Government of Alberta Hydrology Community of Practice Annual Conference
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Applications of the Raven Hydrologic Modelling Framework within Western Canada

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Today

- Hydrologic modelling: a Primer
- What is Raven?
- Some applications of Raven in Western Canada
- Recent advances and augmentations
- What's next?

Hydrologic Simulation Models: Goals

Forecasting
- short & long term forecasting of floods or inflows to a reservoir

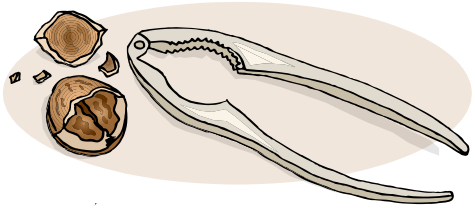
Design
- Determination of design floods (peaks and hydrographs) from design storms
- Assessment of system reliability (reservoirs, water supplies)

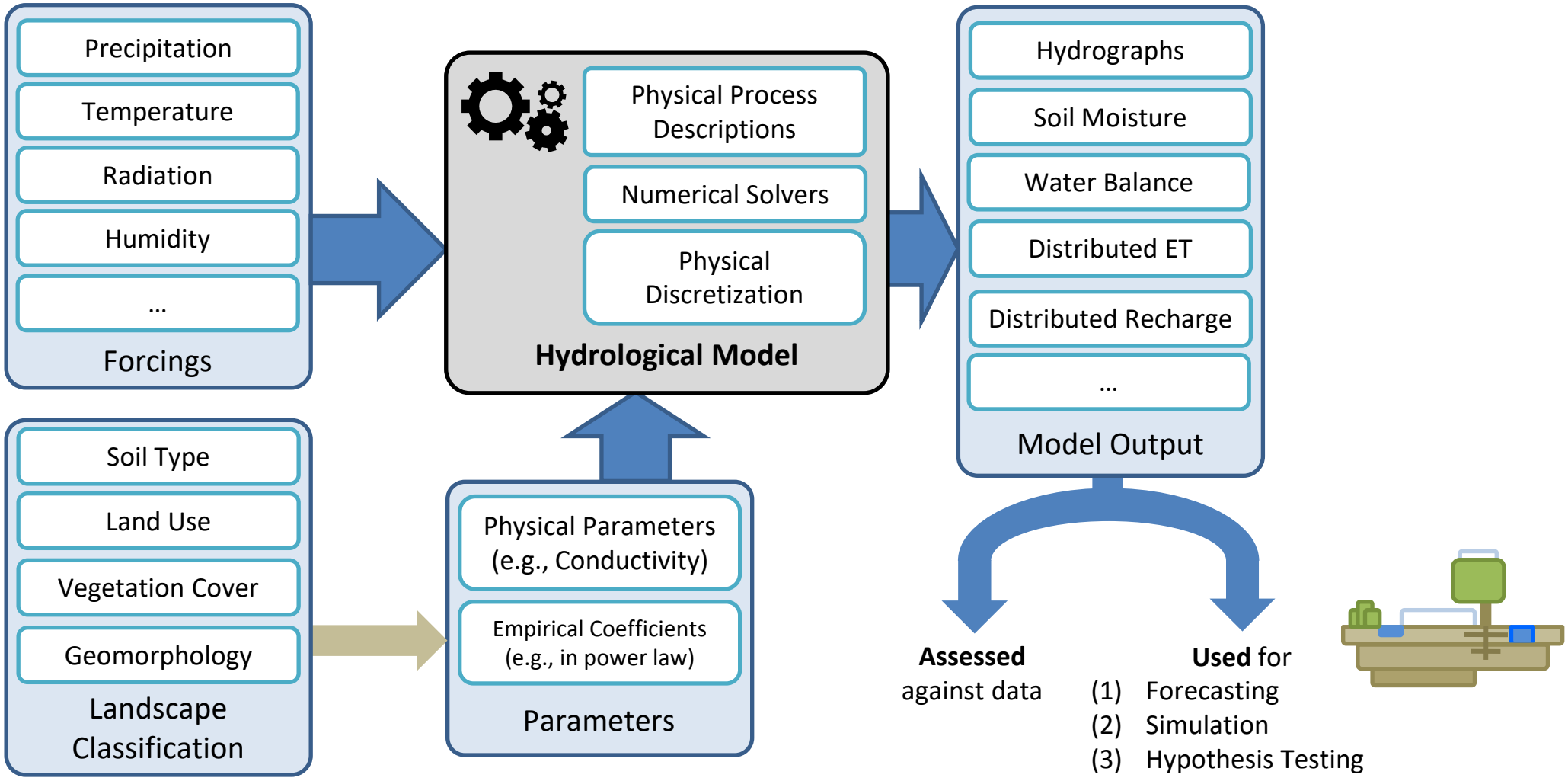
Simulation / Scenario analysis – ‘what if?’ questions
- Understanding potential impacts of land use/climate change/wildfire
- Estimating impacts of future policy or operational choices

Understanding / Hypothesis testing
- Attempting to understand/untangle causality in complex systems
- Used to confirm (or reject) conceptual models about how the world works

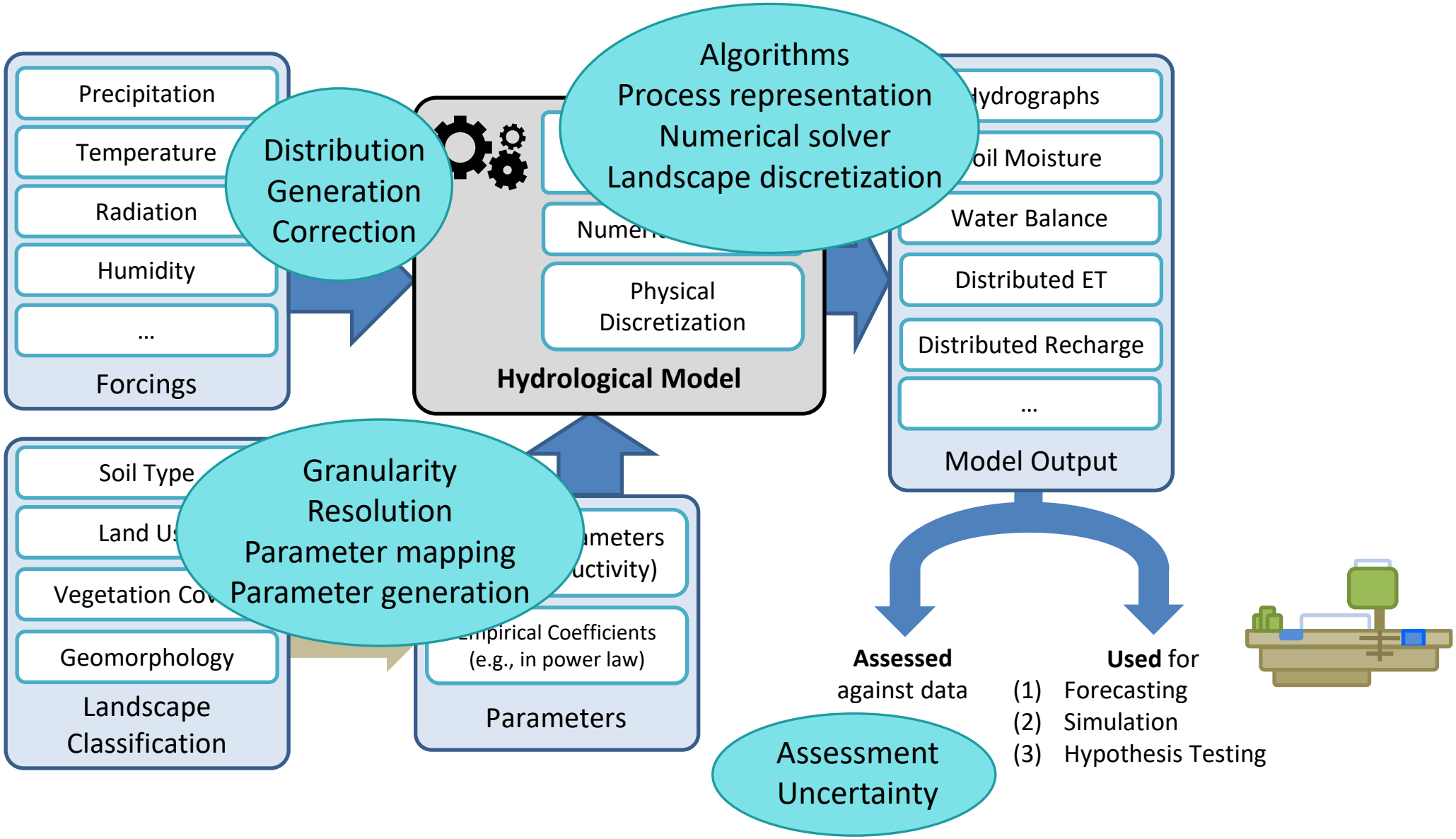
Wide variety of models used to these ends

Hydrological Models in a Nutshell





Why modelling is difficult…



the Raven framework

Hydrological modelling framework designed for

- **Research**:
  - Investigating impacts of model choices on model quality
  - Development and testing of new modelling techniques
- **Operational Use**:
  - *Flexible/Nimble* means of simulating flow and transport in both simple and complex watershed systems
  - Highly optimized open-source code; readily scripted
  - Distributed modelling with reservoirs, lakes, water management
  - netCDF integration with Delft-FEWS
  - Used by several Canadian forecasting organizations
- **Educational Use:**
  - Flexible: experimentation-based, stepwise approach to modelling encouraged
  - Rigorous QA/QC on inputs

Ultimately intended to improve our ability to develop trustworthy models for water resources management

Craig, J.R., et al., *Flexible watershed simulation with the Raven hydrological modelling framework*, Environmental Modelling and Software, 129, 104728, doi:10.1016/j.envsoft.2020.104728, July 2020

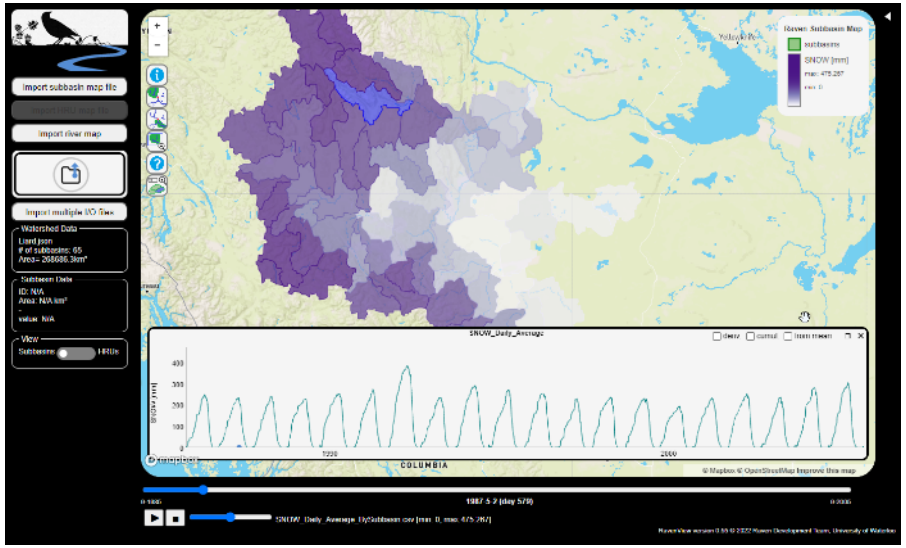
What makes Raven different?

Open-source (Artistic License 2.0)
- Object-oriented C++

Platform independent (Windows/Linux/Unix/MacOS)

Extremely flexible (*unique*)
- Extensive library of options available for
  - estimating precipitation/radiation/humidity/potential melt/etc.
  - interpolating gauge data
  - simulating evaporation/infiltration/snowmelt/routing/etc.
  - discretizing the watershed

- Any parameter may be temporally, spatially variable
- Different process algorithms can be conditionally applied



Emulation capabilities (*nearly unheard of*)
- Raven is NOT ONE MODEL
- Level 1 (exact) Emulation: UBC Watershed Model, HBV-EC, HBV-Light, GR4J, MOHYSE, HMETS, HYPR, HYMOD, SAC-SMA
- Level 2 (conceptual) Implements some algorithms and submodels seen in existing models (VIC/ARNO, Brook90, PRMS, SWAT, …)

User-friendly
- Robust error checking, user-friendly & intuitive I/O, custom output options, etc.
- Extensive community of practice and growing software ecosystem

Design Philosophies

A hydrological model should not be handicapped by built-in assumptions

- Maximize flexibility and user control
- Provide room for future improvements

A useful model may need to be run thousands of times to learn from it

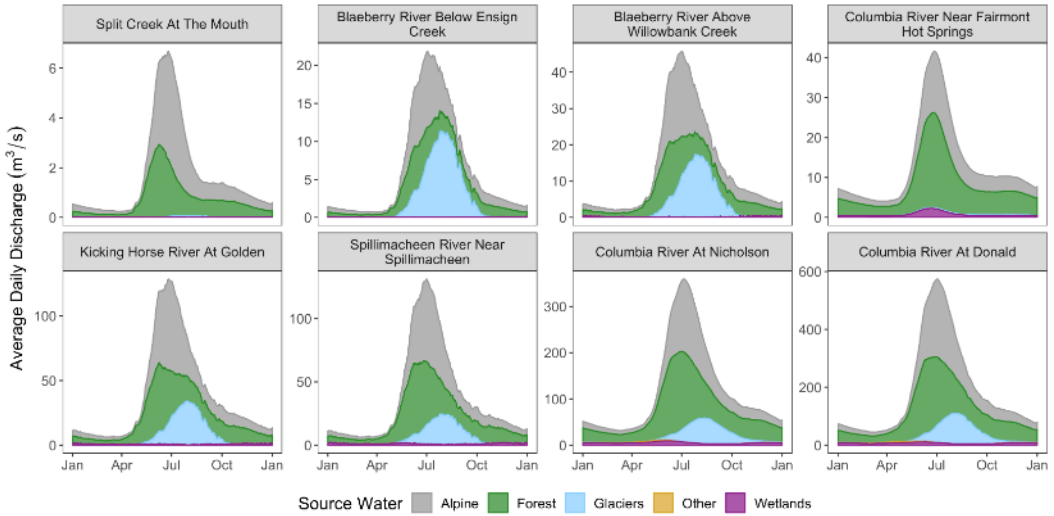
- Optimize performance (Raven is really fast) and stability
- Support use for calibration, uncertainty analysis, sensitivity analysis
- You can learn more by running a 1-minute model 600 times than a 10-hour model once

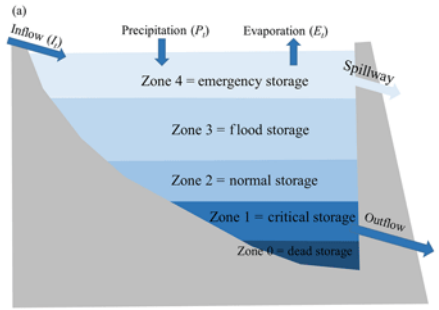
A model should provide the right results for the right reasons

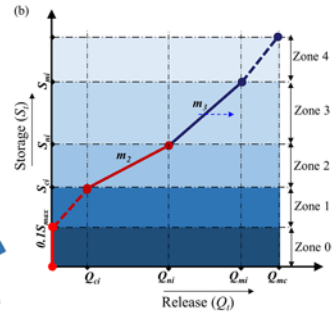
- Supports testing of conceptual models
- Encourage stepwise modelling: user-specified complexity justified by data availability

Some Special Features

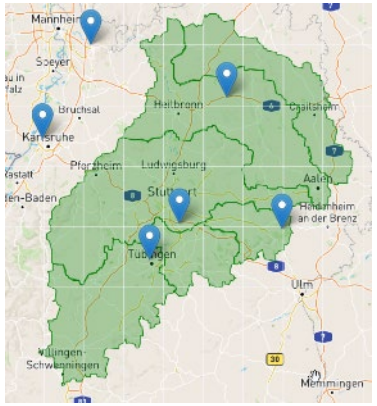
- Synthetic tracer transport
- Explicit handling of land cover change
- Extensive lake/reservoir treatment
- Prairie pothole-specific submodels
- Supports mixed gridded / station climate data

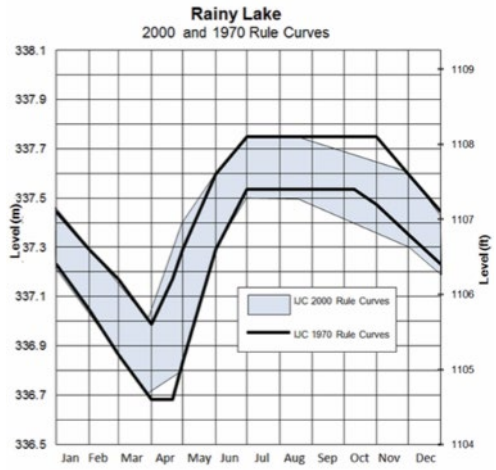


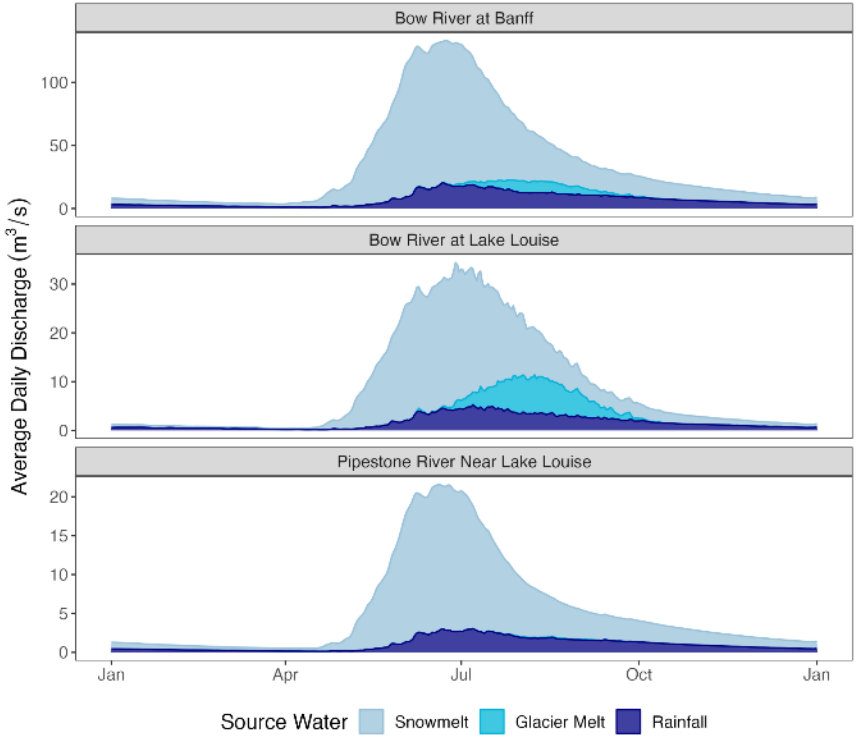




From Yassin et al., 2019

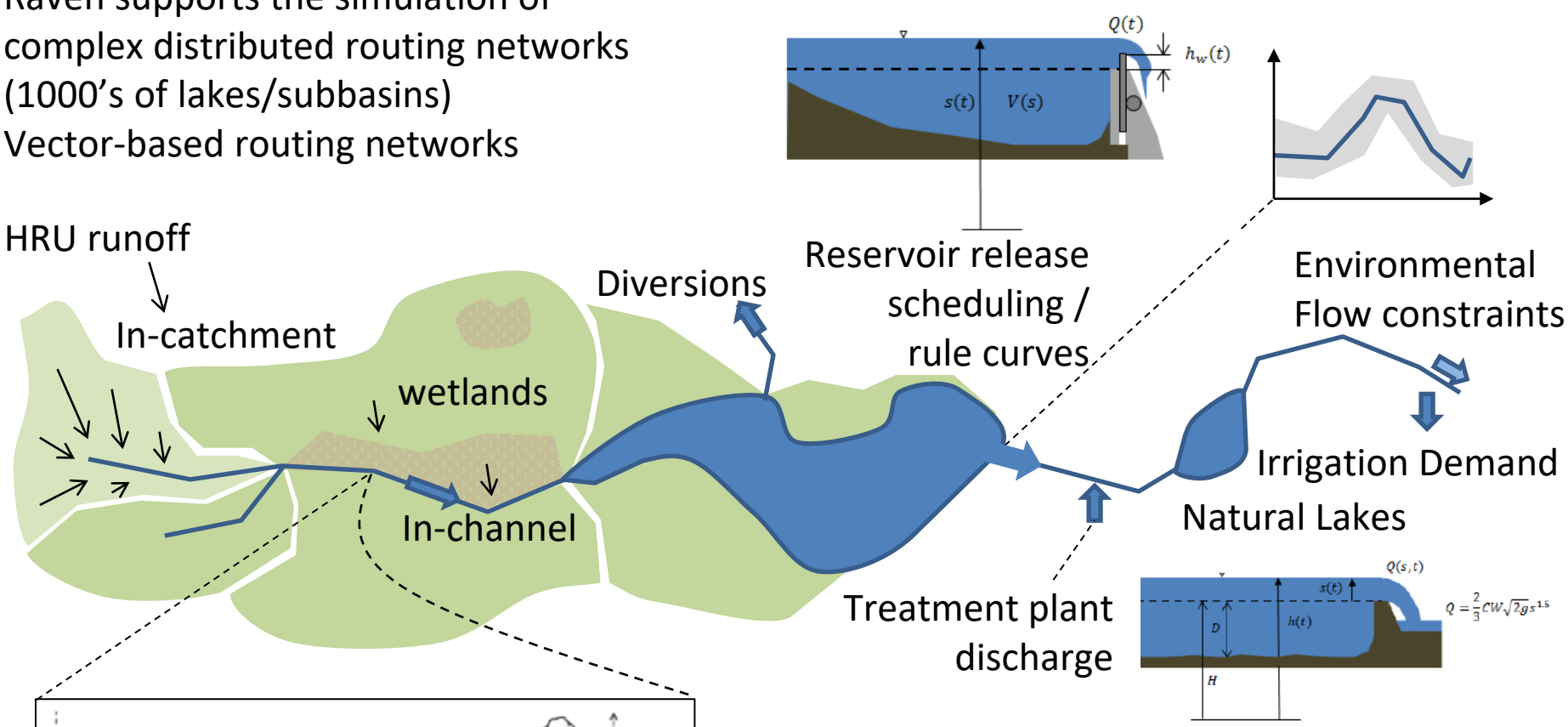


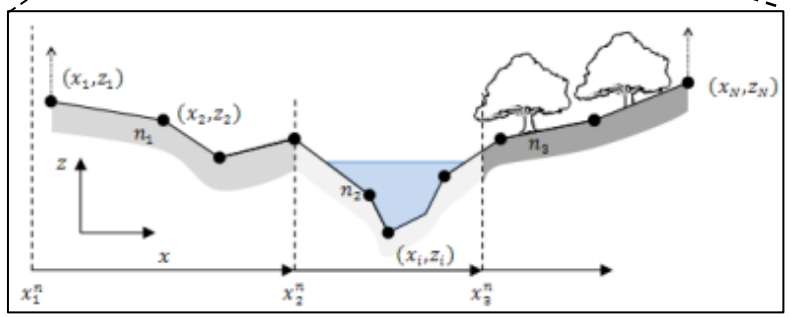




Routing and Water Management Support

Raven supports the simulation of complex distributed routing networks (1000's of lakes/subbasins)
Vector-based routing networks

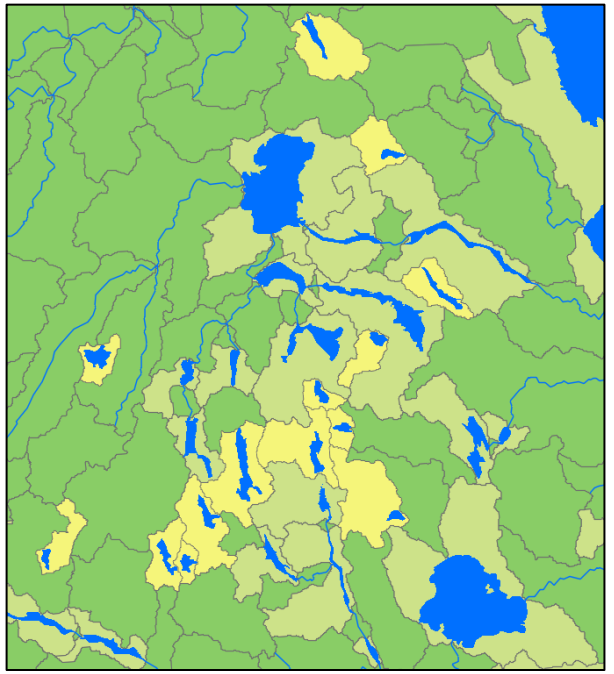




various control structures with sophisticated generalized operational rules

Currently contracted to support global **water demand optimization** – implementing flow constraints and priority allocation of irrigation demand

Using linear programming optimization w/ constraints



Raven support

Raven is not only an academic research tool

Raven is used throughout Canada as an operational forecasting tool

- OPG, BC Hydro, TransAlta, NB Power | BC/AB/SK/NB provincial | Calgary/Montréal | NWT

Supports modelling efforts of ON MNRF / ECCC / NRCan / Lake of the Woods / OBWB / PCIC

Multiple consultants using – hundreds of models across North America

- $16B 900 MW Site C dam; $8B Trans Mountain pipeline assessment; Athabasca River Basin stakeholder engagement model; Pipeline crossings across Canada

Case Studies

Forecasting

Water management

Climate change assessment

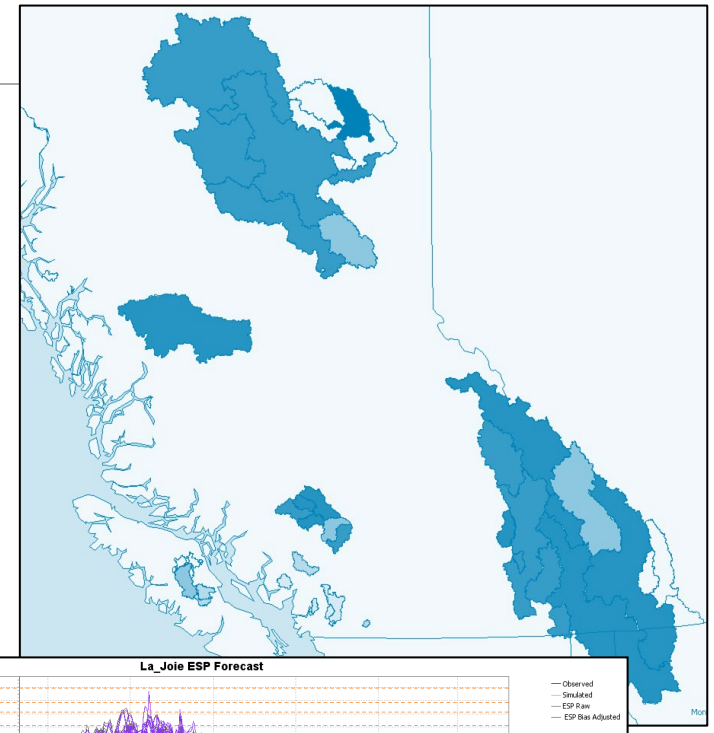
Forestry

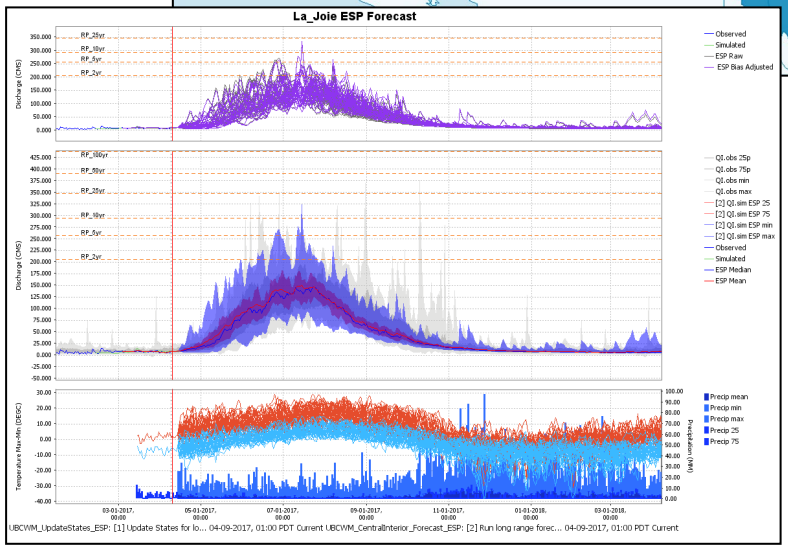
Application: BC Hydro Forecasting

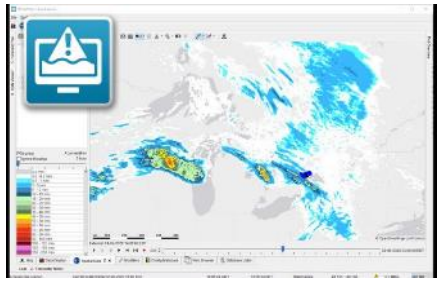
11,300 MW capacity
- 85% from Peace/Columbia

21 watersheds over a range of hydroclimates since 2015
- Short range deterministic / probabilistic forecasts
- Long range ensemble forecasts
- Climate change projection
- Dam safety
- Forecasts during construction work ($16B site C dam: predict 1:500 year flow exceedances for wettest September on record)

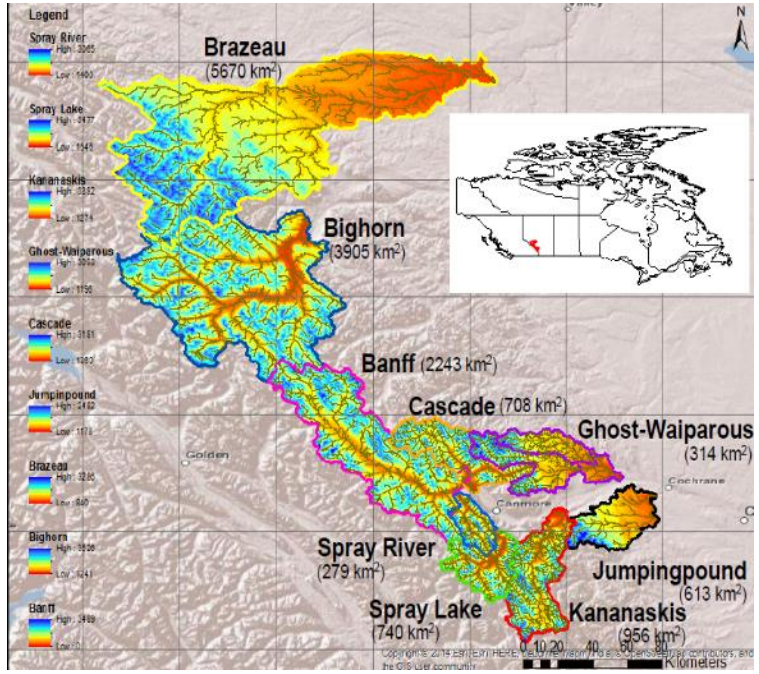
Fully integrated in Deltares Delft-FEWS system
- Raven directly interfaces with flood early warning system

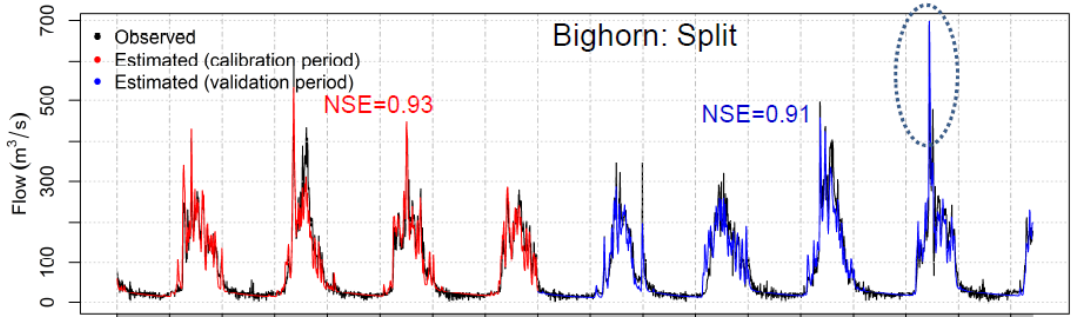


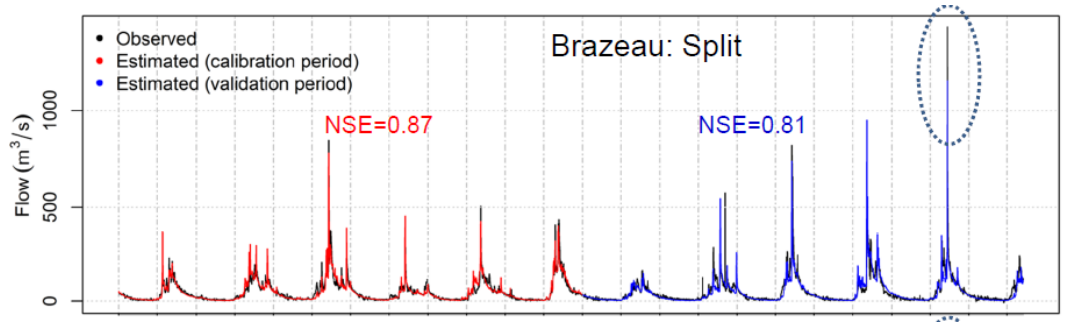


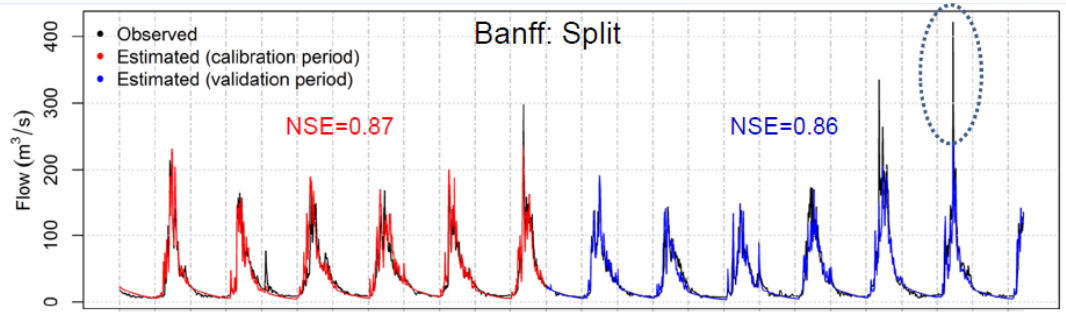


Application: TransAlta forecasting system







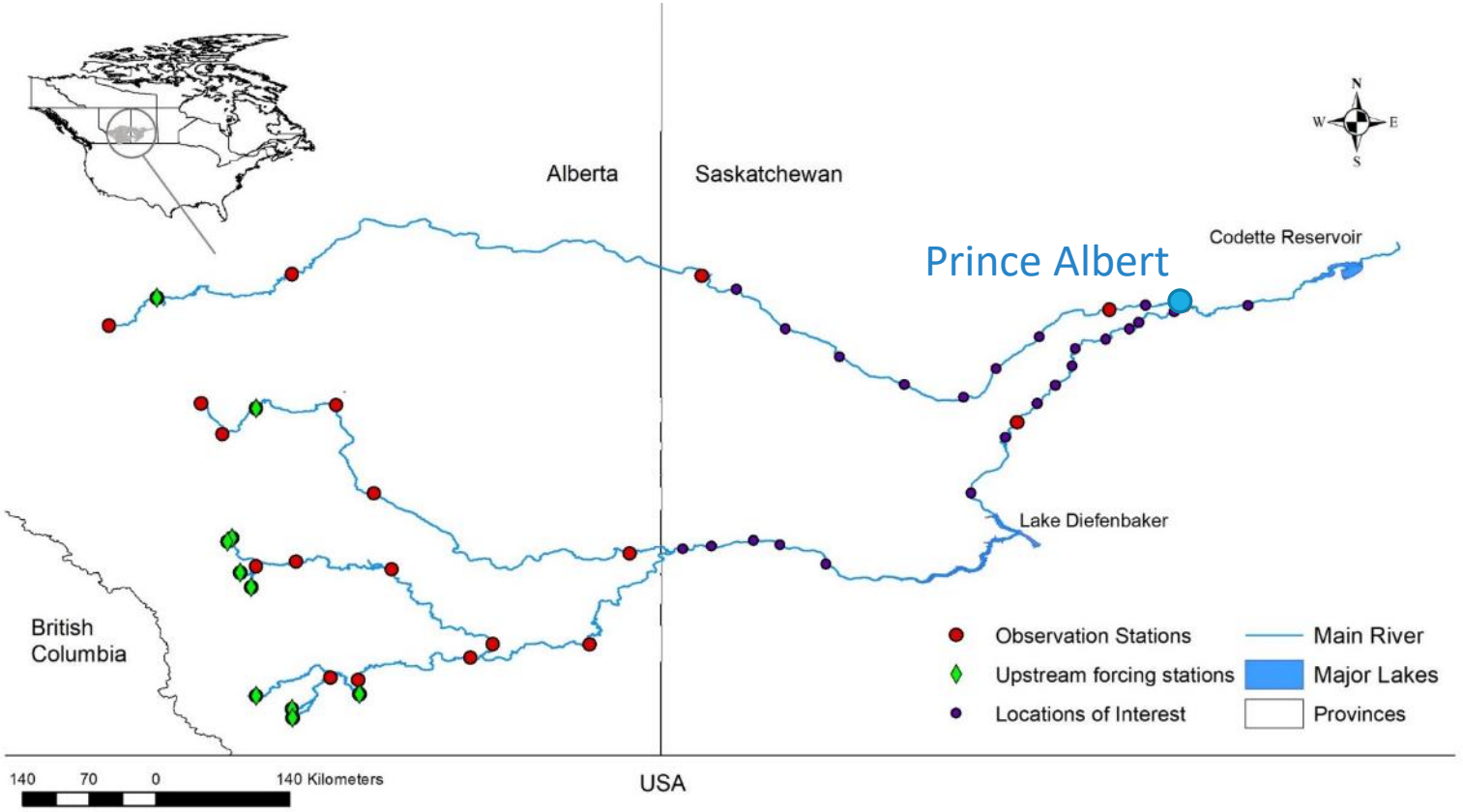


TransAlta™

NRC·CNRC Canada

heron hydrologic

Application: WSA Routing-only forecast model



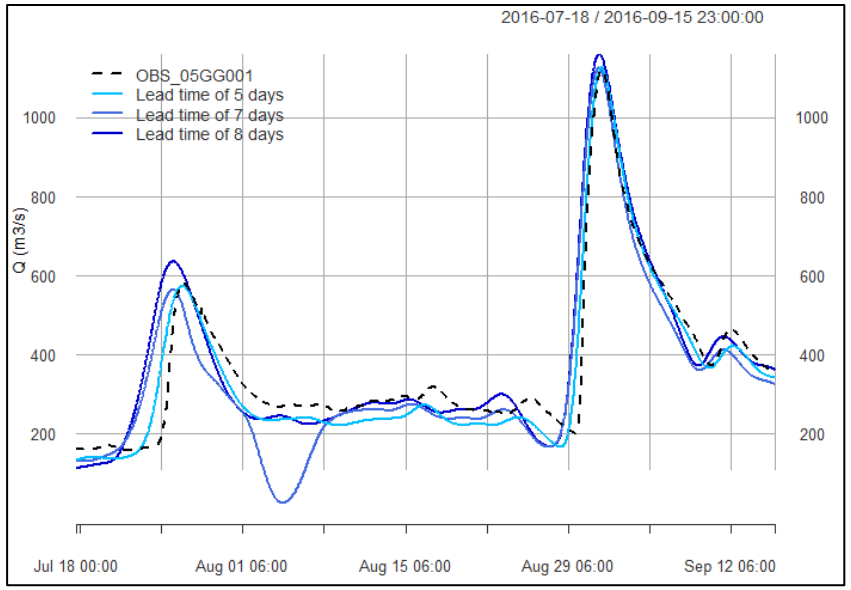


***Figure**: Simulated flows at different lead times at gauge D (05GG001)*

Application: Okanagan Basin Water Board

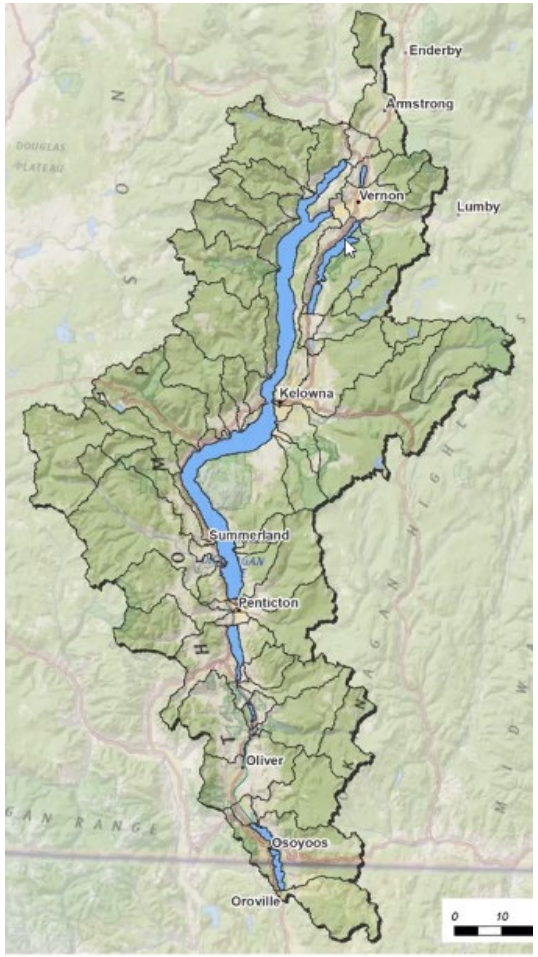
Used to

- Assess future susceptibility to climate change
  - Run several climate scenarios at 500m forcing resolution; 84 WSC gauges
- Evaluate operation strategies to reduce lakeshore flooding

These projects with OBWB, AE, & NHC led to advances in Raven support for water management, now available to all:

- Irrigation demand with environmental minimum flow constraints
- Flow diversions
- Reservoir management linked to downstream demands
- Transient controls on reservoir outflow
- Optimized support for high-resolution climate grids

OBWB models currently most sophisticated Raven deployment with respect to direct management representation (model publicly available)



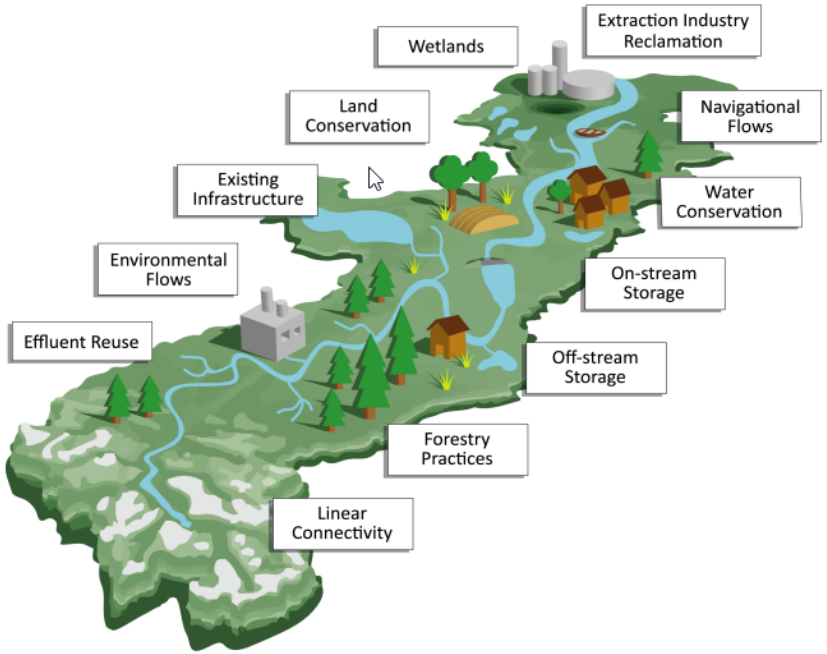
Athabasca River Basin:
Stakeholder engagement initiative

Raven coupled to OASIS water management model across 159,000 km^2 Athabasca River Basin (2017-2018)

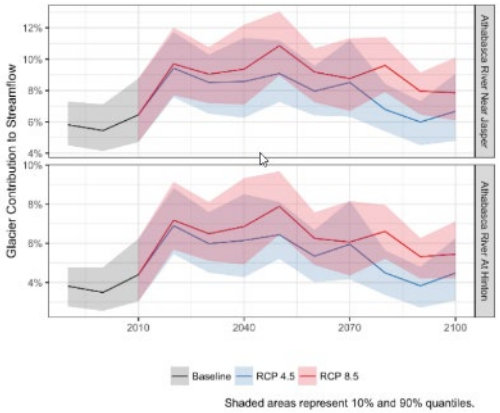
Real-time model scenario analysis with working group consisting of:

- First Nations and Métis communities
- Federal and Provincial Governments and related agencies
- Municipalities, Counties and Districts
- Watershed Planning and Advisory Councils (WPACs)
- Environmental non-government organizations (ENGOs)
- Industry (coal, agriculture, oil and gas, forestry, oil sands, utility companies)

Model results used to spur discussion on trade-offs of water management strategies



From watersmartsolutions.ca ARB initiative infographic



ALBERTA INNOVATES

ALBERTA watersMART Water Management Solutions

MacHydro

Application: the South Saskatchewan

Raven was again coupled to OASIS to inform the South Saskatchewan Reservoir Operations Model (SSROM)

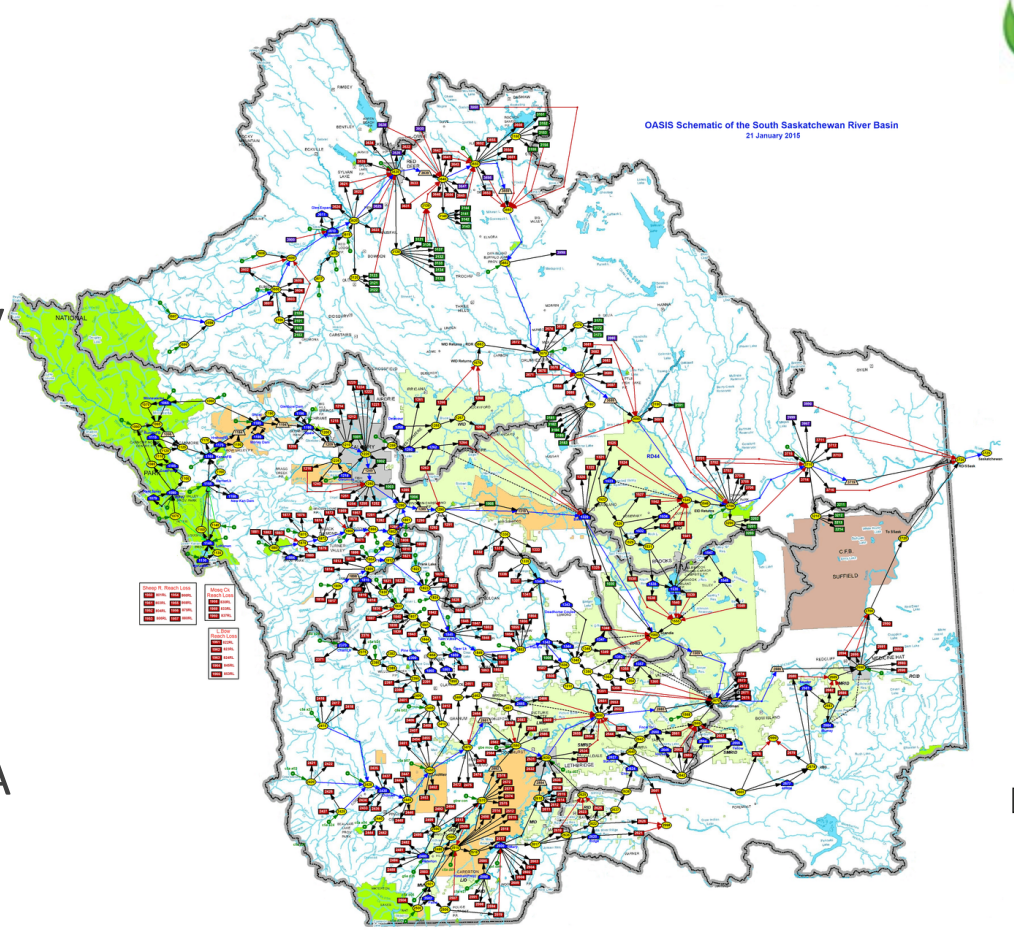
- supported by Alberta Agriculture and Rural Development, Prairies Can, the Alberta Irrigation Districts Association, and industry

Bow/Oldman/Red Deer

- 600 demand nodes
- 71 reservoirs

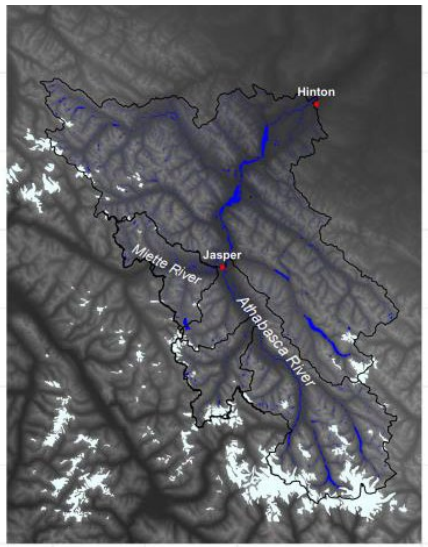
Developing a water management roadmap for the SSRB

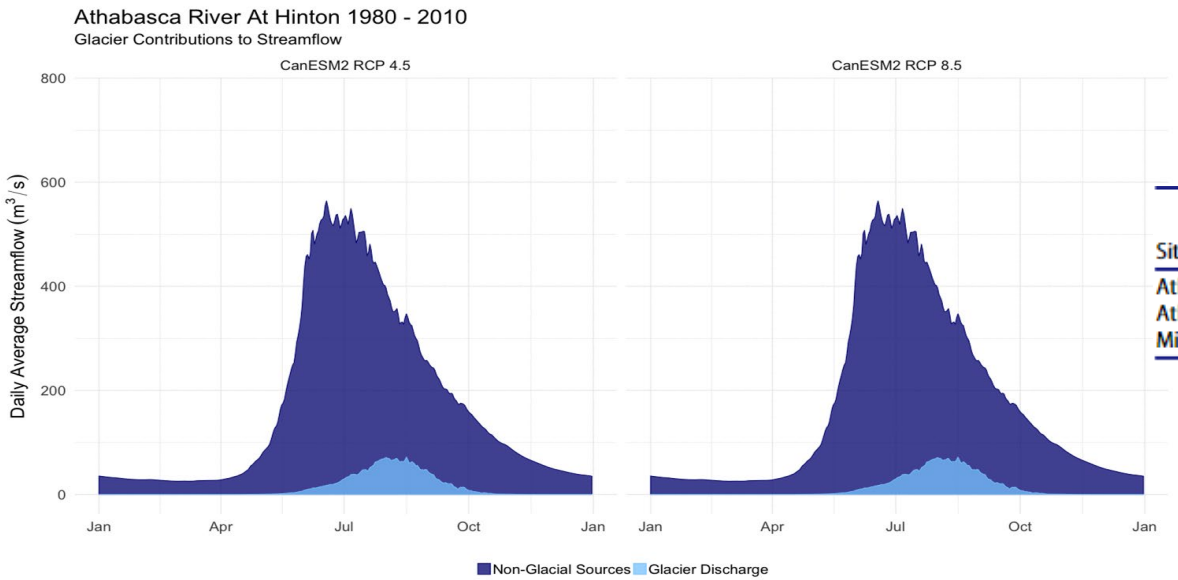
- 12 future climate scenarios provided by EPA
- Evaluating natural infrastructure options



from https://www.hazenandsawyer.com/

Application: Glacier Decline

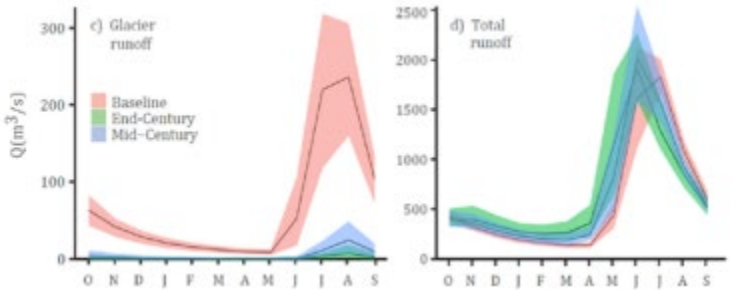




	Verification (22 years)	
Site	*NSE*	*PBIAS*
Athabasca River at Hinton	0.91	1%
Athabasca River near Jasper	0.93	−5%
Miette River near Jasper	0.86	2%

Chernos, M., R. MacDonald, M.W. Nemeth, and J.R. Craig, *Current and future projections of glacier contributions to streamflow in the Upper Athabasca River basin*, Canadian Water Resources Journal, 45, p324-344, 2020

Raven directly handles change from glacier-covered to open



From PCIC 2019-2020 corporate report

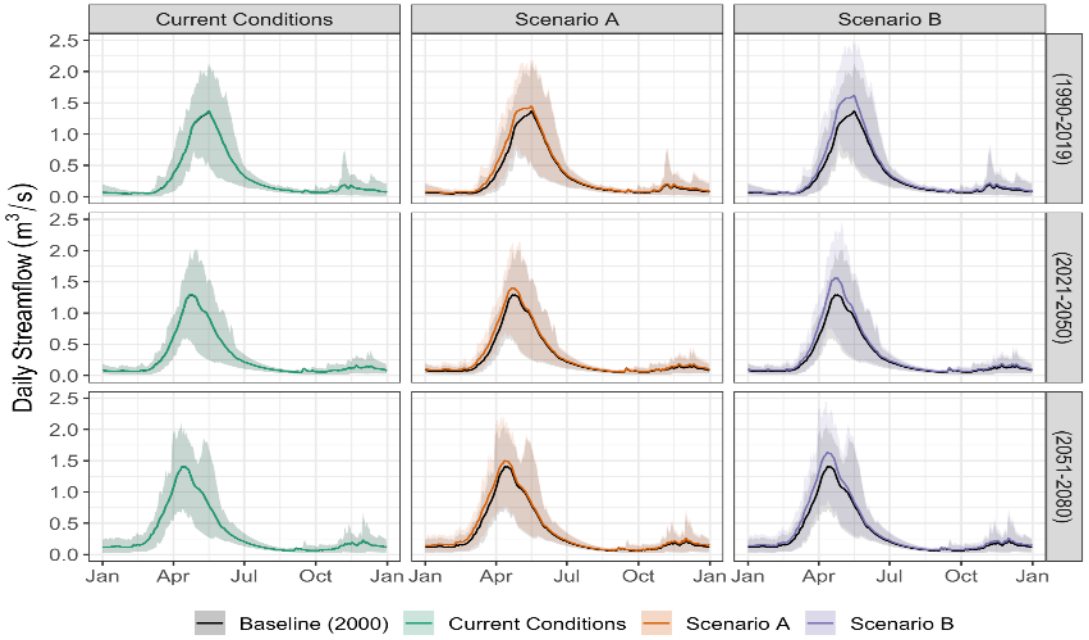
PCIC has coupled Raven directly to glacier mass balance model (the Regional Glacier Model)

Application: Oldman River

Raven can explicitly represent land use change

MacHydro has used this capability to examine impact of forest harvesting strategies in support of Alberta Agriculture and Forestry

- Similar work ongoing in BC, leveraging impressive historical cutblocks inventory



MacHydro

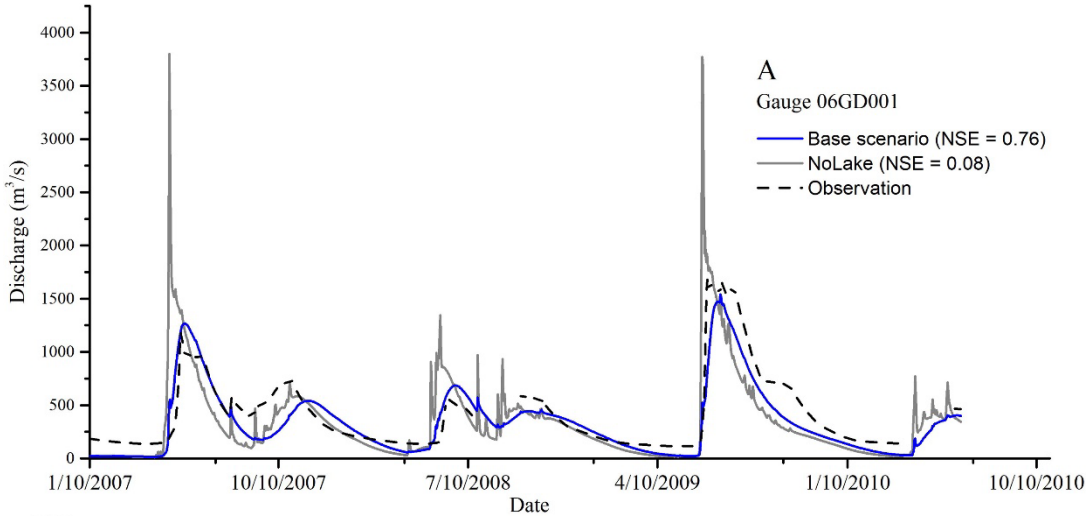
Application: Hudson Bay Routing

Image from: https://www.canada.ca/en/environment-climate-change/services/freshwater-quality-monitoring/hudson-bay-watershed.html

Using ECCC GEM-Surf outputs
(surface runoff, lateral flow, and drainage)

- Aggregated to a 0.5° resolution (~50 km)
- Hourly time step
- Explicit simulation of 15,000+ lakes and 26,000+ subbasins

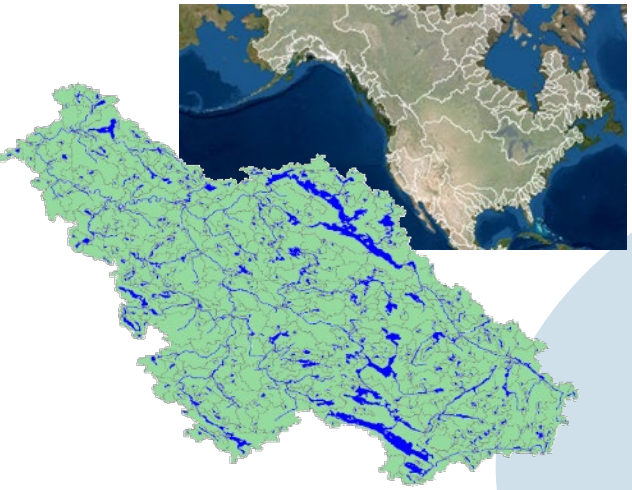
Demonstrated positive influence of inclusion of lakes at massive scales



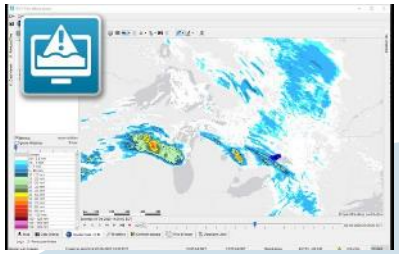
Han, M., J. Mai, B.A. Tolson, J.R. Craig, É. Gaborit, H. Liu, and K. Lee, *Subwatershed-based lake and river routing products for hydrologic and land surface models applied over Canada*, Canadian Water Resources Journal, doi:10.1080/07011784.2020.1772116, 2020

3.8 million km^2 – 17 minutes/1 year simulation at hourly time step

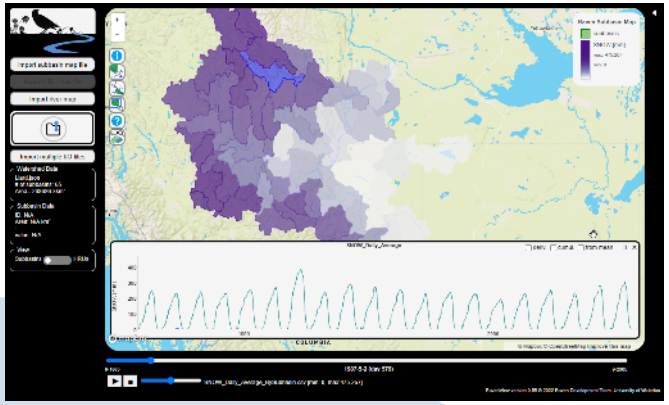
the Raven Ecosystem



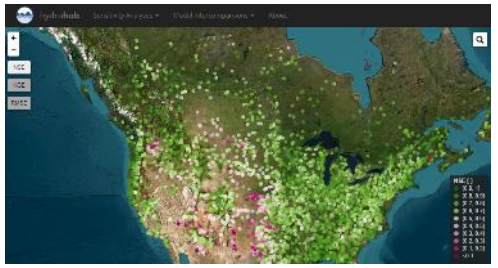
BasinMaker
lake-river discretization toolkit



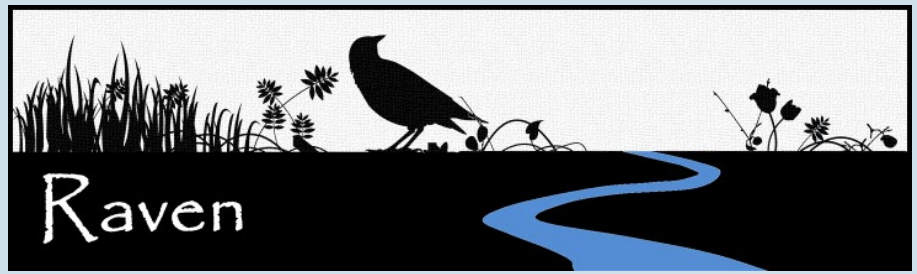
Delft FEWS
flood and early warning system



RavenView
online output visualization

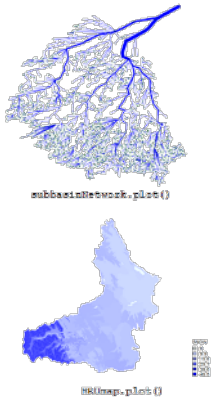


HydroHub
model download & intercomparison

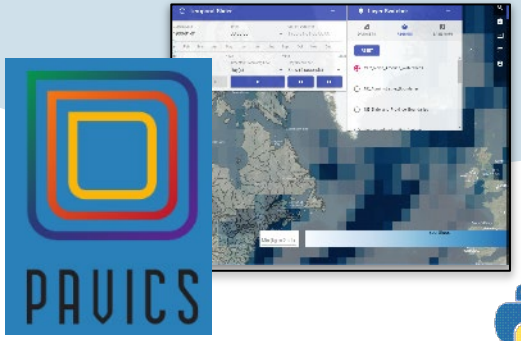


Raven Thermal Model
stream/lake temperature simulation

QRaven
QGIS plugin



RavenR
hydrologic analysis library

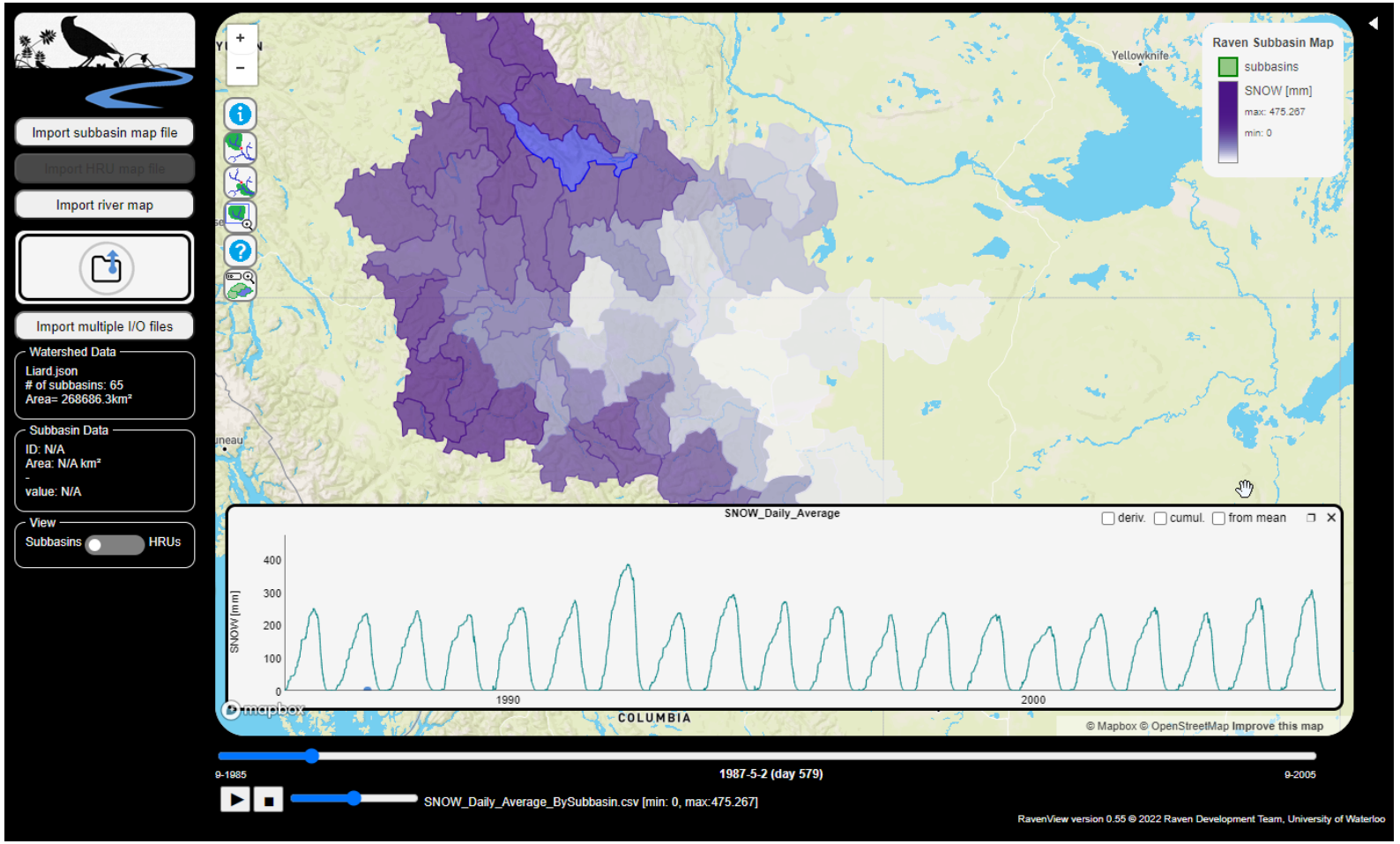


PAVICS-Hydro / RavenPy
climate analysis and visualization (w/Ouranos)

Robin Vegetation Growth Library
wildfire/forestry disturbance impacts

Magpie
Google colab workflow

the Raven Software Ecosystem: RavenView



Visualization of all model outputs via drag-and-drop interface

- Basin connectivity tracking
- Time series plots
- Flow duration curves
- Day-of-year quantile plots
- Animated state maps
- Diagnostics tables
- Land cover mapping

http://raven.uwaterloo.ca/RavenView/RavenView.html

Canadian Lake and River Hydrofabric (CLRH)

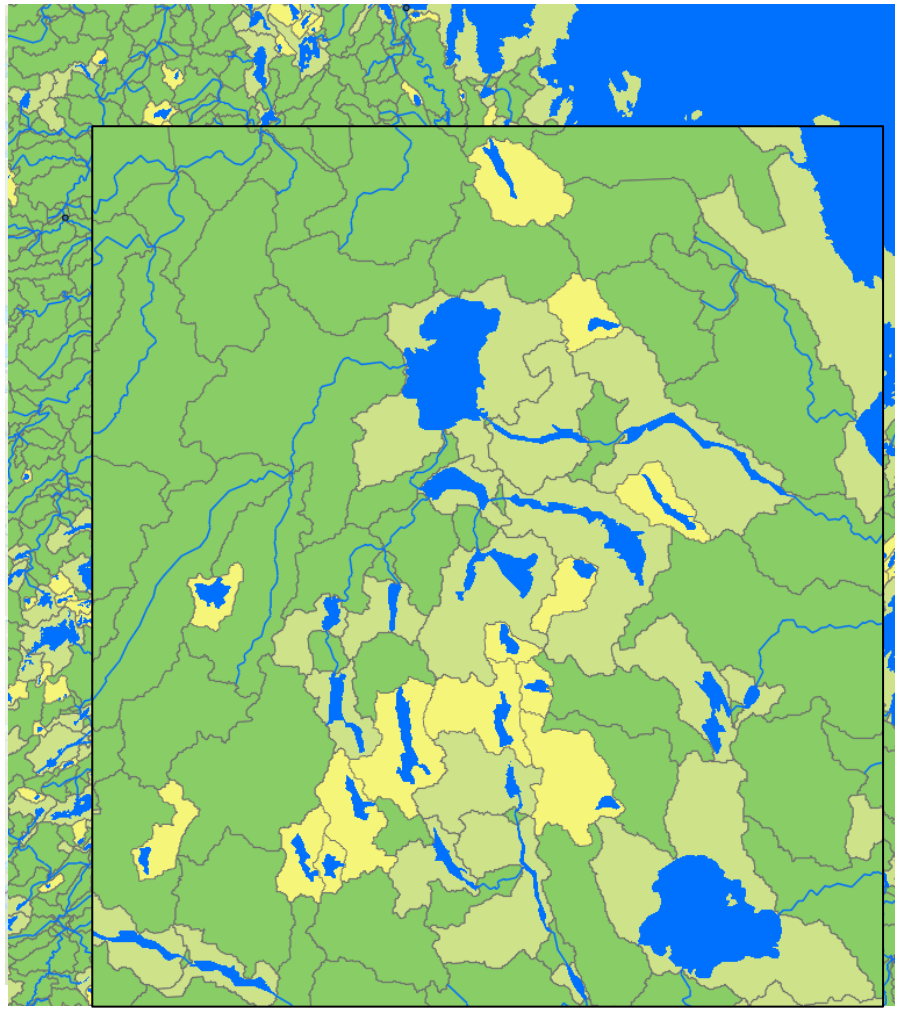
Pan-Canadian multi-scale routing product developed at UW from HydroLakes (Messager et al., 2016) and ECCC National Hydrometric Network basin Polygons v2 geospatial dataset

- Based upon newly developed 30m DEM and hydrologically conditioned flow direction raster (adjusted to conform to National Hydrometric Network (NHN) river network)
- Estimates of 14 catchment, channel, and lake property estimates (e.g., bankfull width, lake crest width, depths, etc…)

Leverages UW toolkit (BasinMaker) for generating subbasin delineations of watersheds which include lakes

Readily downloadable; BasinMaker can convert directly to Raven input files

http://hydrology.uwaterloo.ca/CLRH/Hydrofabric.html



Recent Advances: Raven-Robin Coupling:

Coupled Simulation of Vegetation Growth

inputs

Precipitation
Air temperature
Radiation
Humidity

simulates

Water storage
- Soil moisture
- Depression storage
- Channel/Lake storage
- Snowpack, etc.

Energy/Temperature
Streamflow
Water fluxes

impacts

Evapotranspiration
Sub-canopy radiation
Canopy interception

provides

<Soil moisture>
Atmospheric forcings
PET and AET

impacts

Water availability
Energy availability

simulates

Vegetation characteristics
- Biomass (leaf, stem, root, seed)
- LAI, SLA, Height
- Basal area, DBH, standing volume
- Root depth, etc.

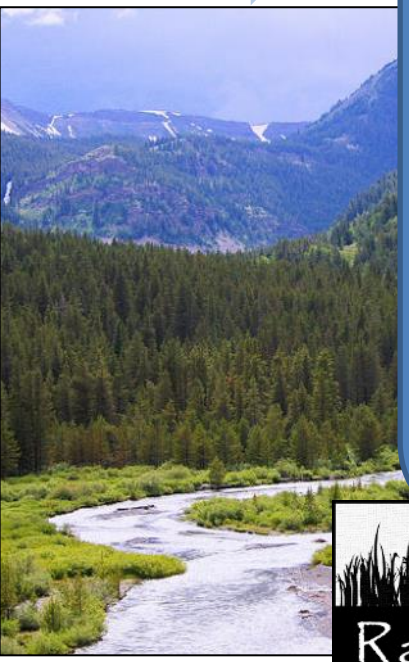
Nutrient demand/stress

provides

LAI, height, SLA
<Root depth>
<Vegetation cover>
PET corrections

inputs

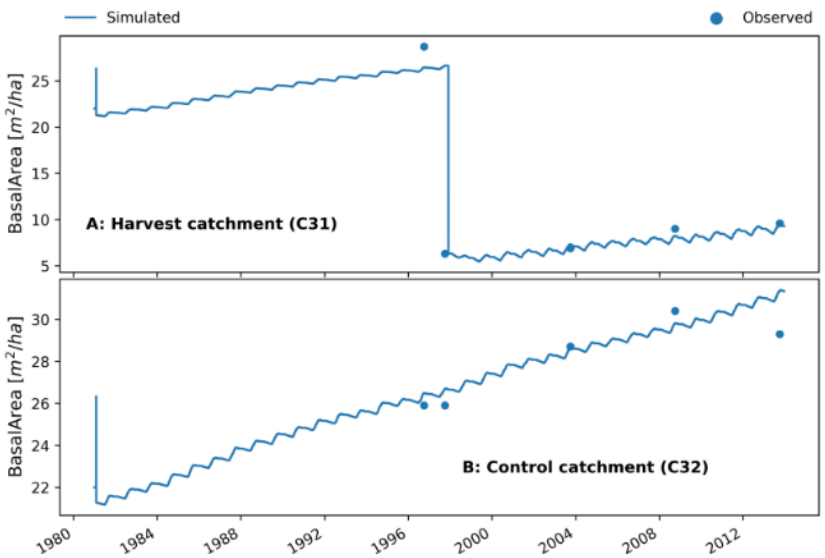
Harvesting schedule
Rotation
Management

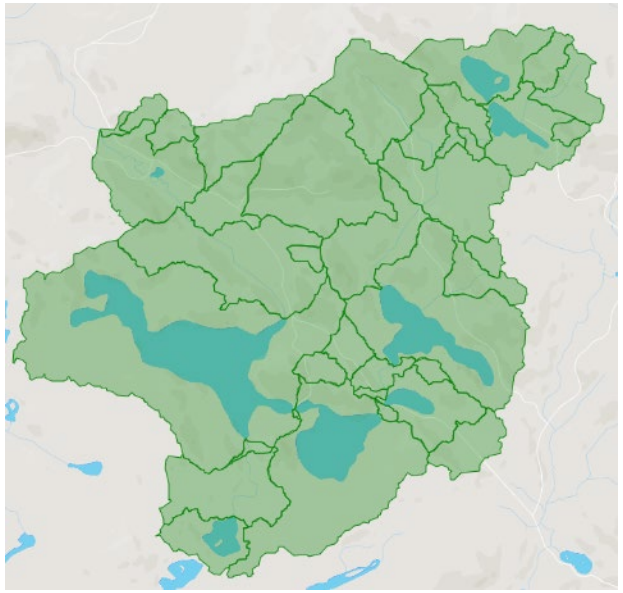


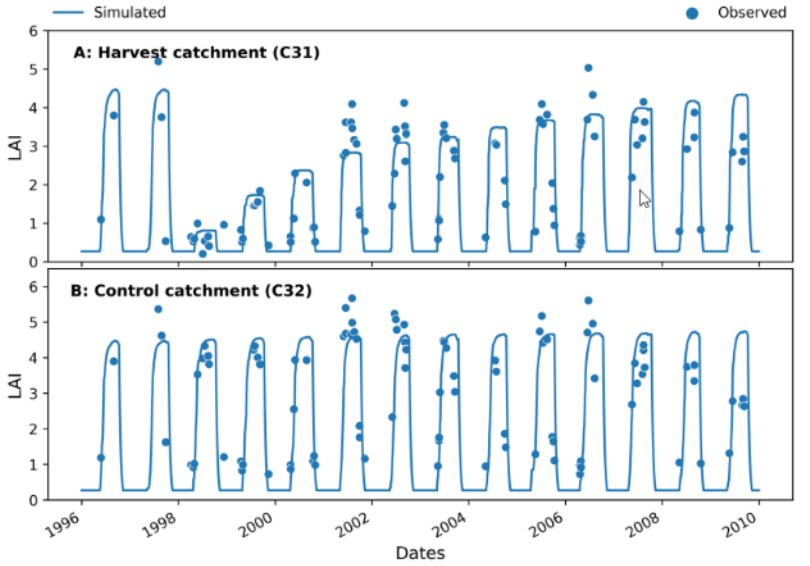
Raven

ROBIN

Coupled Simulation of Vegetation Growth



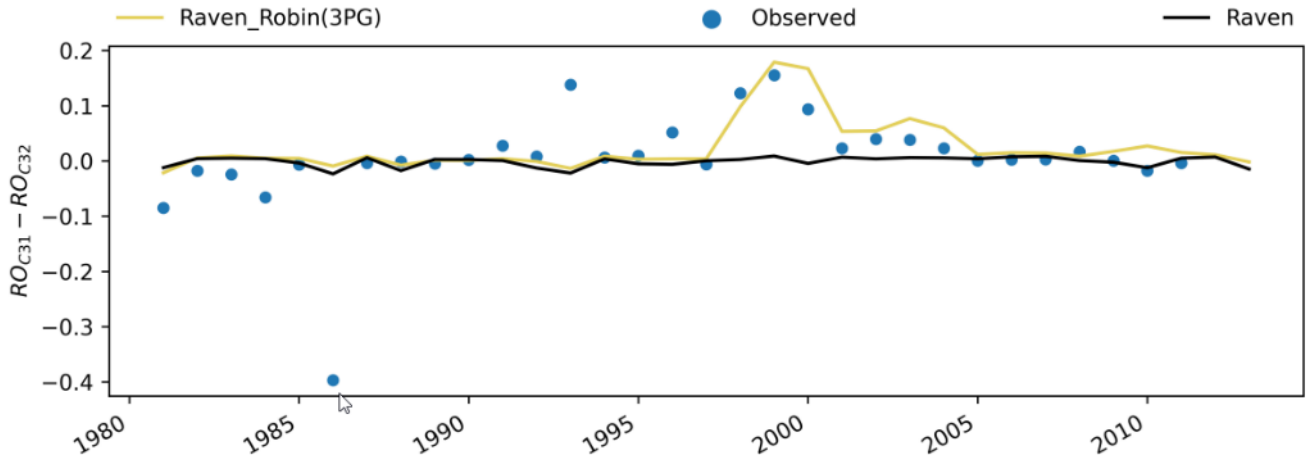




Paired catchment study in Turkey Lakes Experimental basin, ON

Clearcut in 1998

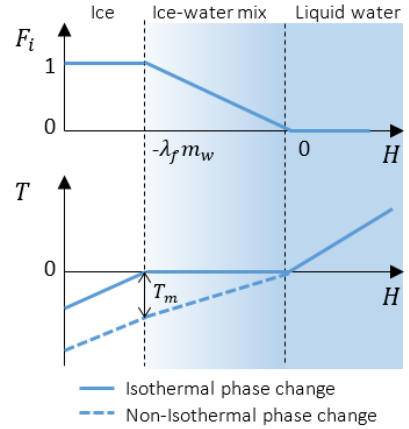
From Han (2022)

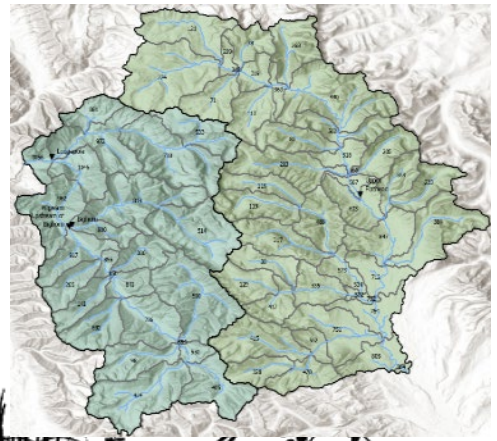


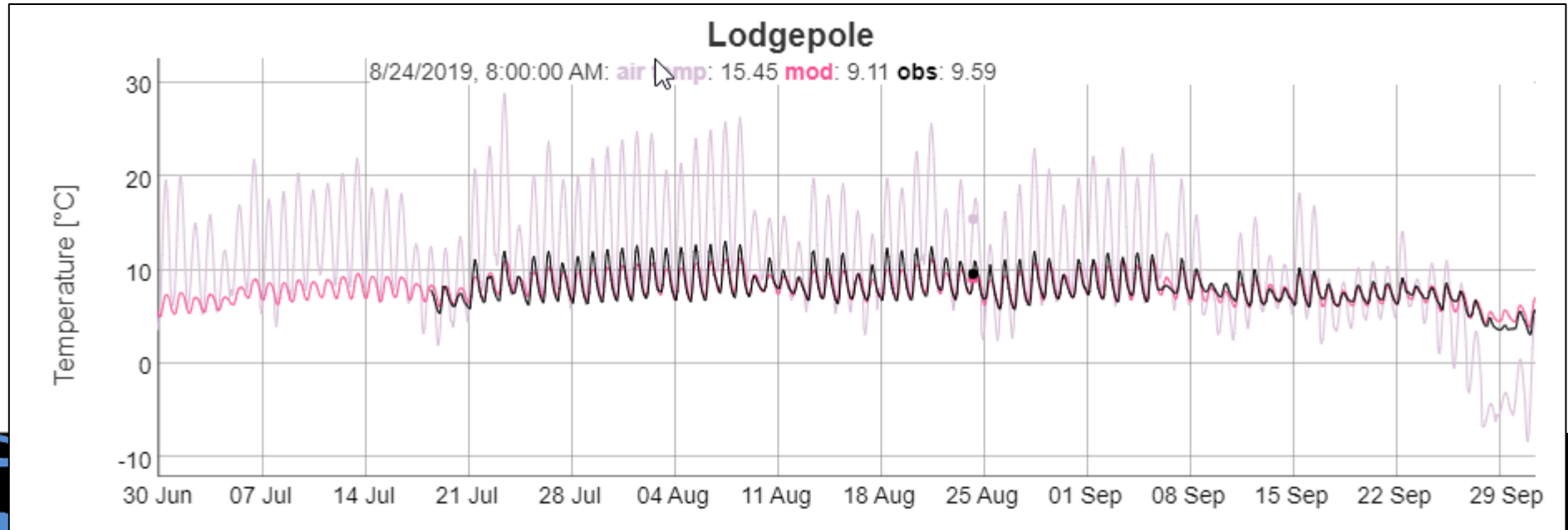
Recent Advances:
Stream Temperature/Thermal model

Raven Thermal Transport Wrapper

- Frozen ground/permafrost simulation
- Stream temperature routing using semi-analytical Lagrangian method
- Full energy budget
- Tracking net latent/sensible heat transfer with atmosphere







Raven

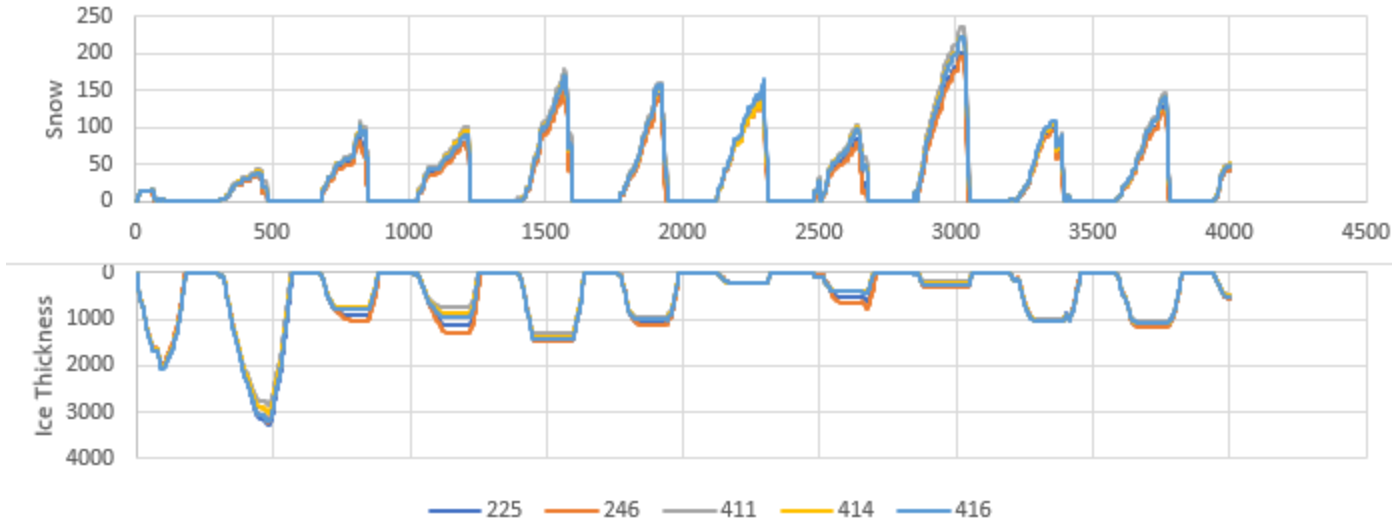
Recent Advances: Frozen Lakes

Previous Raven configuration treated lakes as always unfrozen– snowfall and rainfall added direct to lake

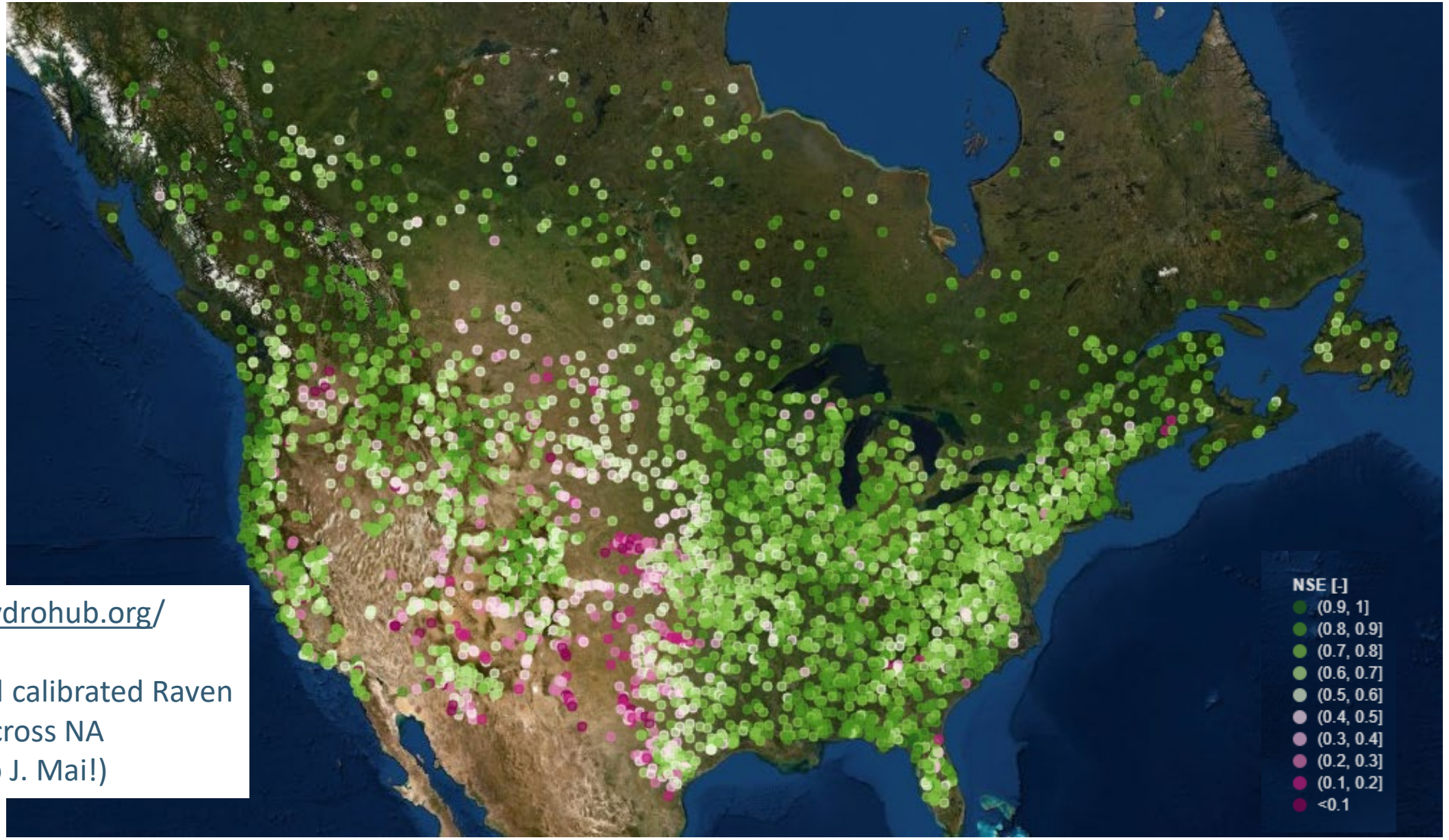
This misses snow accumulation on frozen lakes– can be a significant volume in lake-dominated watersheds.

Simple potential melt-driven technique to track ice depth

- Handles thermal buffering of ice by snow presence



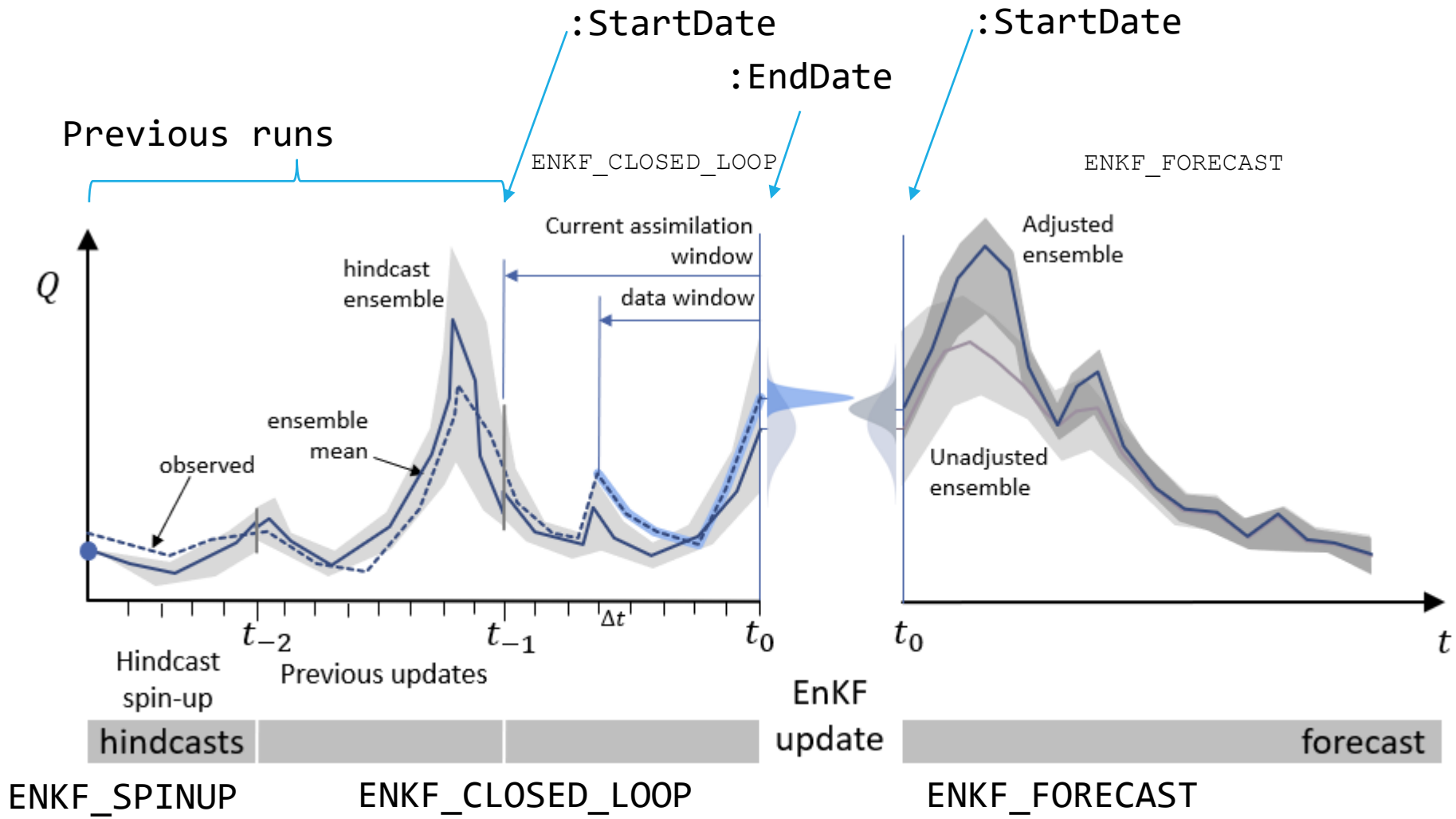
Deployment Across North America



https://hydrohub.org/

Download calibrated Raven models across NA (thanks to J. Mai!)

Recent Advances: EnKF Data Assimilation



Raven: What's next (2-3 yrs?)

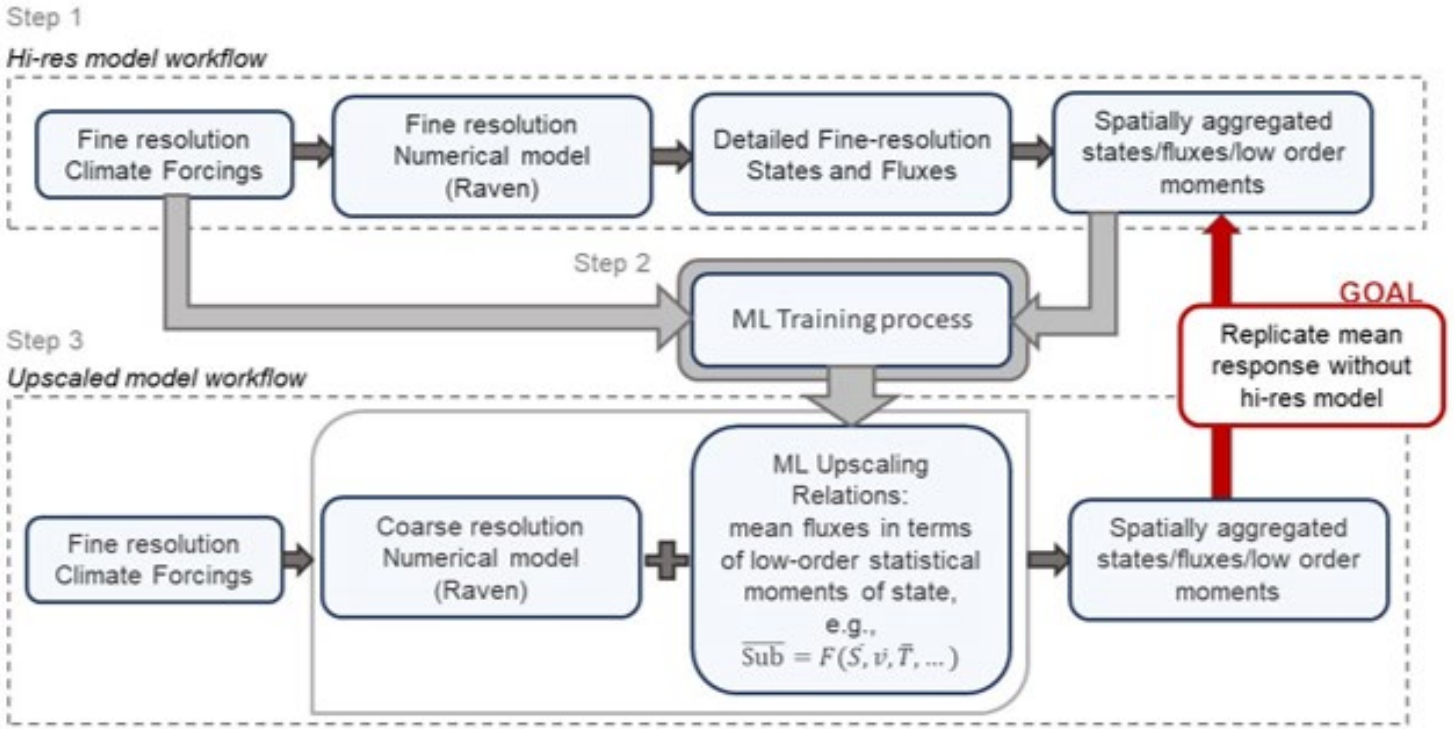
Ongoing projects:

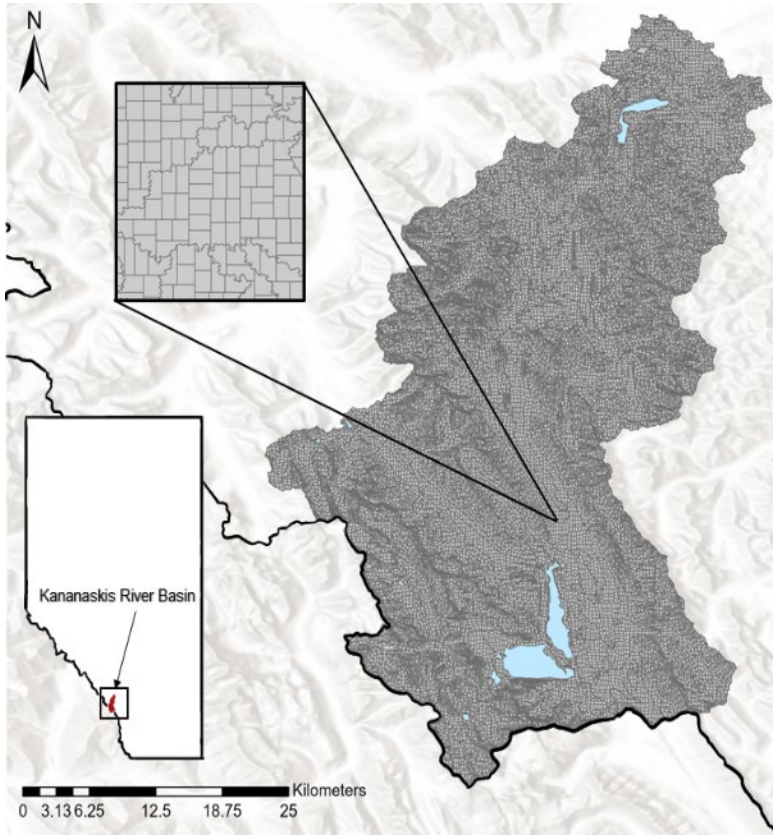
- Improved wetland model development and evaluation (w/ Ontario MNRF)
  - Improved cold regions wetland treatment
- ML-guided upscaling/downscaling of snow ablation (w/ Alberta Innovates, NSERC)
- Integration of LSTM (machine learning) forecasting models (w/ ECCC)
- Coupled demand management optimization (w/ MacHydro)
- Further work into model structural optimization/uncertainty analysis
- Increased support for uncertainty analysis and probabilistic modelling
- Coupling via BMI to U.S. NextGen system (uManitoba)

Unfunded/fun:

- Isotopes
- User interface improvements
- Inevitable improvements in support of consulting firms and organizational partners

Machine Learning-aided upscaling





Raven

Not just another hydrologic model

- Well-tested multipurpose framework for building range of models
- Architecture for supporting difficult applications

Capacity to apply, test, and *improve upon*:

- various model configurations (multi-model ensembles possible)
- most model assumptions

Ever-improving support for management & cold regions hydrological processes

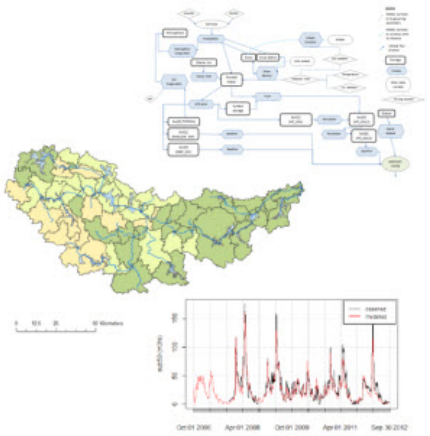
Strong support for integration with forecasting and management tools

CSHS Principles of Hydrologic Modelling Course

Early May 2023 – 5 days (Mon-Fri)

Professional Short Course and Graduate Course offered at the University of Waterloo, ON

Hands-on course covering the development and application of hydrological models



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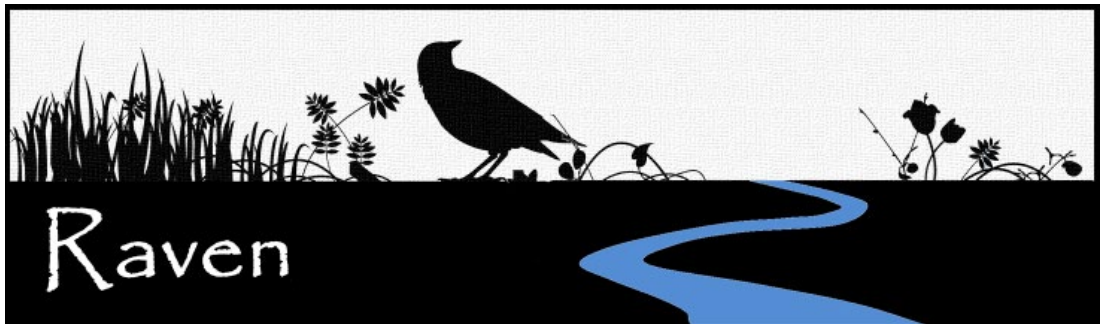
CSHS SCSH
Canadian Society for Hydrological Sciences
Société Canadienne des Sciences Hydrologiques

CWRA ACRH
Canadian Water Resources Association
Association Canadienne des Ressources Hydriques

Questions?



raven.uwaterloo.ca

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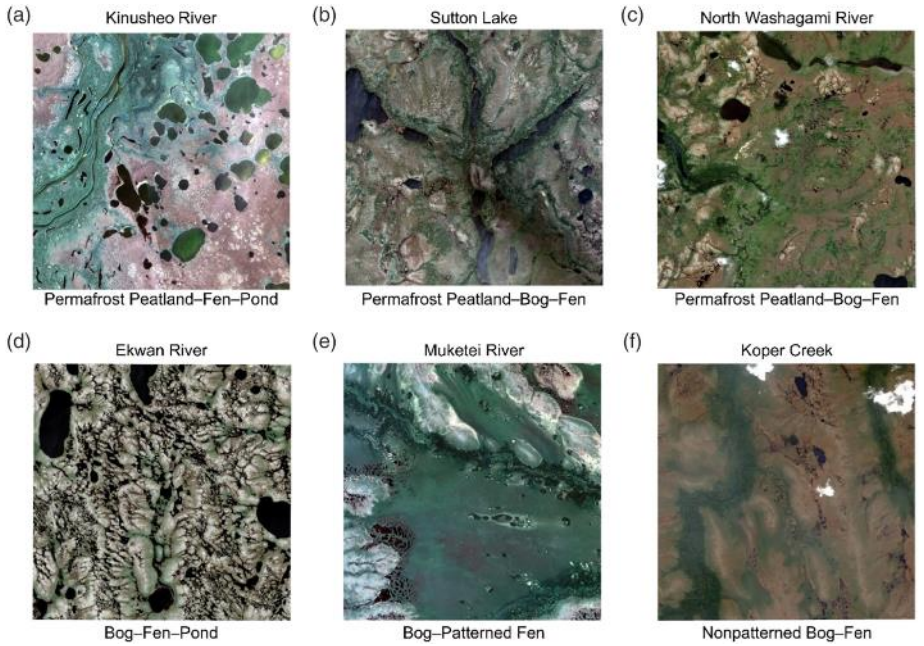
Extra Slides

MNRF Wetland Work

Numerous problems related to simulating influence of wetlands at regional and local scales

- Treatment of riparian vs. isolated wetland vs wetland complexes
- Estimating wetland water level, not just influence on hydrograph
- Support for frozen wetlands and corresponding snow accumulation/insulation
- Watershed delineation with ‘soft’ headwaters – wetlands that can drain to multiple downstream areas
- Unique hydrologic function such as mixed connectivity in patterned bog/fen peatlands of Hudson Bay Lowlands (Balliston and Price, 2022)

https://www.ontarioparks.com/parksblog/tag/wetlands/



Northern ON Wetlands

Recent Advances: BMI (new as of July!)

Raven can now be compiled as .dll library

Uses BMI: Basic Model Interface

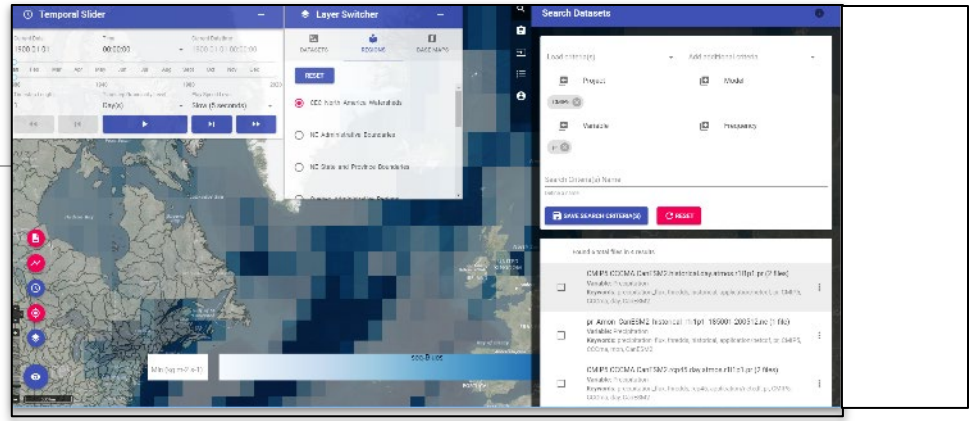
- Protocol shared by many existing earth systems models (USGS, NASA, NWS…)

Wraps Raven functionality such that it can be directly called by other applications

Plans to integrate with U.S. NextGen Framework with support from University of Manitoba colleagues

```
#include "BMI.h"
#include "Model.h"

class CRavenBMI : public bmixx::Bmi
{
  private:
    CModel      *pModel;
    optStruct    Options;
    time_struct tt;

  public:
    CRavenBMI();
    ~CRavenBMI();

    // Model control functions.
    void Initialize(std::string config_file);
    void Update();
    void UpdateUntil(double time);
    void Finalize();

    // Model information functions.
    std::string GetComponentName();
    int GetInputItemCount();
    int GetOutputItemCount();
    std::vector<std::string> GetInputVarNames();
    std::vector<std::string> GetOutputVarNames();

    // Variable information functions
    int GetVarGrid(std::string name);
    std::string GetVarType(std::string name);
    std::string GetVarUnits(std::string name);
```

Raven Software Ecosystem: Ouranos' PAVICS-Hydro system



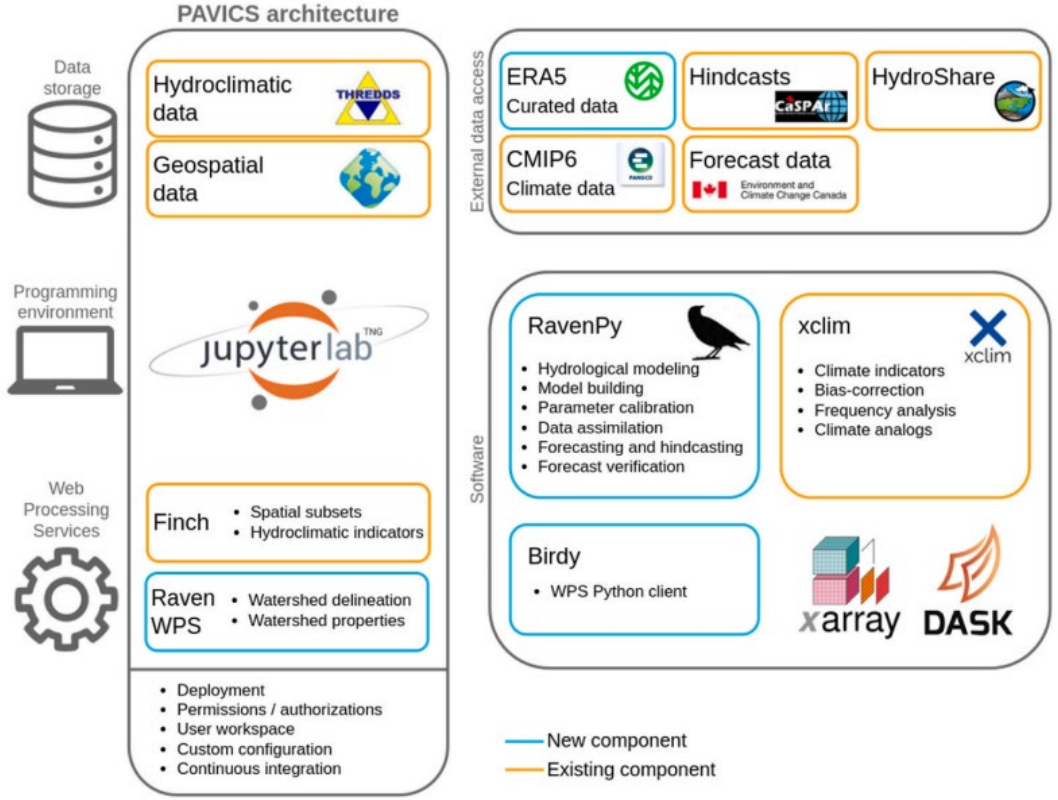
PAVICS (Platform for the Analysis and Visualization of Climate Science)

- Developed by Ouranos, ETS, and CRIM

Raven is the hydrological model supporting the system

Calibrated Raven models can be deployed on 5700+ basins across North America

- 3 different model configurations
- a plethora of bias-corrected Regional Climate Model forcings
- Server-side computation
- Python-script based

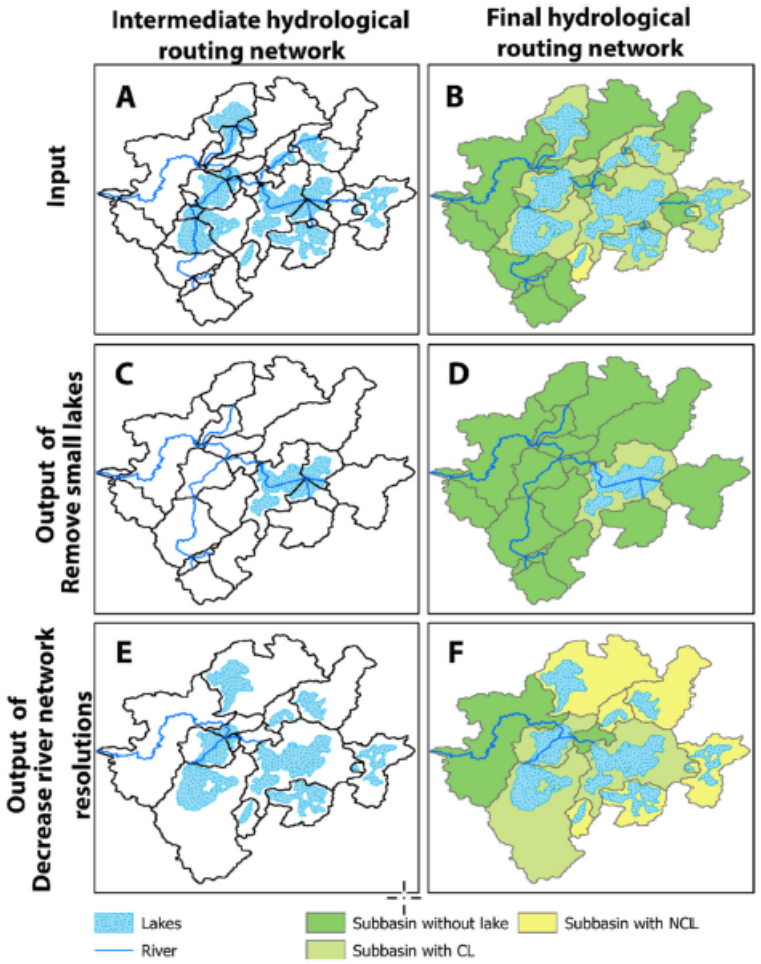


Arsenault, R., D. Huard, J. Martel, M. Troin, J. Mai, F. Brissette, C. Jauvin, L. Vu, J.R Craig, T. Logan, T.J. Smith, B.A. Tolson, M. Han, S. Langlois, *The PAVICS-Hydro platform: a virtual laboratory for hydroclimatic modelling and forecasting over North America*, Environmental Modelling and Software, 168, 105808, 2023

Complex Routing in Lake-dominated systems

We have developed tools (BasinMaker) to help discretize lake-dominated landscapes into subbasin networks and estimate river and lake properties

- Applied these across north America to produce hydrofabric products



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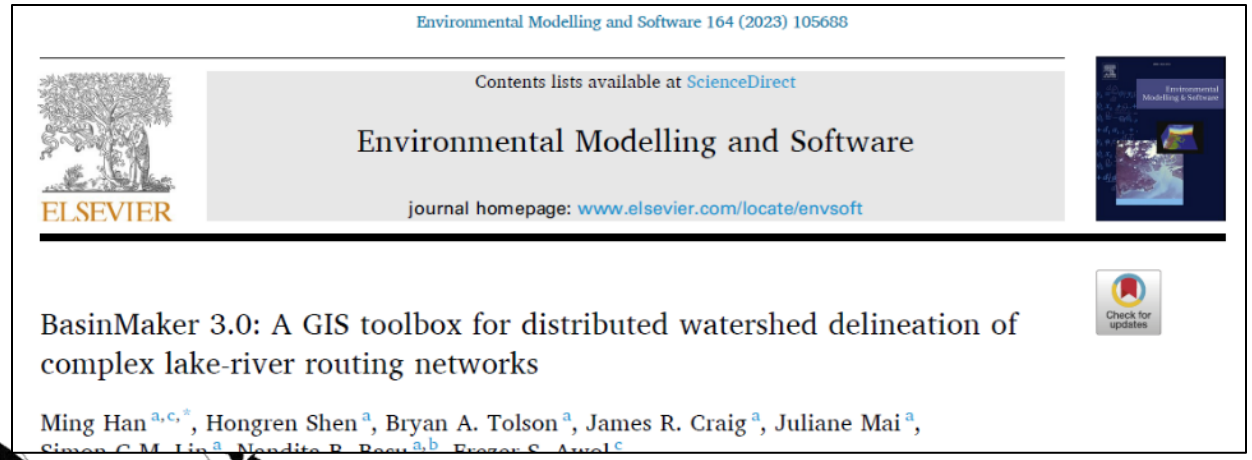

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journal homepage: www.elsevier.com/locate/envsoft

ELSEVIER

BasinMaker 3.0: A GIS toolbox for distributed watershed delineation of complex lake-river routing networks

Ming Han [a,c,*], Hongren Shen [a], Bryan A. Tolson [a], James R. Craig [a], Juliane Mai [a],

Control Structures

Raven supports:

- User-supplied stage-discharge curves
- Basic weirs
- Pumps
- Orifices

Each of these control structures can turn on and off or have its properties change via the use of multiple ***operating regimes***

Operating regimes define when and under what hydrological conditions different structure setups are operated

- Also can be used to define constraints on flow or flow ramping

Used for EXPLICIT simulation of actual reservoir operations

- Testing long term operational strategies
- Forecasting short term operational choices