Isotope method for gauging ungauged watersheds and evidence of permafrost thaw in the RAMP Lakes

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InnoTech Alberta

Water Resources Assessment
Environmental Impacts

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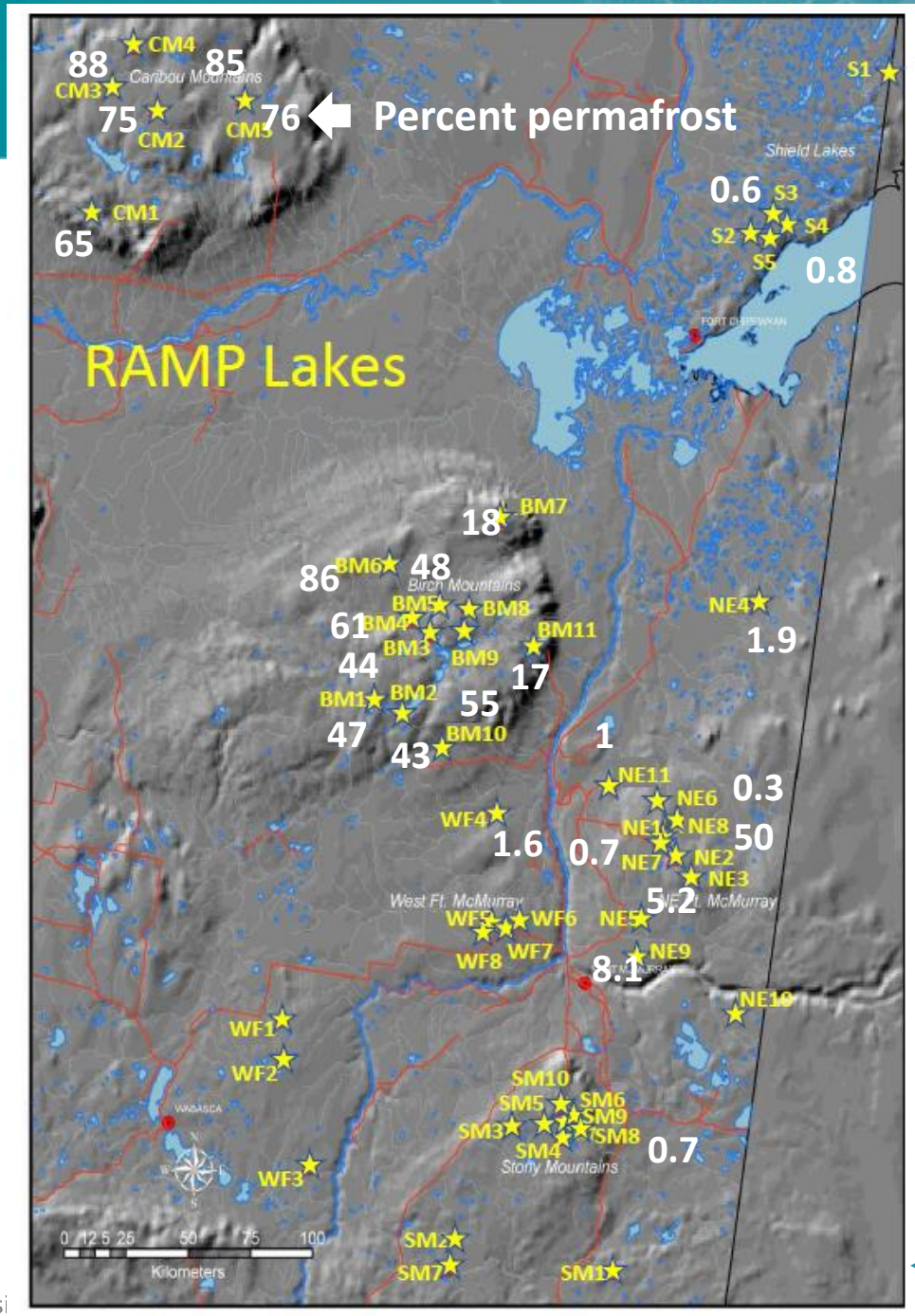
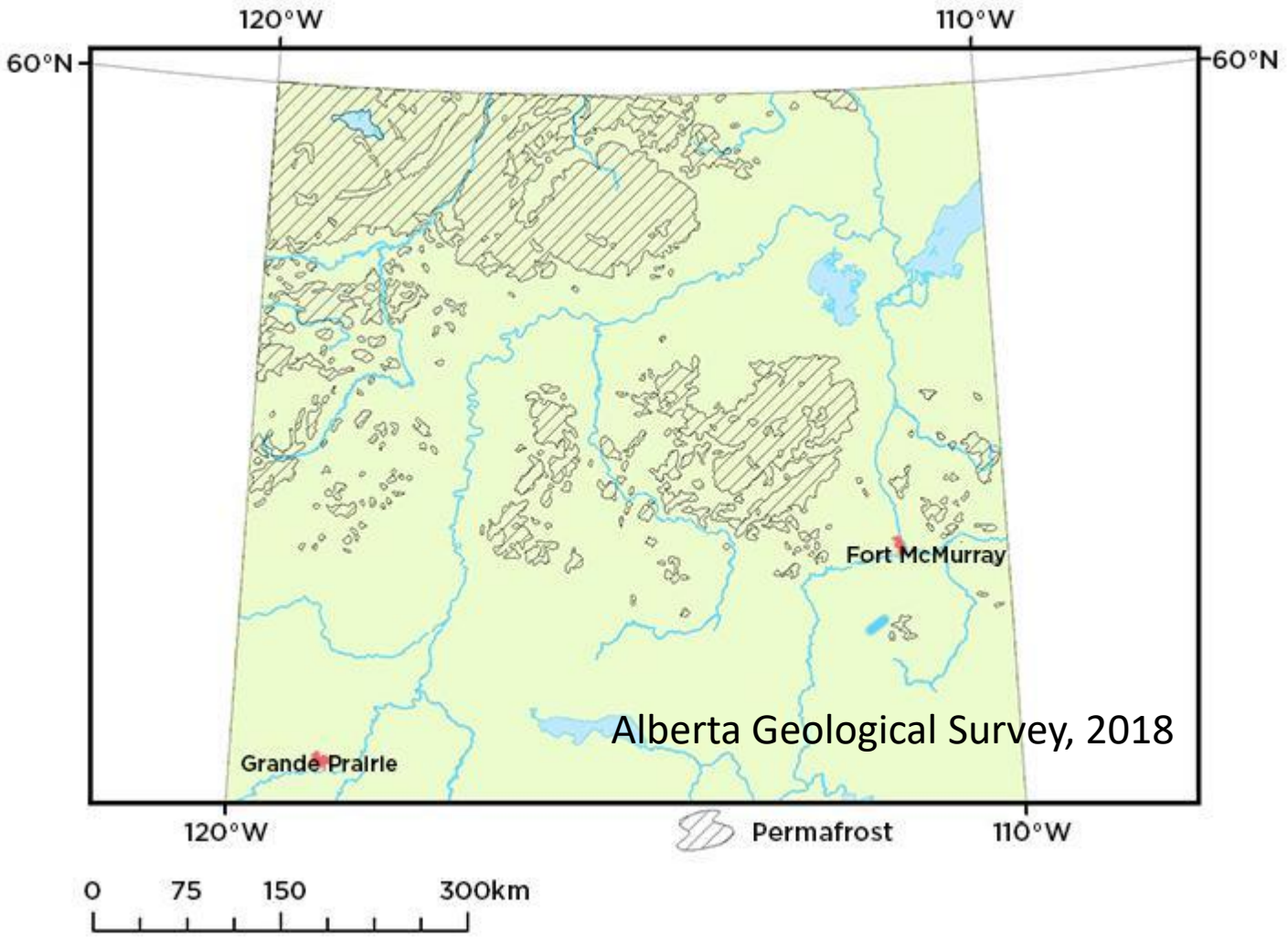
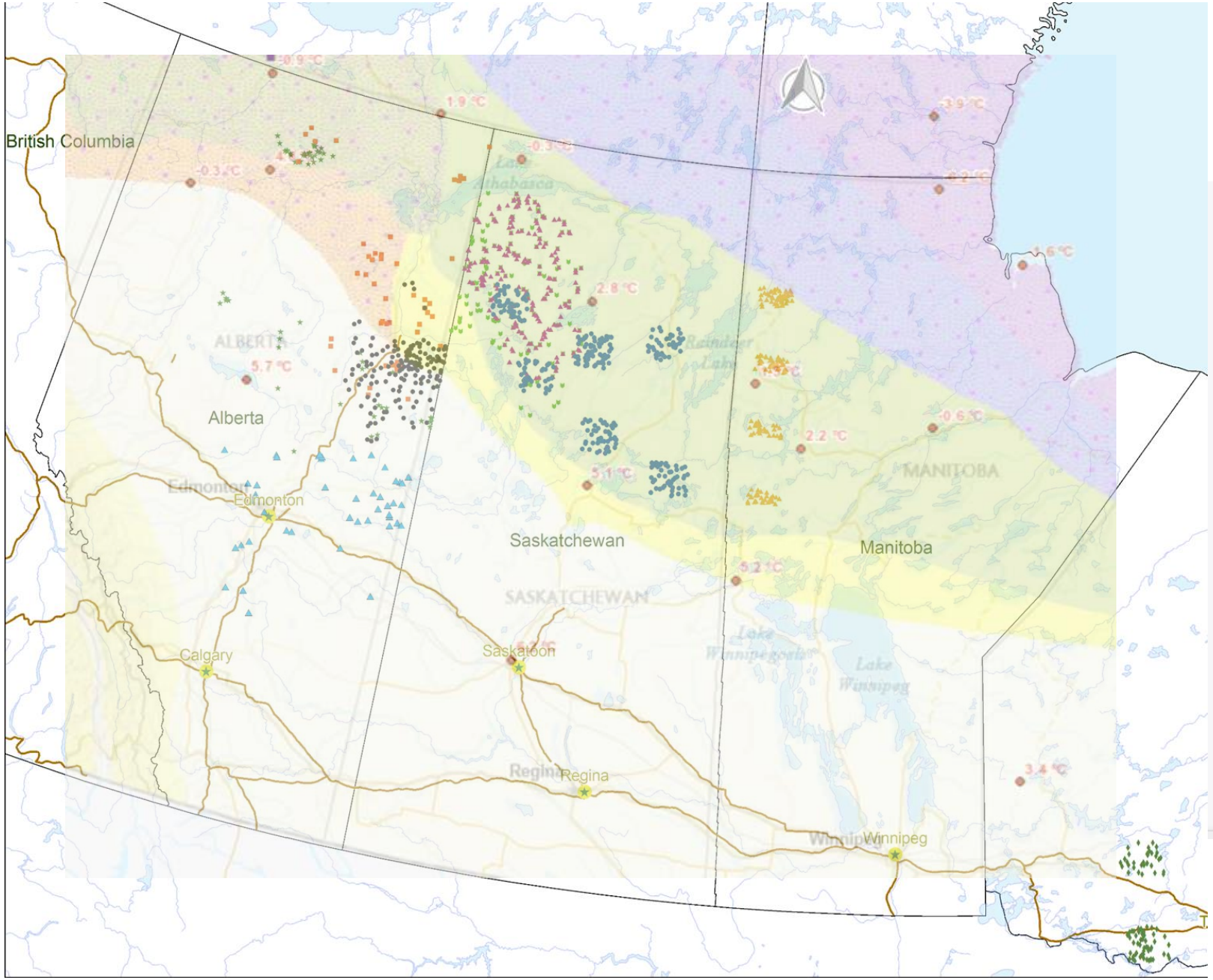
Permafrost extent and distribution





← Based on RAMP landcover mapping



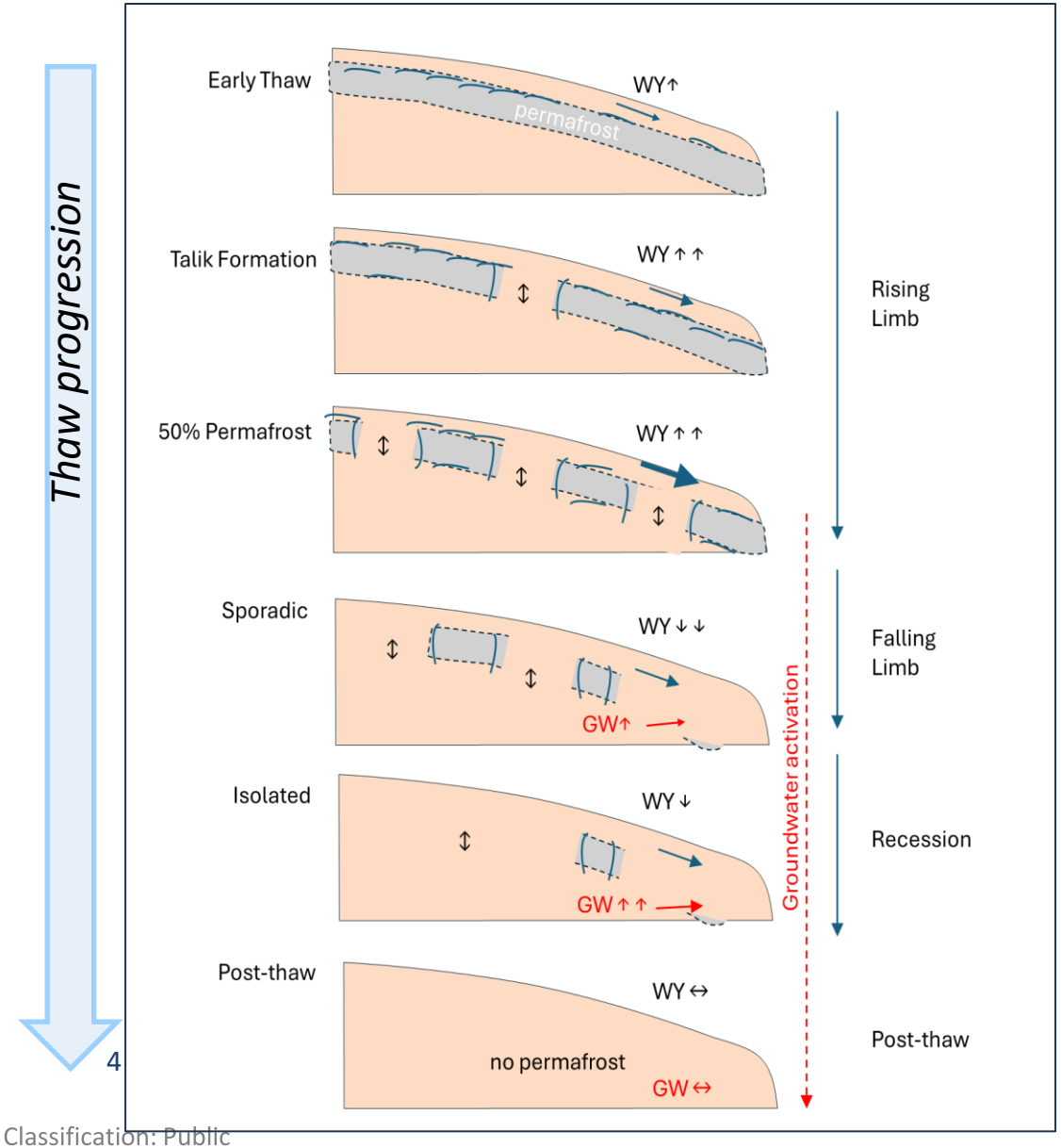
Lakes surveyed in Western Canada

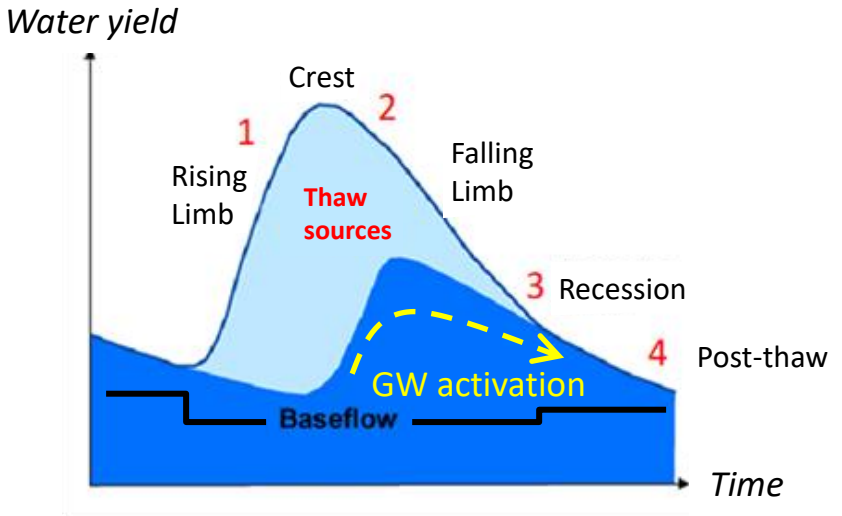
Permafrost zones

- Continuous, high ice (>20%)
- Continuous, high-medium ice (10% to >20%)
- Continuous, medium ice (10% to 20%)
- Continuous, medium-low ice (10% to <10%)
- Continuous, low ice (<10%)
- Extensive discontinuous, medium ice (10% to 20%)
- Extensive discontinuous, medium-low ice (20% to...
- Extensive discontinuous, low ice (<10%)
- Extensive discontinuous, low-nil ice (<10% to 0%)
- Sporadic discontinuous, medium-low ice (20% to ...
- Sporadic discontinuous, low ice (<10%)
- Sporadic discontinuous, low-nil ice (<10% to 0%)
- Isolated patches, medium-low ice (20% to <10%)
- Isolated patches, low ice (<10%)

Classification: Public

Conceptual model: Episodic thaw effects on water delivery





Hydrograph dynamics

Classification: Public

Our contributions

1. We developed an isotope method for estimating water yield (aka runoff) in ungauged watersheds
2. Two decades of observations at 50 RAMP Lakes
3. Observed a pronounced influence of permafrost thaw on runoff coefficients
4. Simulated thaw succession for individual watersheds to predict potential future impacts

Ob

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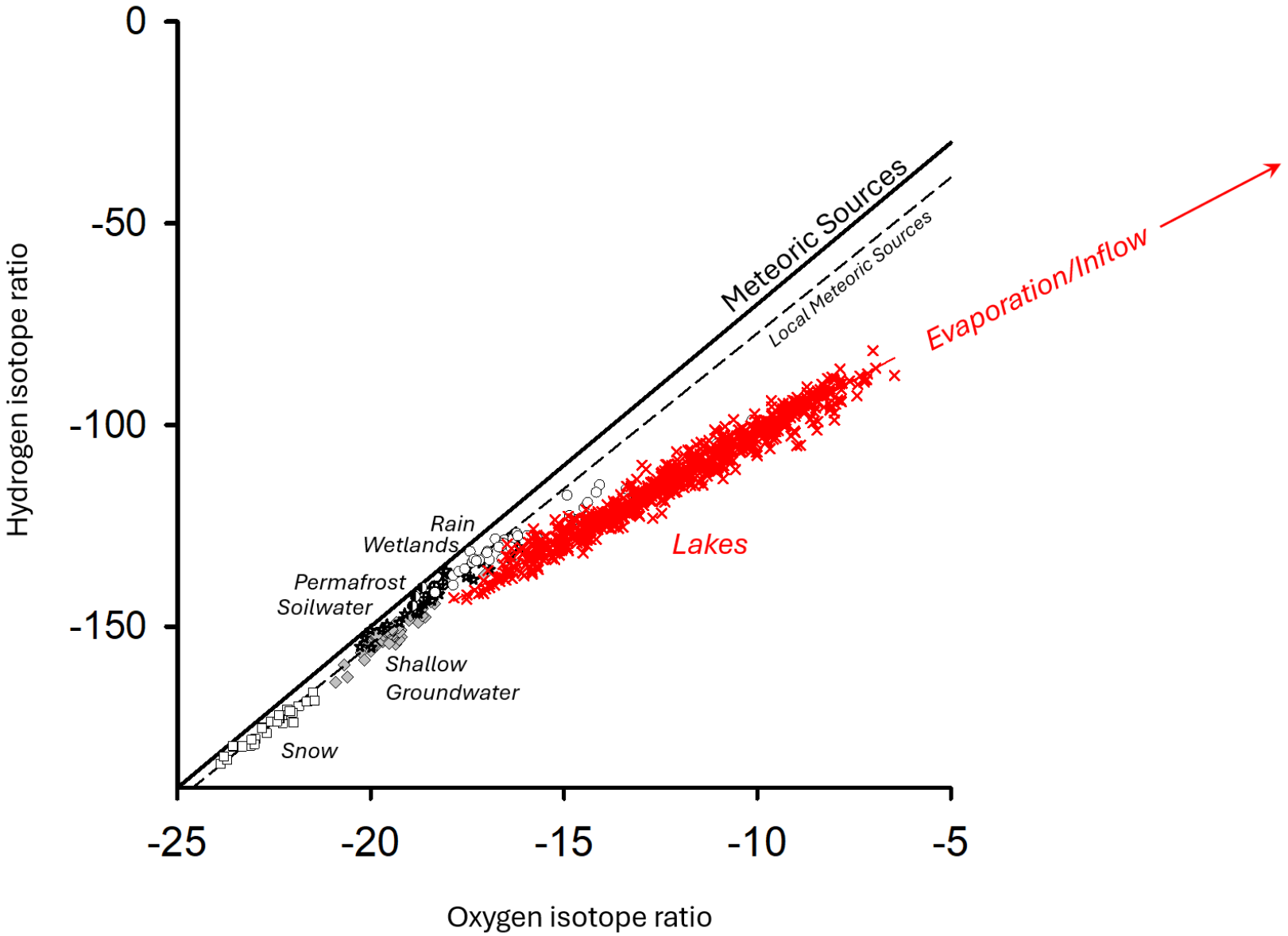
1. Method development

a. Natural isotope labelling of water

We measure oxygen and hydrogen isotopes naturally present within the water molecule

Key applications:

-differentiating water sources
-quantifying evaporation losses
-for lakes, it is an ideal flushing indicator



Classification: Public

1. Method development:

b. Isotope Mass Balance (IMB)

IMB Data Flow Schematic RAMP

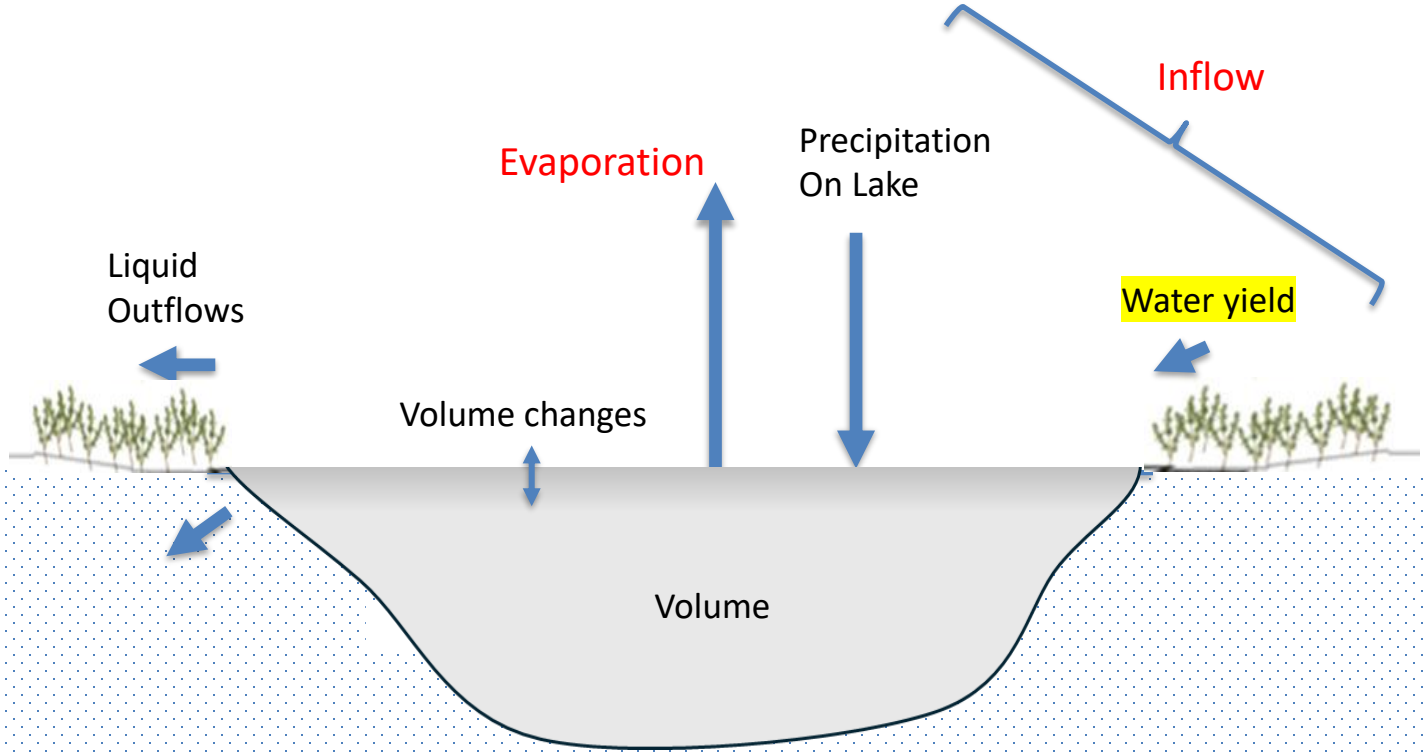
Site-specific data

Atmospheric Parameterization: NARR (32-km grided): Precipitation, Evaporation, 2-m T_{fw}, h_{fw}
Isotope climatology: Chad et al. (2022); Delavau et al. (2013) calibrated on CNIP
GIS Input: Lake area, Watershed area
Field data: Bathymetric surveys, stratification, hydraulic conductivity, groundwater/permafrost $\delta^{18}O$, $\delta^{2}H$
Time-series monitoring: Lakewater $\delta^{18}O$, $\delta^{2}H$, water chemistry, other isotopes
Isotopic exchange: Craig- Gordon model

IMB Output: Evaporation/Inflow
IMB Calcs: Volumetric fluxes
Residence time
Water yield

Uncertainty: ~ 10%

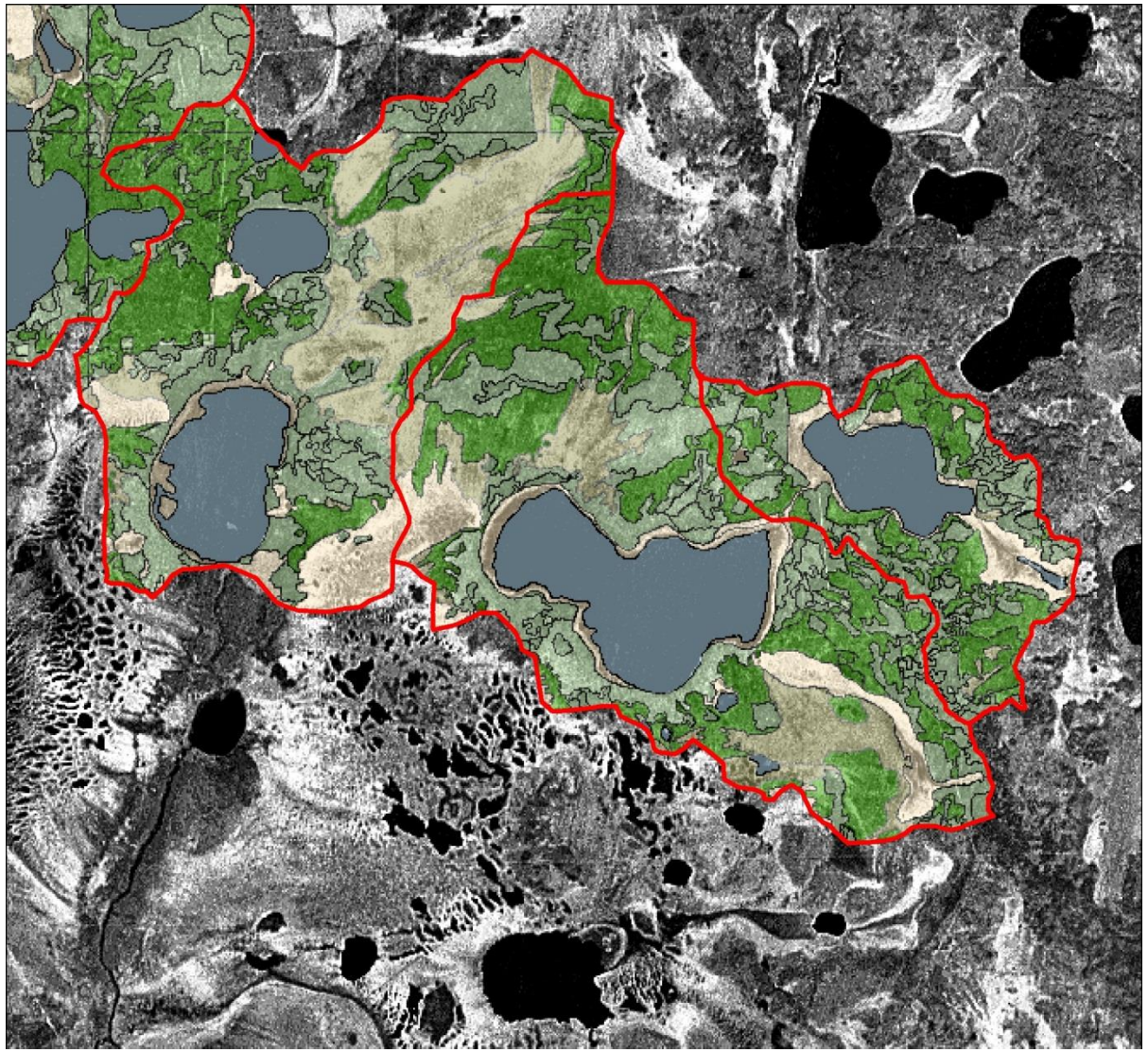
Notable clients/endorsements:
ECCC Acid Sensitivity Program
ECCC Water Survey of Canada
US EPA National Lakes Assessment
INAC GNWT Water Management
Chinese Academy of Sciences

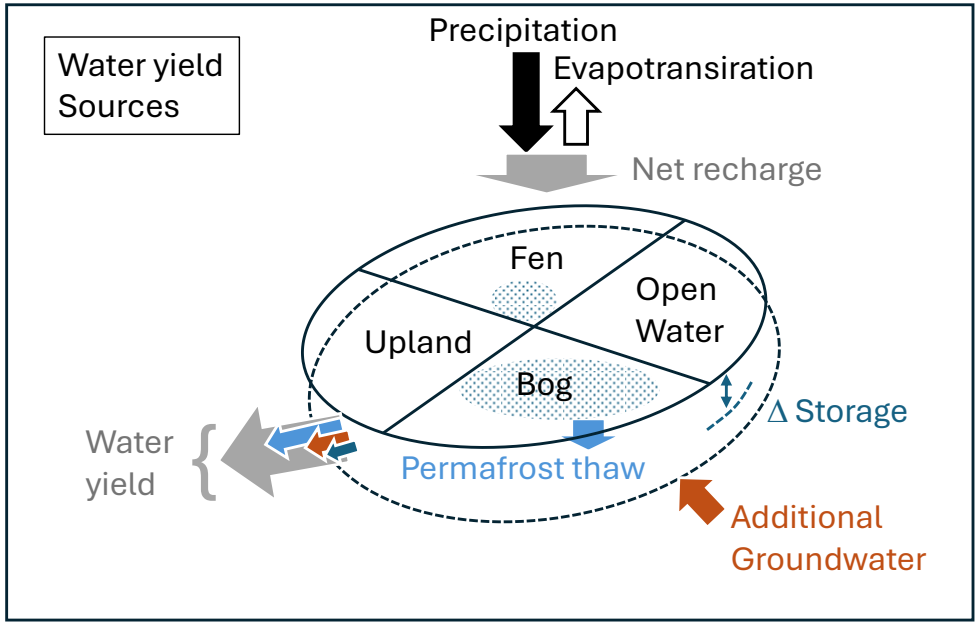


Classification: Public

1. Method development:

c. Inverse modelling of landcover unit water yields





Linear systems of equations:

4 unknowns

50 equations

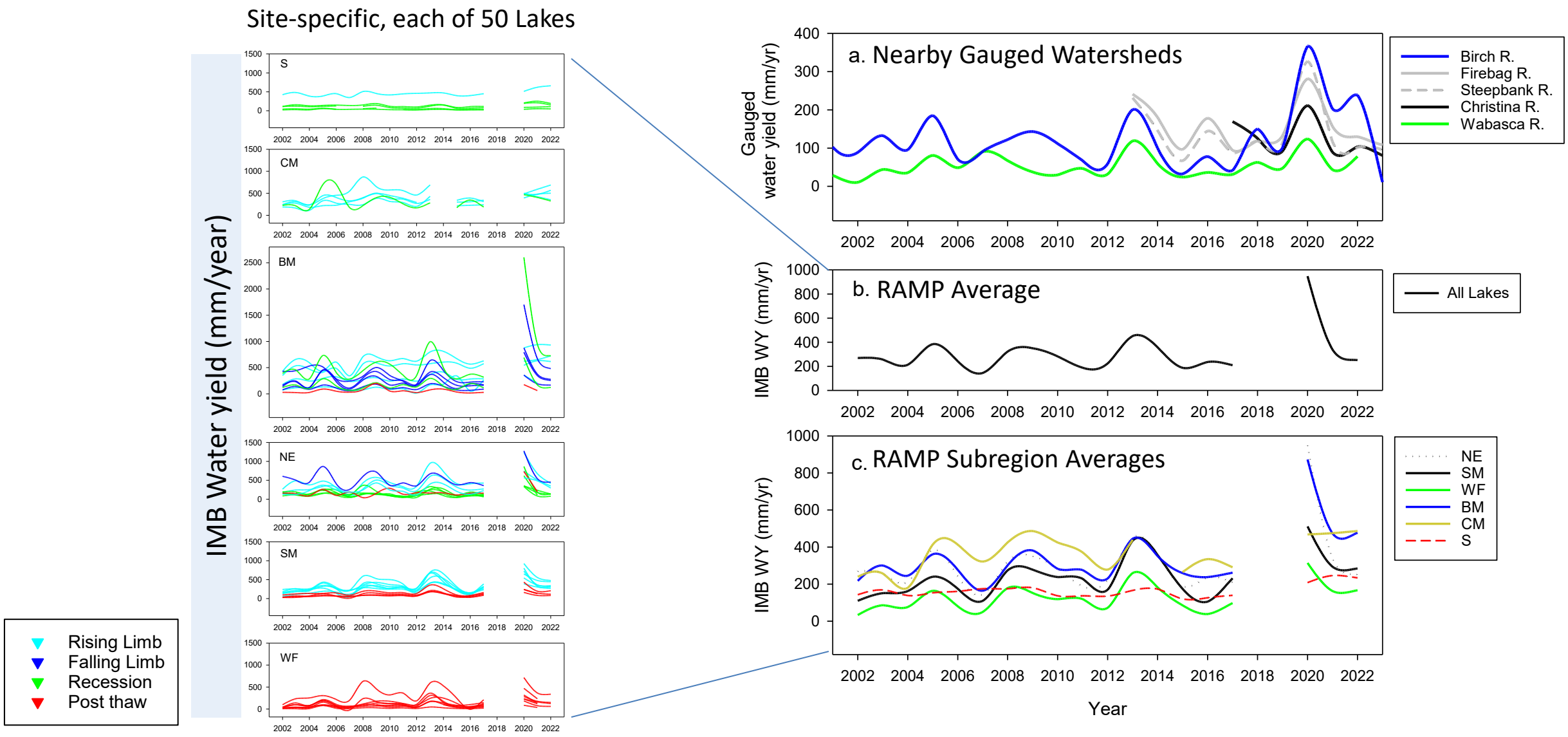
$$\begin{cases} B_1 wy_b + F_1 wy_f + U_1 wy_u + OW_1 wy_{ow} = WY_{L1} \\ B_2 wy_b + F_2 wy_f + U_2 wy_u + OW_2 wy_{ow} = WY_{L2} \\ B_3 wy_b + F_3 wy_f + U_3 wy_u + OW_3 wy_{ow} = WY_{L3} \\ \vdots \\ B_n wy_b + F_n wy_f + U_n wy_u + OW_n wy_{ow} = WY_{Ln} \end{cases}$$

Dataset includes 931 watershed - water years

Classification: Public

2. Water yield record over 2 decades

a. Comparison with gauged watersheds



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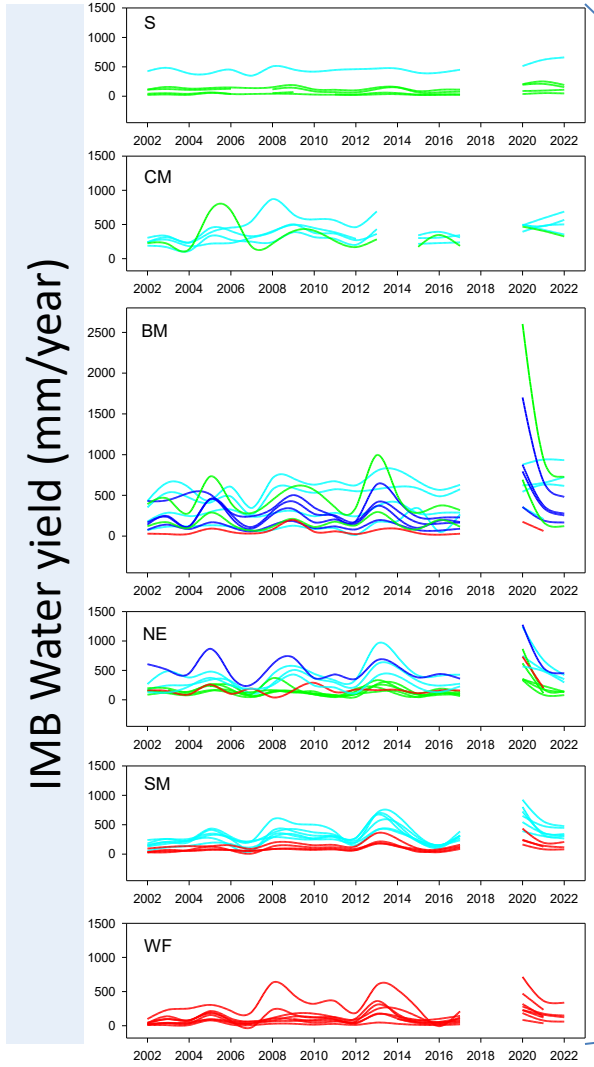
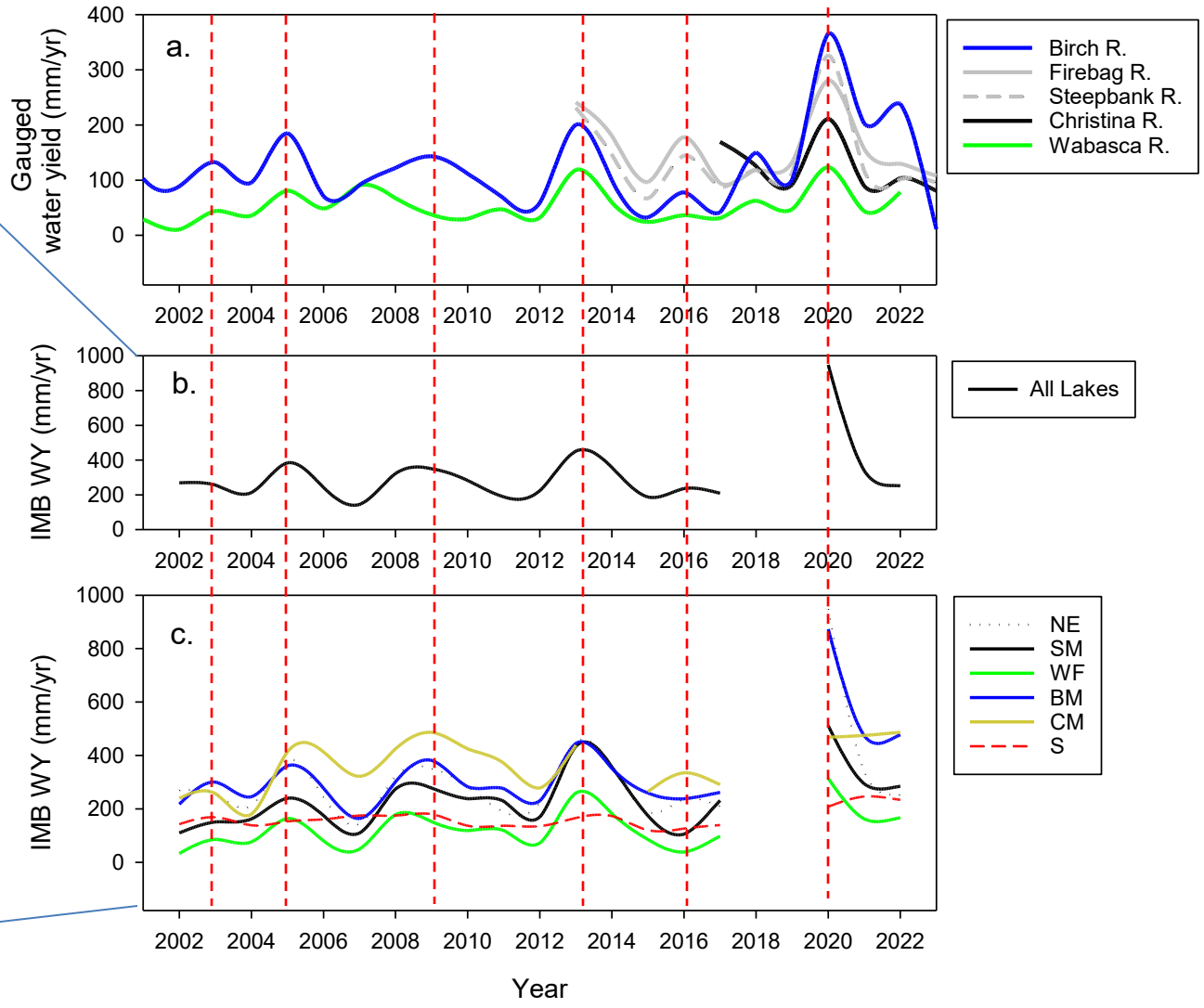


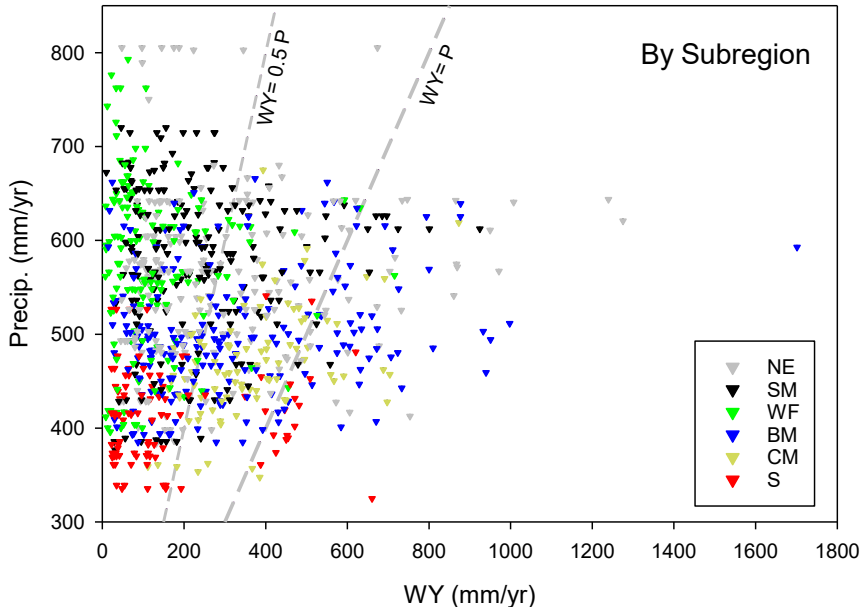


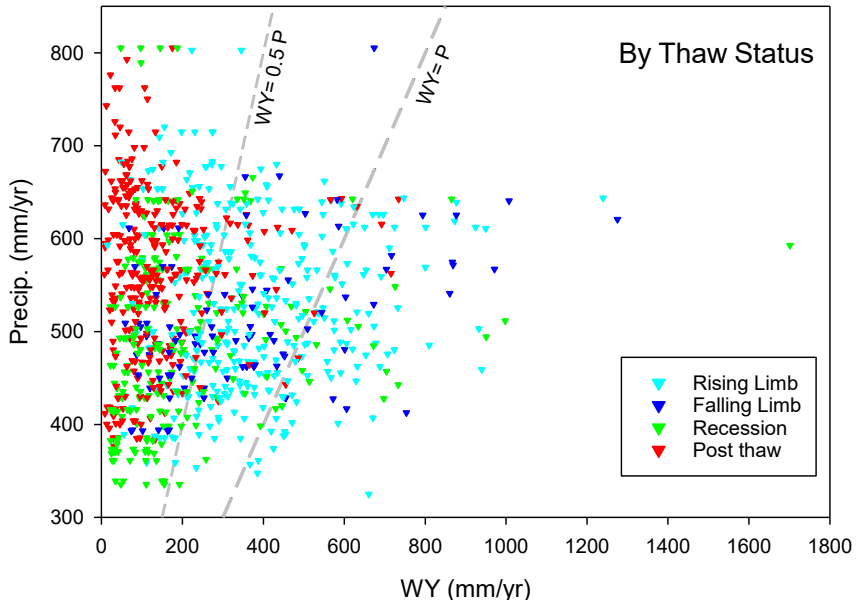
- Good temporal agreement between IMB WY and gauged WY

Classification: Public

2. Water yield record over 2 decades

b. Water yield vs precipitation





By Subregion:

NE: 3% ; 9%

SM: 2% ; 6%

WF: 0% ; 2%

BM: 5% ; 12%

CM: 8% ; 18%

S: 2% ; 2%

By Thaw stage:

Rising Limb: 24% ; 68%

Falling Limb: 24% ; 61%

Recession: 5% ; 20%

Post-thaw: 2% ; 9%

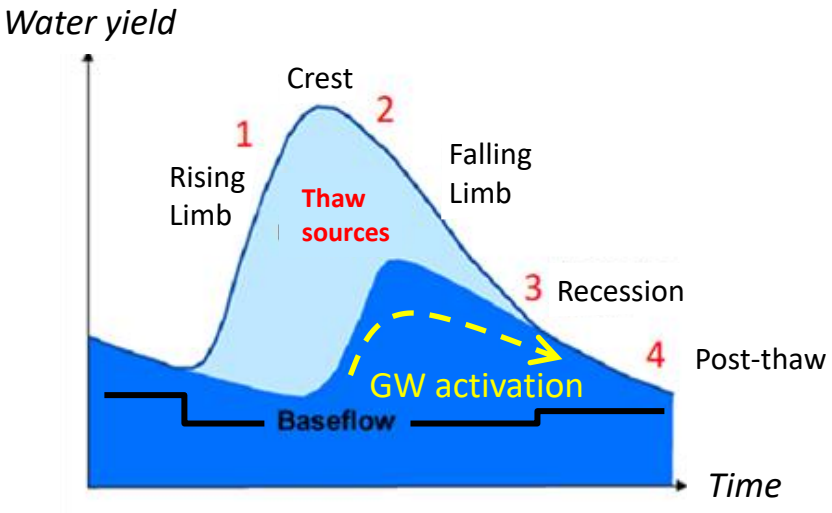
Overall: 13% WY > P ; 38% WY > 0.5P

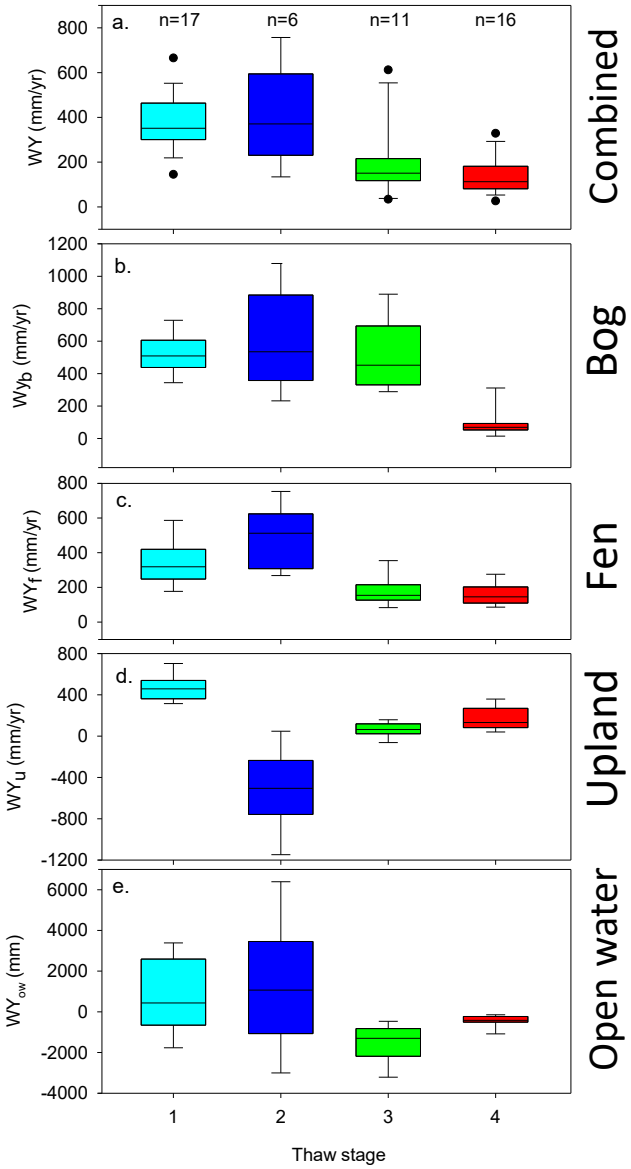
Classification: Public

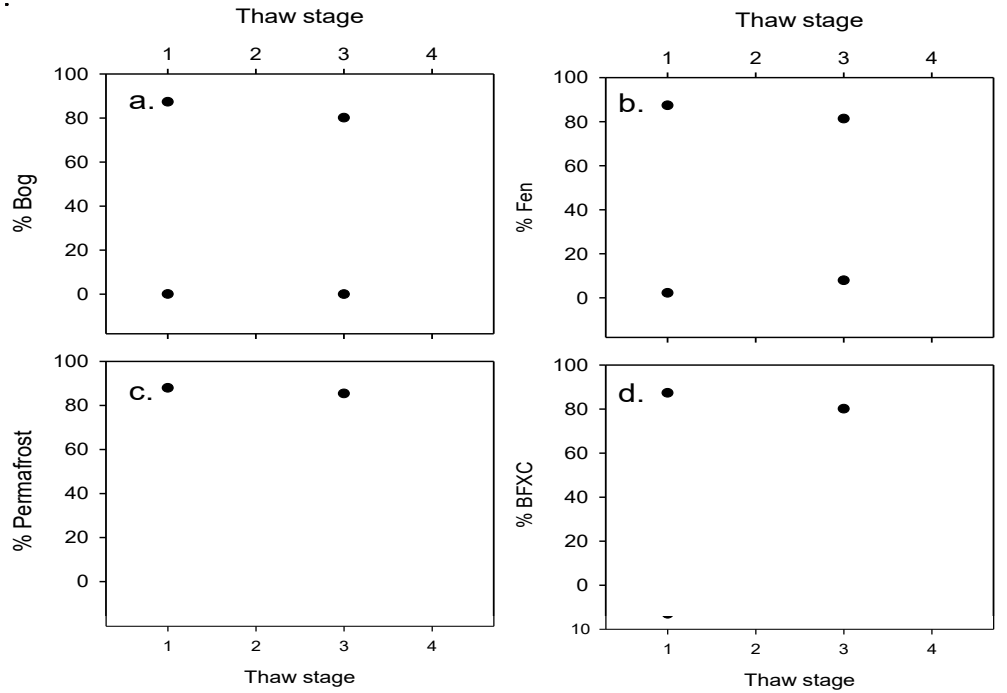
3. Permafrost thaw effects

Stage classification, water yield/vegetation succession

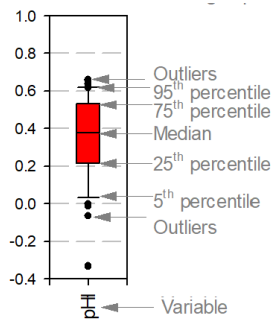
Space-for-time hydrograph dynamics







Legend



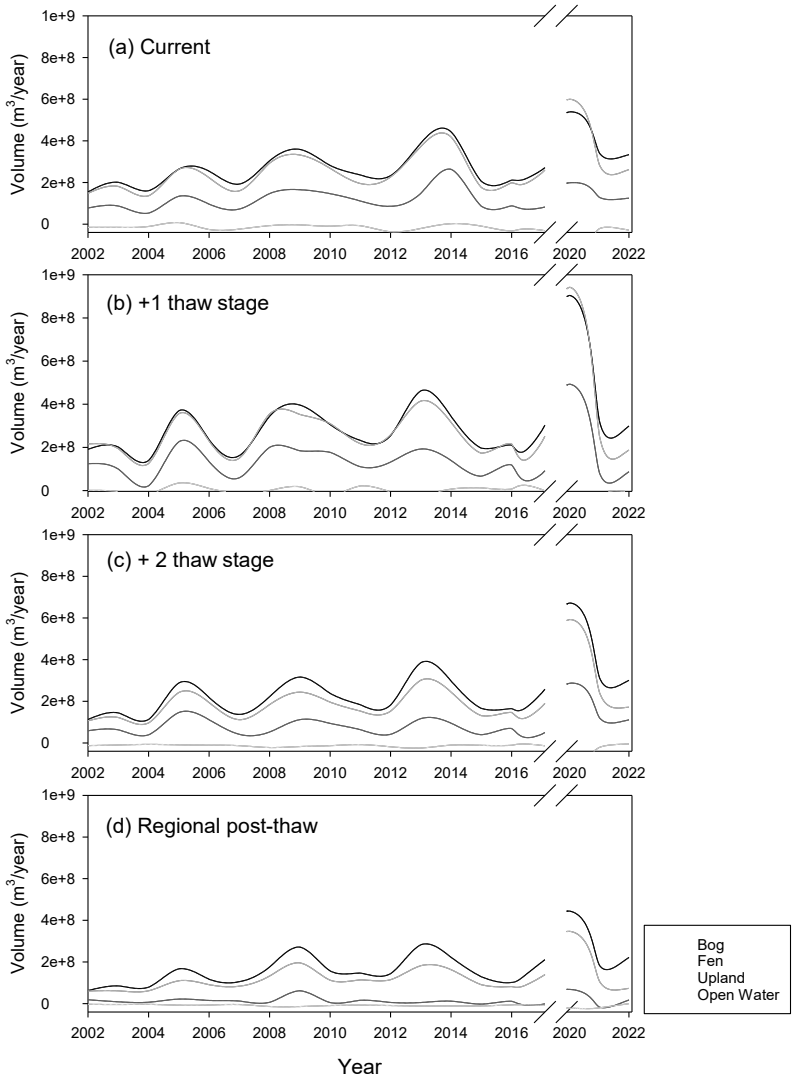
Overall:
Alignment between hydrologic response and vegetation cover distribution.

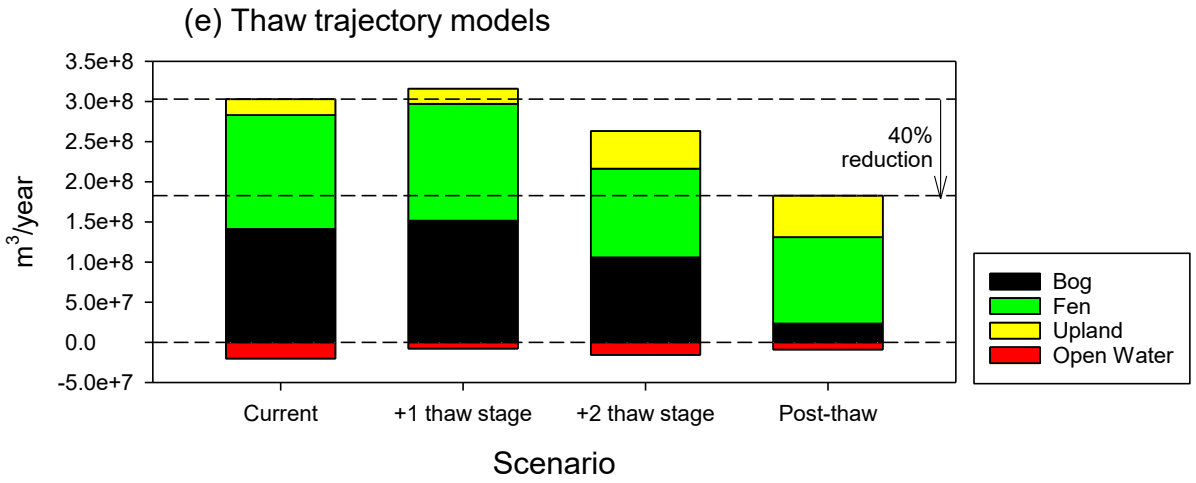
Classification: Public

4. Thaw progression simulation

by advancing observed runoff coefficients

Areal footprint: 1086 km^2





- Initial water yield increase predicted in stage +1 followed by eventual 40% decline in WY by post-thaw

Classification: Public

Implications

a. Current water availability conditions are augmented substantially by permafrost thaw sources (~40% of headwater discharge)

b. Significantly reduced river discharge is anticipated once permafrost is absent, *but we expect higher flows to precede this in near-term*

c. Acidification of lakes is currently mitigated by high water yields attributed to permafrost thaw but will likely hasten as permafrost sources decline

d. Reduction in flows may negatively impact wetland- and river-dependent ecosystems, compounded by likely T increases, but mitigated by likely P increases

e. There is an opportunity NOW to incorporate thaw succession processes into water management and mine-closure planning for this region

Classification: Public

Remaining Unknowns

a. How long will it take for permafrost thaw to complete?

b. Are upscaling effects significant when we extrapolate from the 1086 km^2 study footprint to regional river basins?

Classification: Public

Related Publications

1. Wan, C., Gibson, J.J., Yi, P., Pan, X., Chen, C., Skrzypek, G., 2026. Elevation-Dependent Permafrost Thaw on the Tibetan Plateau Delays Seasonal Discharge and Poses a Risk of Reduction in Downstream Water Availability. *Earth's Future* 14, e2025EF007809. https://doi.org/10.1029/2025EF007809.

2. Gibson, J.J., Eby, P.E., Jaggi, A., 2026. Carbon cycle succession across a permafrost thaw gradient as revealed by $d^{13}C$ in dissolved solids, gases and particulates in lakes. J*ournal of Geophysical Research: Biogeosciences* 131, e2025JG009260. First published: 29 January 2026 https://doi.org/10.1029/2025JG009260.

3. Gibson, J.J., Jaggi, A., Castrillon-Munoz, F., 2025. Widespread pH increase and geochemical trends in fifty boreal lakes: evidence, prediction and plausible attribution to climate and permafrost thaw impacts. *Journal of Hydrology Regional Studies* 58, 102253. https://dx.doi.org/10.1016/j.ejrh.2025.102253.

4. Castrillon-Munoz, F.J., Gibson, J.J., Birks, S.J., 2022. Carbon dissolution effects on pH changes of RAMP lakes in northeastern Alberta, Canada. *Journal of Hydrology: Regional Studies* 40, 101045. https://doi.org/10.1016/j.ejrh.2022.101045.

5. Zabel, N.A., Soliguin, A.M., Wiklund, J.A., Birks, S.J., Gibson, J.J., Fan, X., Wolfe, B.B., Hall, R.I., 2022. Paleolimnological assessment of past hydro-ecological variation at a shallow hardwater lake in the Athabasca Oil Sands Region before potential onset of industrial development. *Journal of Hydrology Regional Studies* 39, 100977. https://doi.org/10.1016/j.ejrh.2021.100977.

6. Wan, C., Gibson, J.J, Peters, D.L., 2020. Isotopic constraints on water balance of tundra lakes and watersheds disturbed by permafrost degradation in the Mackenzie Delta region, Northwest Territories, Canada. *Science of the Total Environment* 731, 139176, https://doi.org/10.1016/j.scitotenv.2020.139176.

7. Gibson, J.J., Yi, Y., Birks, S.J., 2020. Watershed, climate, and stable isotope data (oxygen-18 and deuterium) for 50 boreal lakes in the oil sands region, northeastern Alberta, Canada, 2002-2017. *Data in Brief* 29,105308, https://doi.org/10.1016/j.dib.2020.105308.

8. Gibson, J.J., Yi, Y., Birks, S.J., 2019. Isotopic tracing of hydrologic drivers including permafrost thaw status for lakes across northeastern Alberta, Canada: a 16-year, 50-lake perspective. *J. Hydrol. Reg. Stud.* 26, 100643. https://doi.org/10.1016/j.ejrh.2019.100643

9. Gibson, J.J., Birks, S.J., Yi, Y., 2016. Higher tritium concentrations measured in permafrost thaw lakes, northern Alberta, *Hydrological Processes* 30, 245-249, http://dx.doi.org/10.1002/hyp.10599

10. Gibson, J.J., Birks, S.J., Yi, Y., 2016. Stable isotope mass balance of lakes: a contemporary perspective. *Quaternary Science Reviews 131B, 316-328*, http://dx.doi.org/10.1016/j.quascirev.2015.04.013.

11. Gibson, J.J., Birks, S.J., Yi, Y., Vitt, D., 2015. Runoff to boreal lakes linked to land cover, watershed morphology and permafrost melt: a 9-year isotope mass balance assessment. *Hydrological Processes* 29, 3848–3861, http://dx.doi.org/10.1002/hyp.10502.

Classification: Public

THANK YOU

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Collaborators: Dale Vitt, Chengwei Wan, Paul Eby, Aprami Jaggi, Andrew Underwood, Tatiana Sirbu, Dayal Wijayarathne, Tiago Morais, Yi Yi, Jean Birks, Mike Moncur, Colin Cooke

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