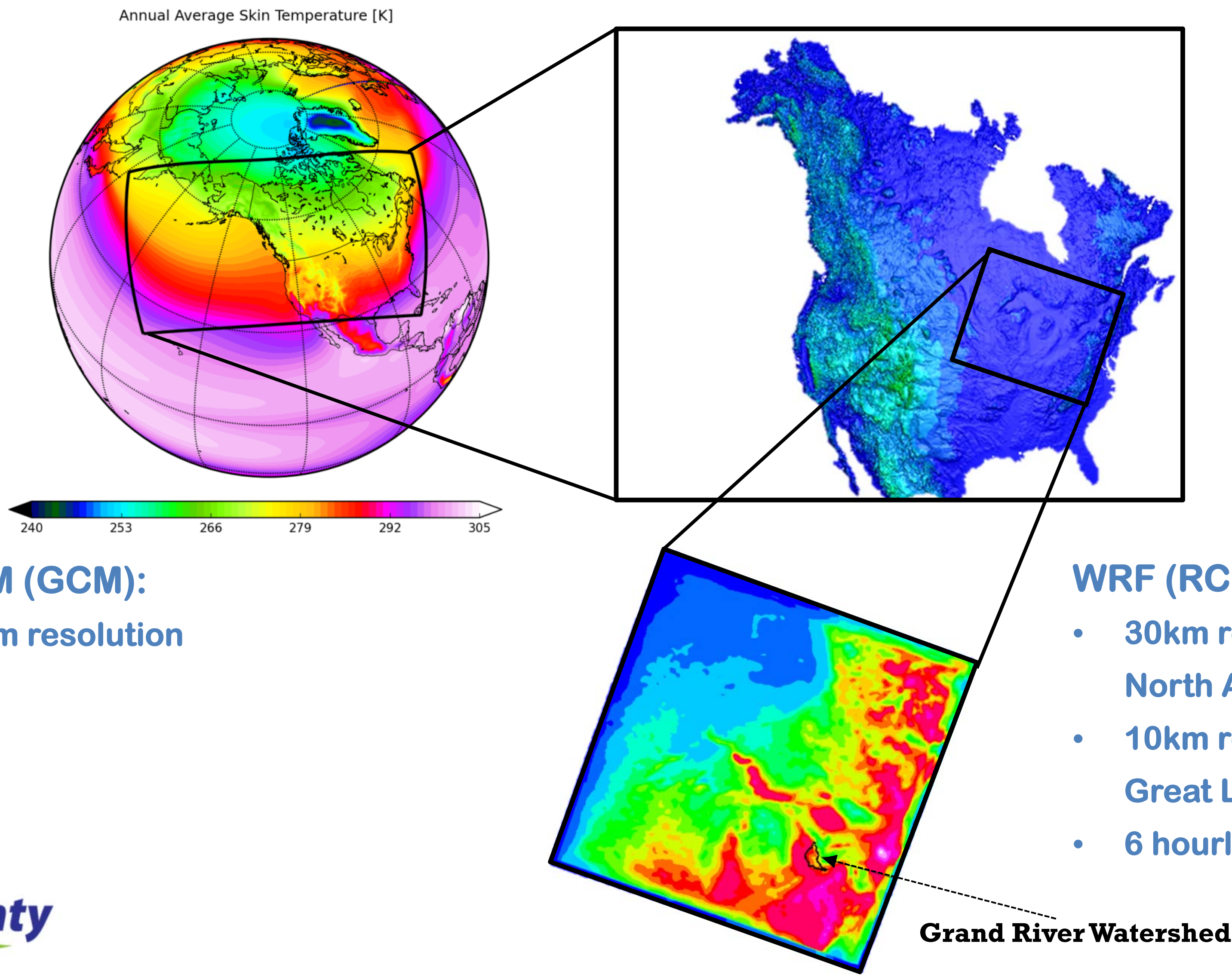
Smart Watershed Monitoring



Climate Projections (Peltier et al., U of T)

Dynamical Downscaling of Climate: CESM & WRF



CESM (GCM):

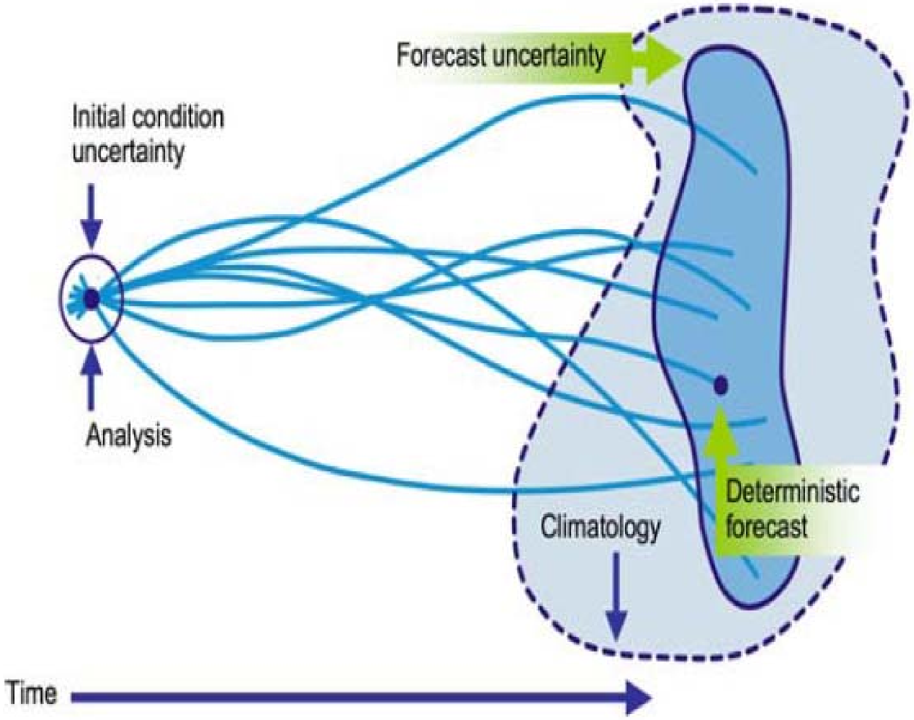
~ 80km resolution

WRF (RCM):

- 30km resolution for North America
- 10km resolution for Great Lakes Basin
- 6 hourly forcing

Background – Climate Projections

Initial conditions and uncertainty



A conceptual model of climate projection: all trajectories begin in a reasonably well defined initial state, they then spread and decorrelate with time to arrive at a random location within a new but equally well defined distribution

Climate is essentially the statistical average of the weather in a particular region over a particular time window.

- Climate change is a shift in these statistical characteristics with time

Even though we cannot predict individual weather events we can predict (project) changes in the nature of their statistical distribution

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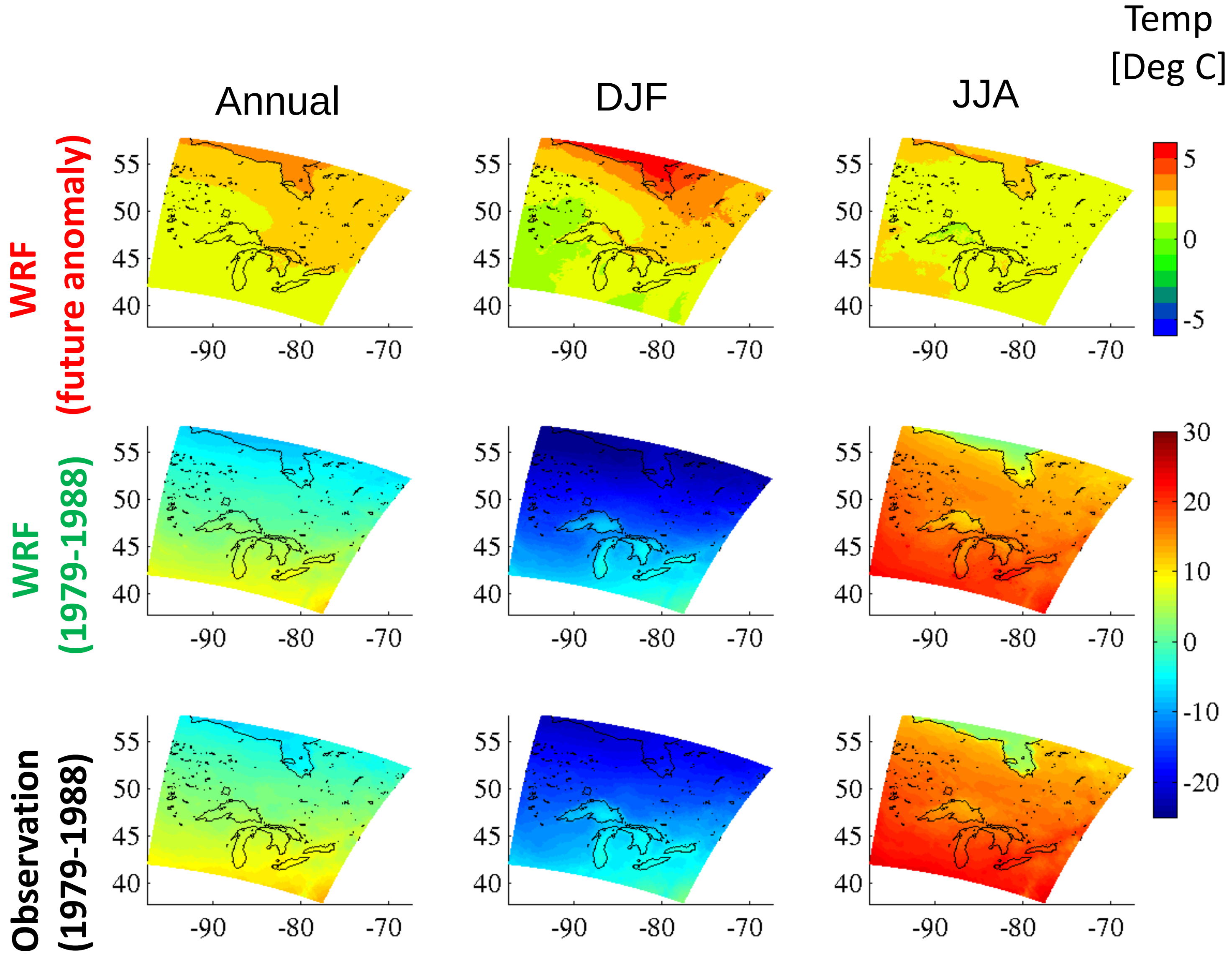
Observation vs. WRF vs. Future (2045-2054)

WRF 10kms
10 years avg

Compared to the
NARR dataset
(Mesinger 2006)



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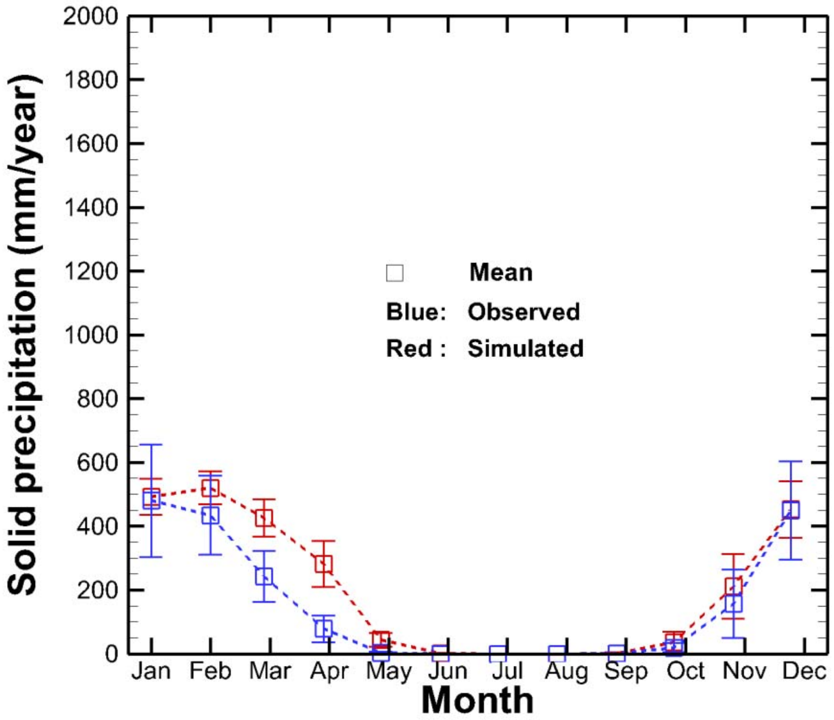
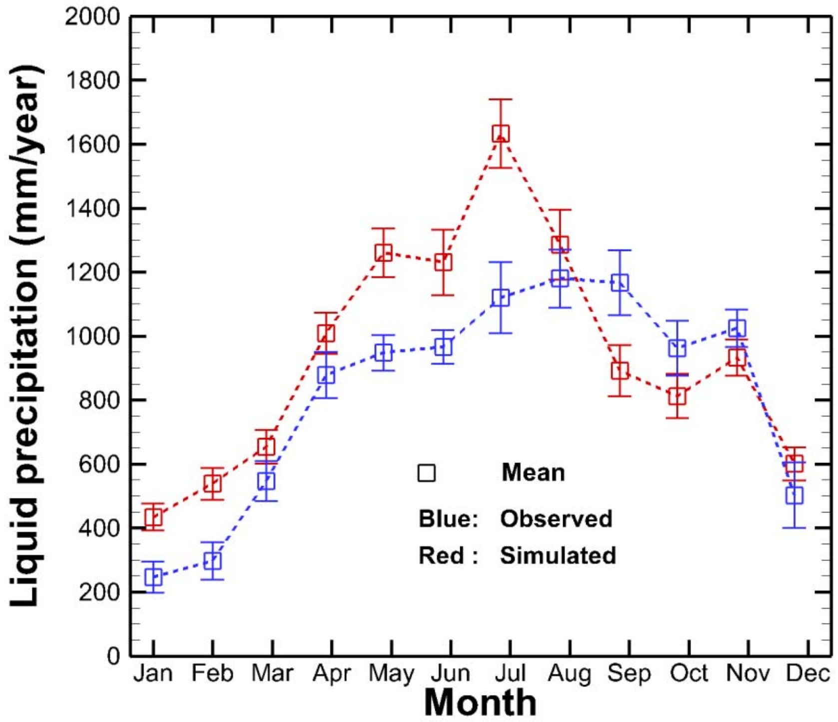
Observed vs. Simulated Precipitation

Monthly averaged liquid and solid precipitation (1979~94)





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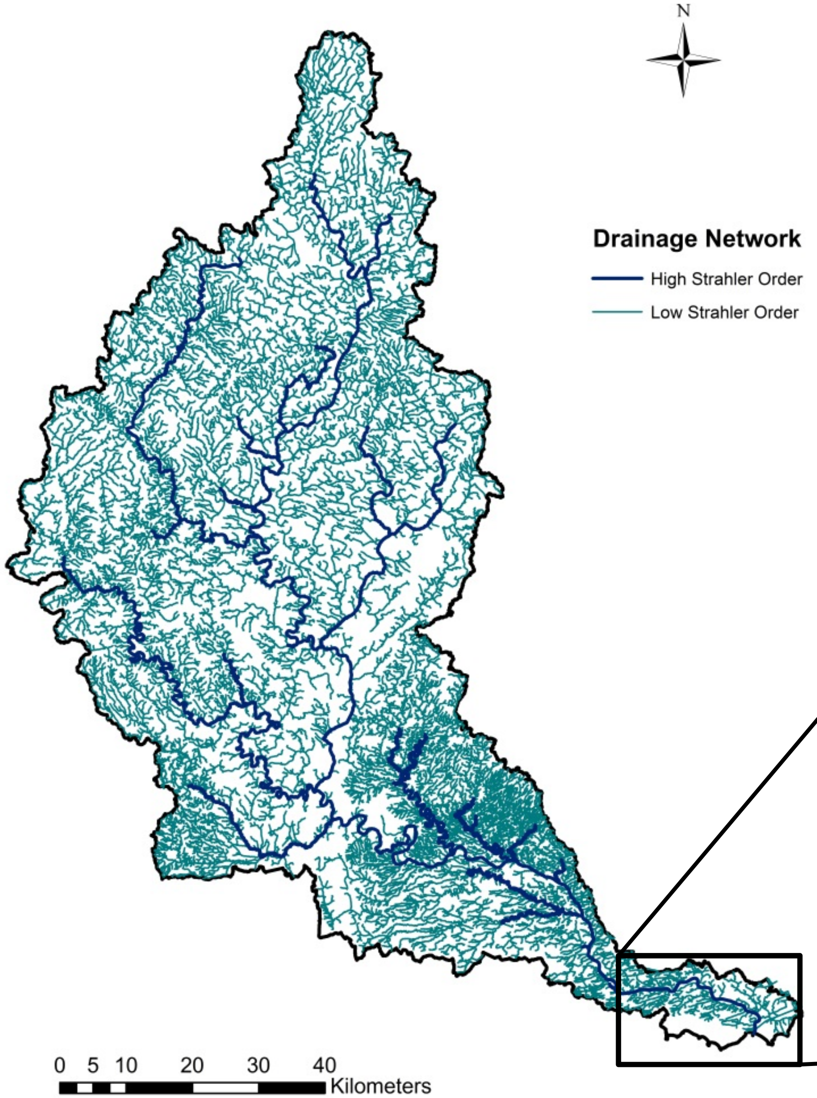
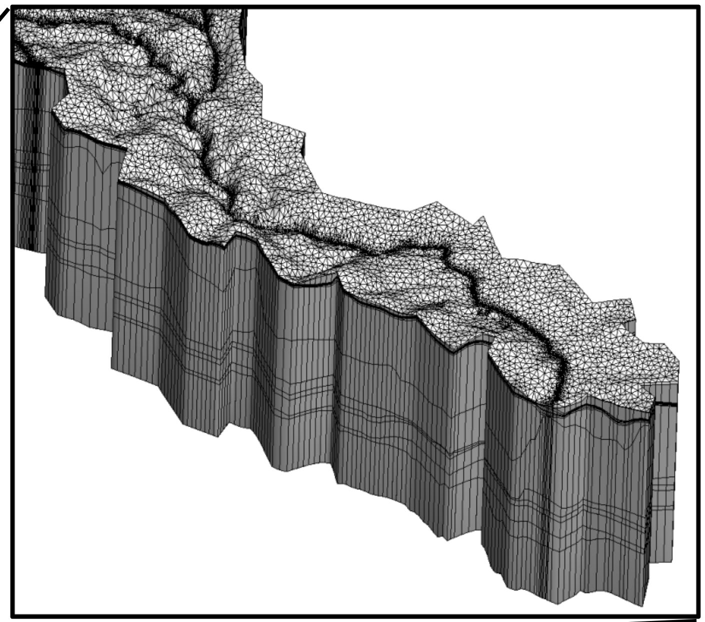
HydroGeoSphere FEM Development



Mesh Details

- 15 Layers
- 220,000 Nodes / Layer
- 437,000 Elements / Layer
- 3,500,000 Total Nodes
- 6,500,000 Total Elements



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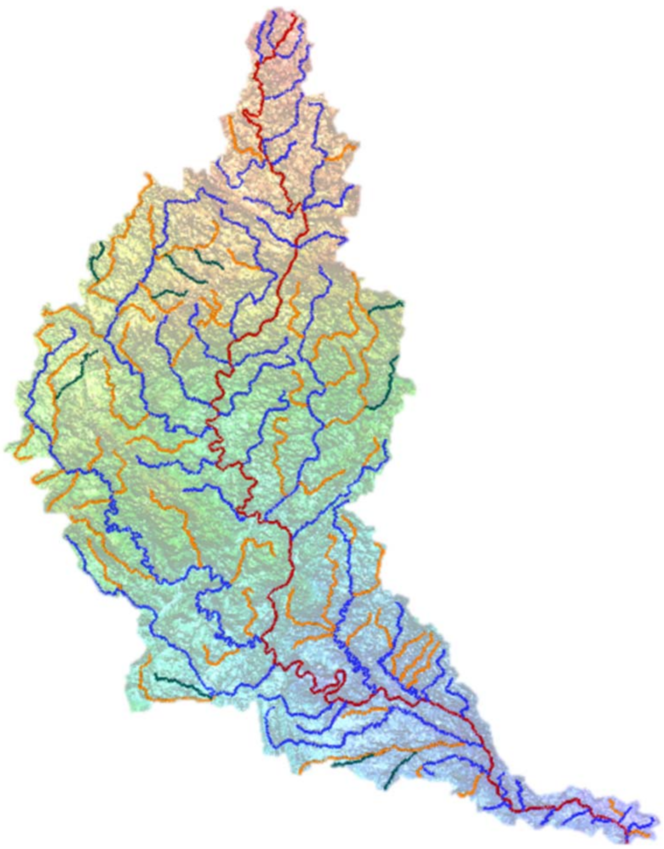
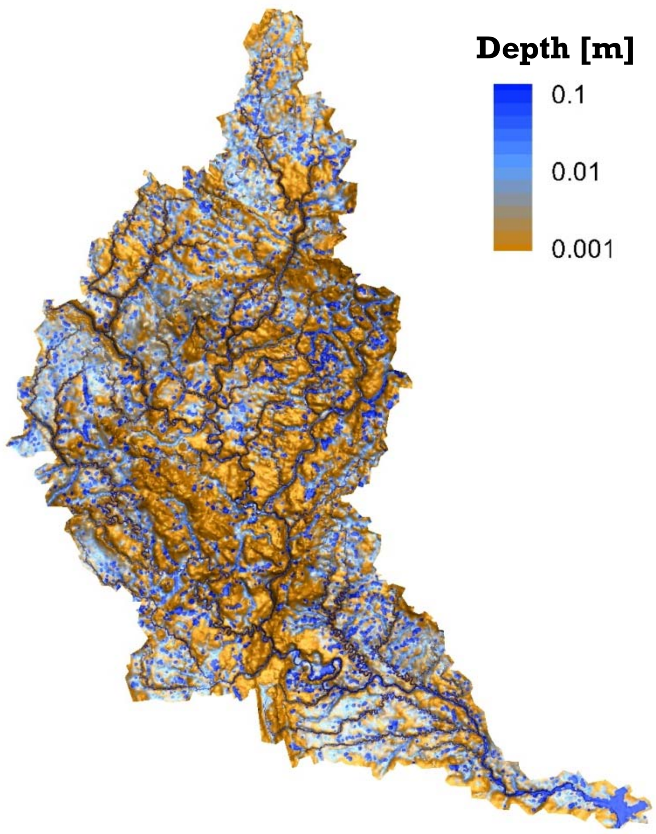
Steady-State Simulations: Historic Averages

Observed vs. Simulated Surface Drainage Network



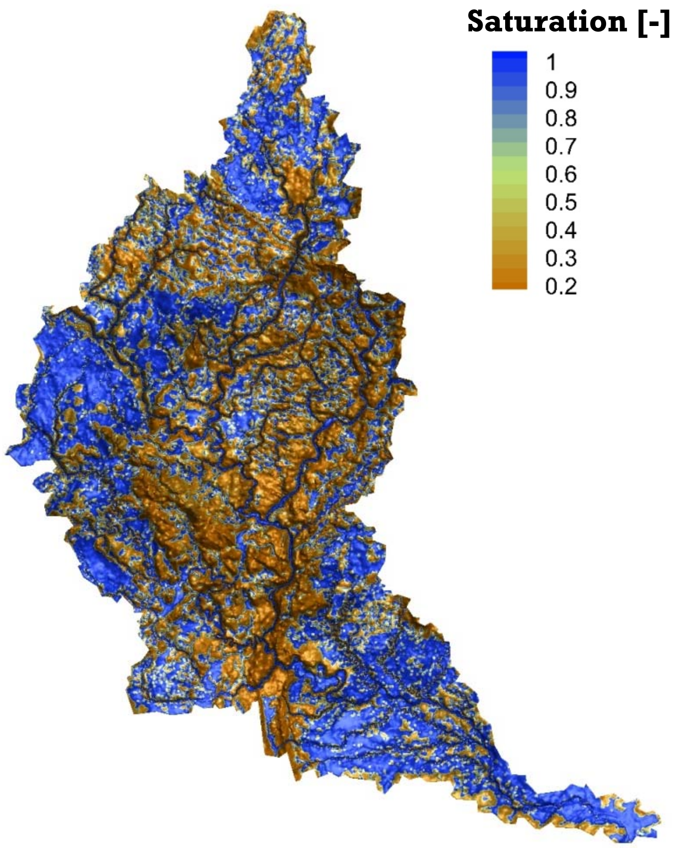
Observed Drainage Network



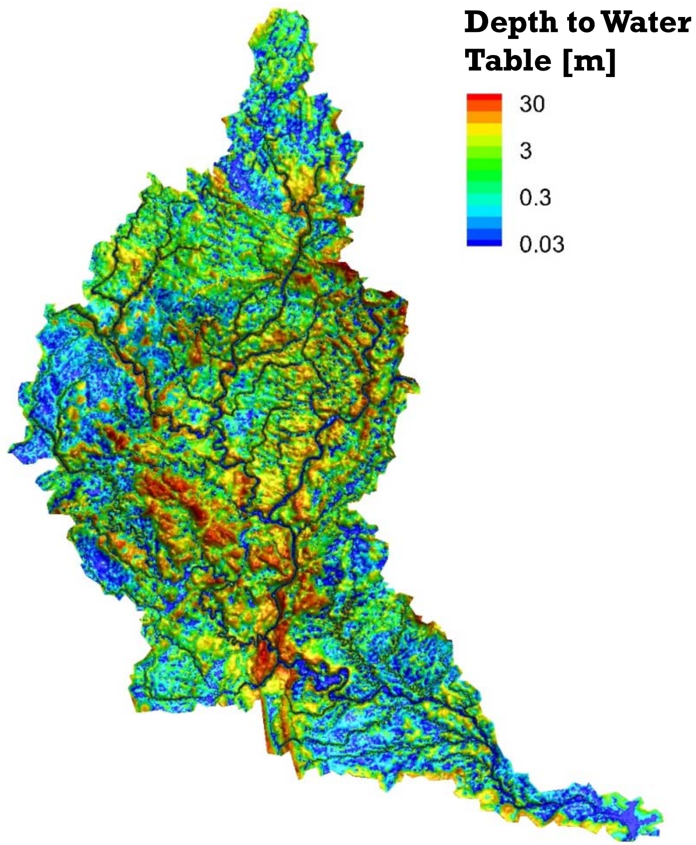
Simulated Surface Water Depth

Steady-State Simulations: Historic Averages

Subsurface Saturation and Depth to GW Table Distributions



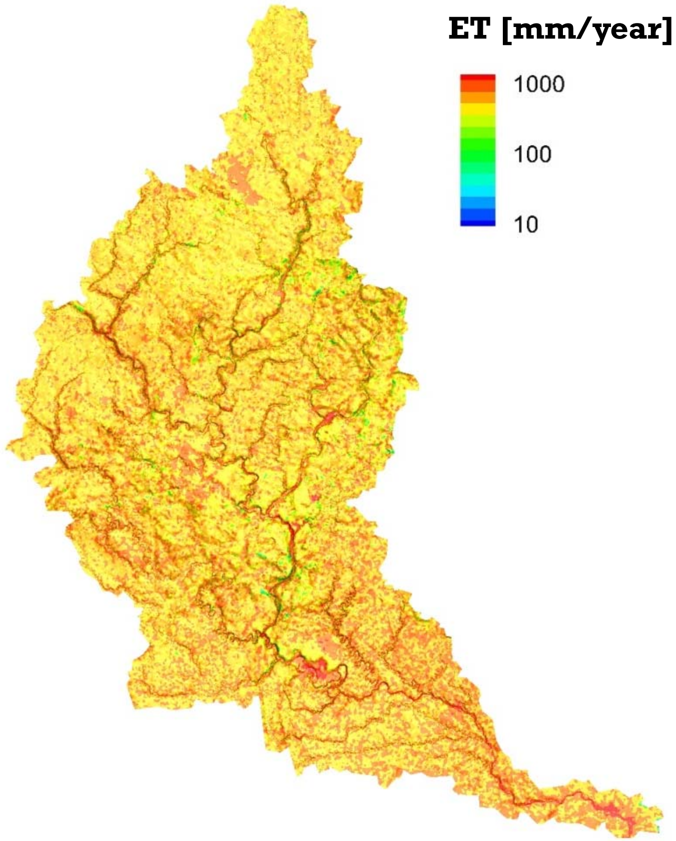
Soil Saturation



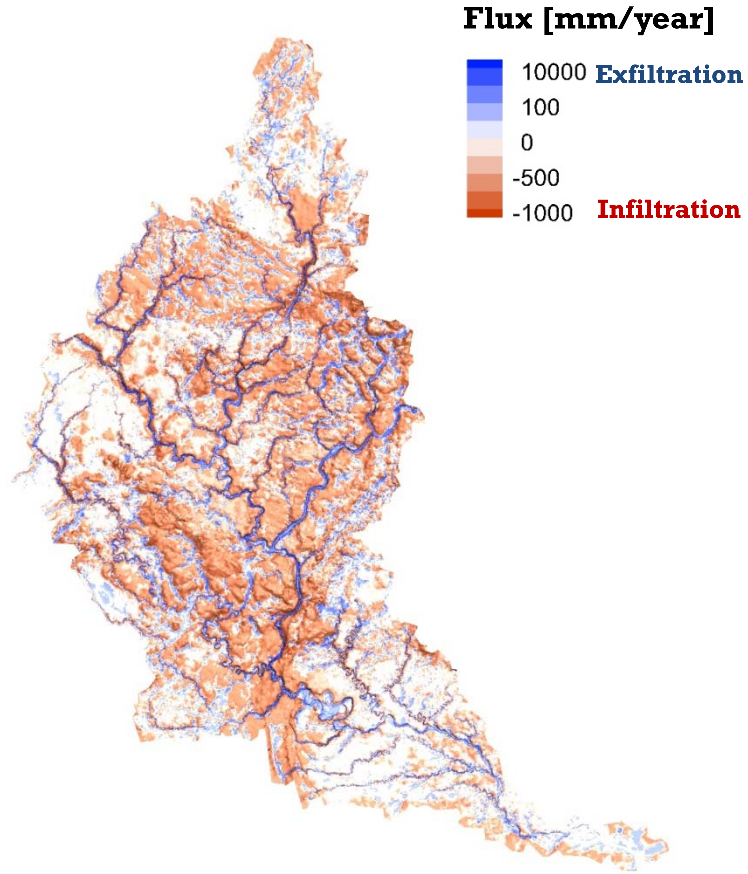
Depth to GW Table

Steady-State Simulations: Historic Averages

Evapotranspiration and Exchange Flux Distributions



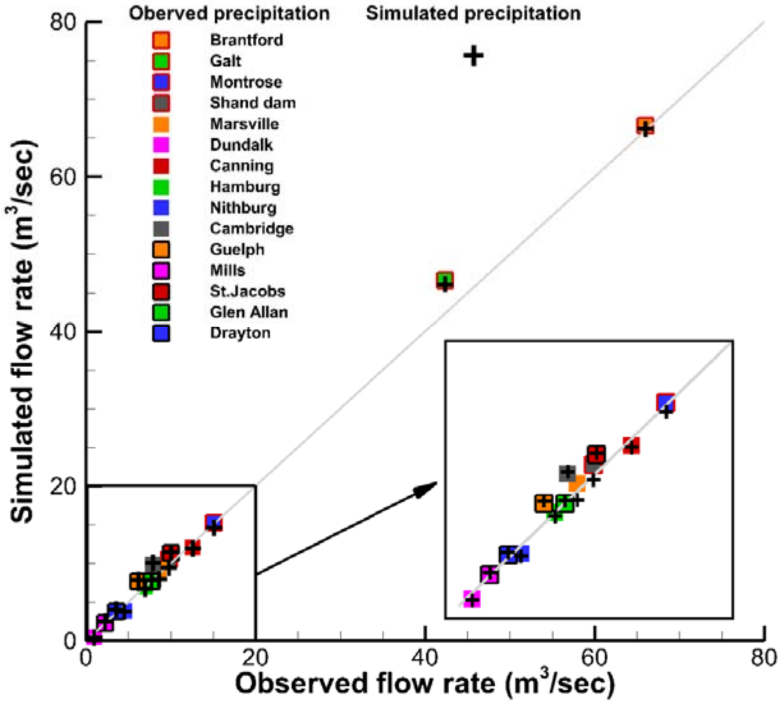
Evapo-Transpiration Flux



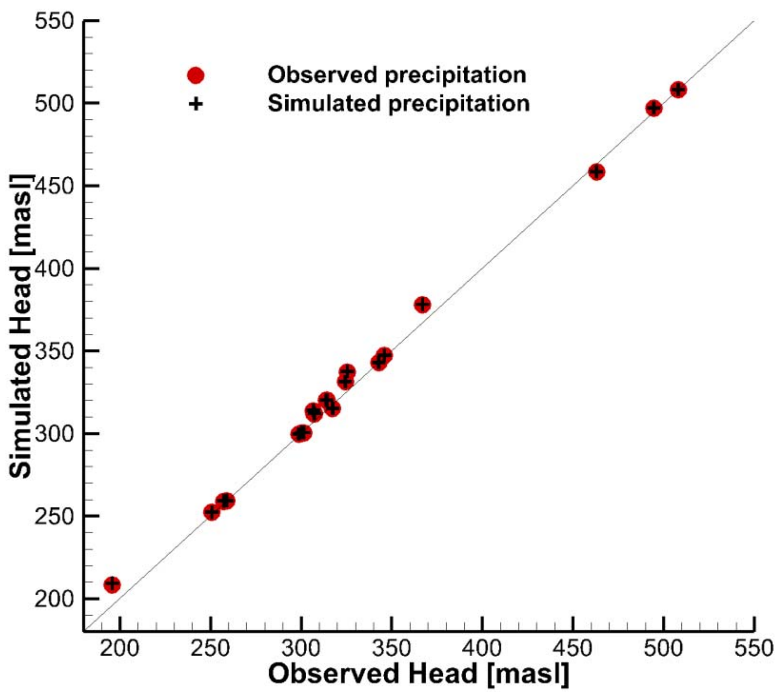
Surface-Subsurface Exchange Flux

Steady-State Simulations: Historic Averages

Observed vs. Simulated: Stream Flow and GW Head



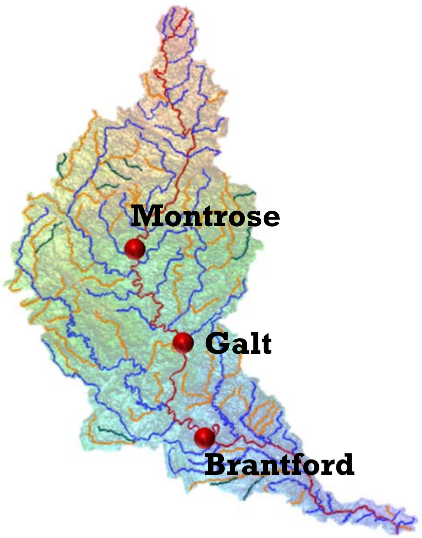
Observed vs. Simulated Stream Flow

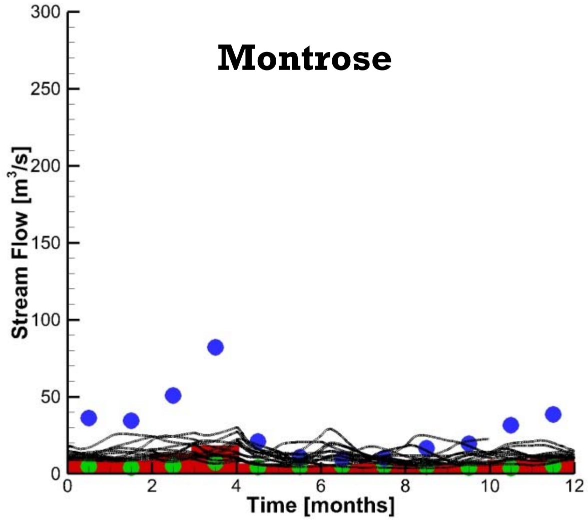


Observed vs. Simulated GW Head

Historic Transient Simulations

Observed vs. Simulated Stream Flow

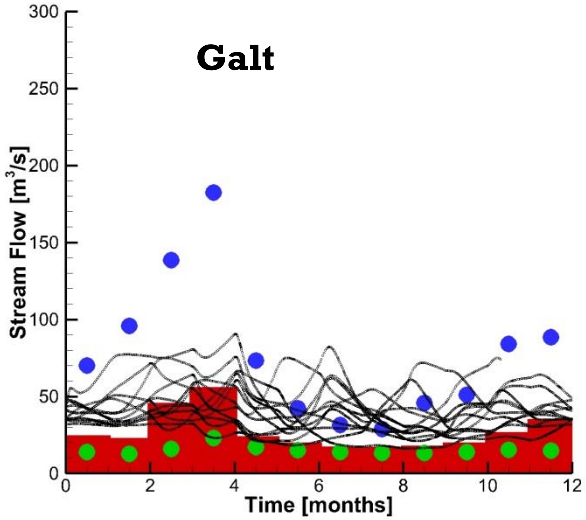


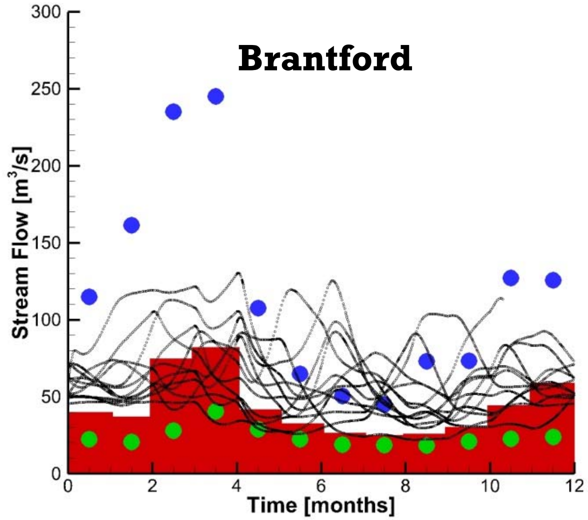


Observed Flow

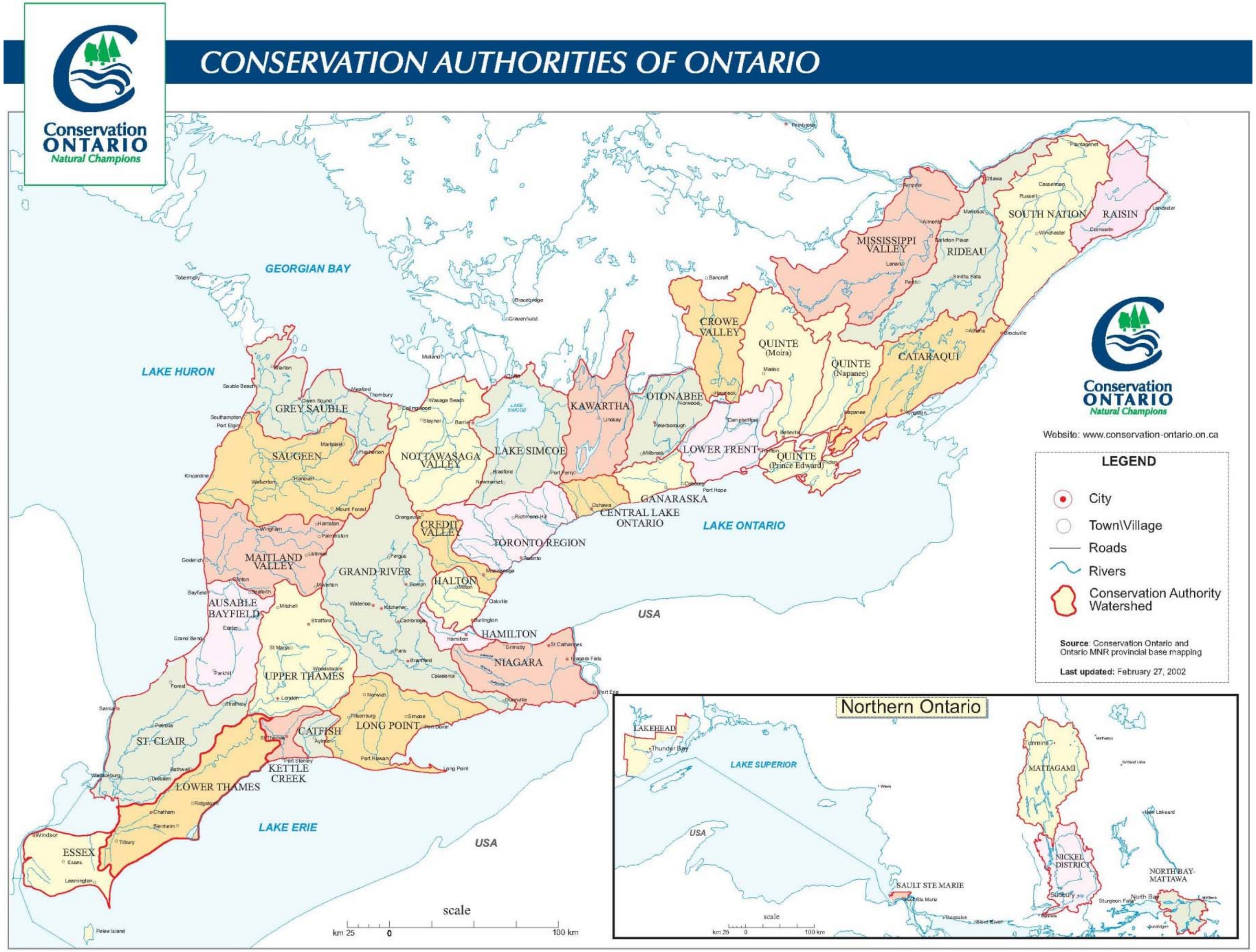
- Median
- 10th percentile
- 90th percentile

Simulated Monthly Flow





Next Step: Cover Ontario's Watersheds



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Integrated Models: Our Lessons from Experience

- Integrated models showing promise in characterizing hydrologic cycle processes at multiple scales in watersheds.
- Parameterization: There is always “missing” data.
- Computational challenges remain, but with modern numerical solution methods, parallel computing & HPC’s, there is optimism for handling very large complex systems.
- Fully integrated solution is robust and provides a holistic view of water, contaminant & heat transport .