The Uncertainties of Modelling Hydrology under a Changing Climate

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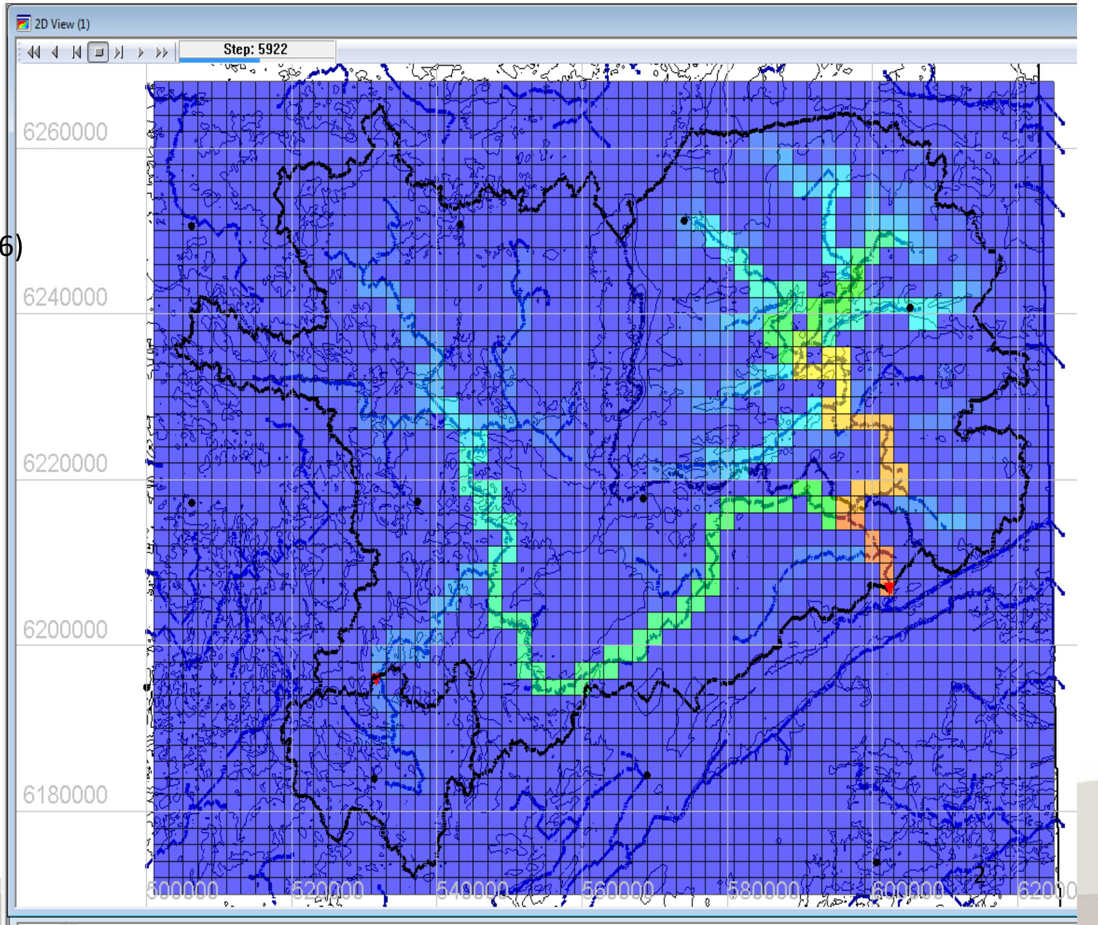
Complex Interdisciplinary ‘Wicked’ Problems

- Need to improve our understanding of hydrology, with specific focus on flow paths, sources/sinks and runoff generation IAEA (2003); Kendall et al. (1995)
- Hydrology is not “scalable” Tetzlaff et al. (2015)
- Uncertainties in watershed modelling
  - *“…Right answers for the right reasons”* Kirchner (2006)
- 23 Unsolved Problems [for Hydrology] Blöschl (2020)
  - Focus on internal water distribution
  - ‘Scalability’ of processes
  - Climate change uncertainty



“KUNKS should be treated with rigour; UnKUNKS should be treated with care; and SKUNKS should be avoided

[V. Klemeš, 1997]”

KUNK = known unknown

UnKUNK = unknown unknown

Avoiding SKUNKS

Outline

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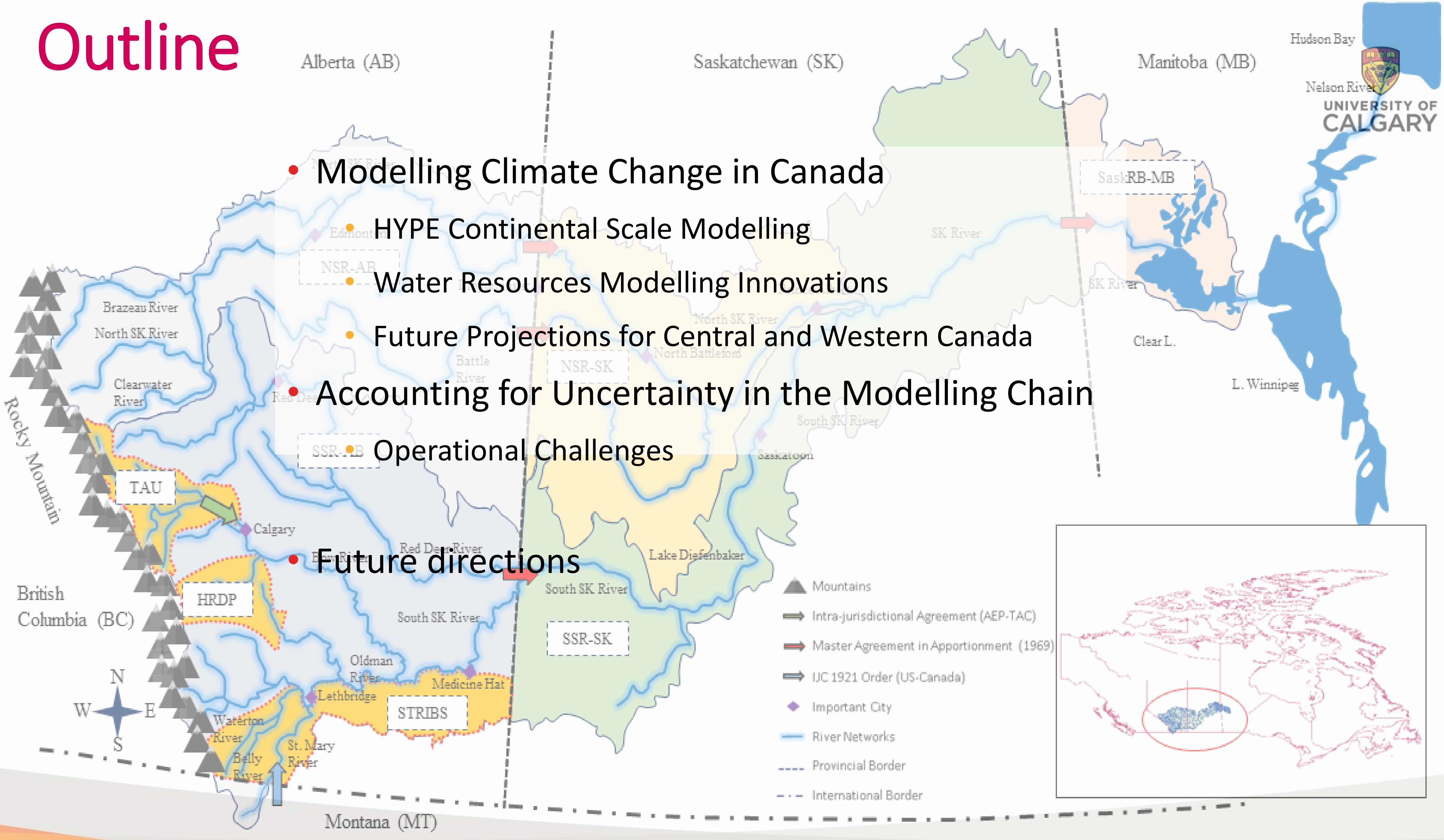
- Modelling Climate Change in Canada
  - HYPE Continental Scale Modelling
  - Water Resources Modelling Innovations
  - Future Projections for Central and Western Canada
- Accounting for Uncertainty in the Modelling Chain
  - Operational Challenges
- Future directions



The Cost of Climate Change

- 3 of top 4 of Canada's costliest natural disasters occurred in AB in the ***past decade***
- **>$8B** dollars total cost to Government of Alberta
  - **2016** Fort McMurray wildfire, **$4B**
  - **2013** AB flood, **$3.5B**
  - **1998** Quebec Ice Storm, **>$2.2B**
  - **2020** Calgary hailstorm, **$1.2B**

https://calgary.ctvnews.ca/hailstorm-damage-in-calgary-tops-1-2b-making-it-4th-costliest-natural-disaster-ever-in-canada-1.5016161

“… fast-track flood risk mitigation to avoid predictable and costly disasters before they strike.”

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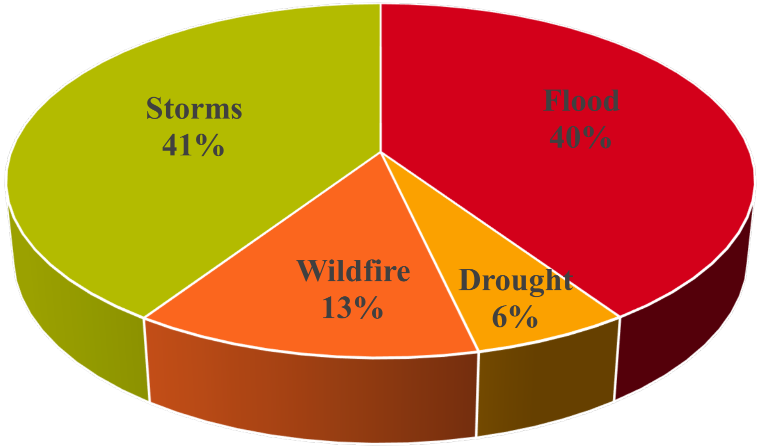
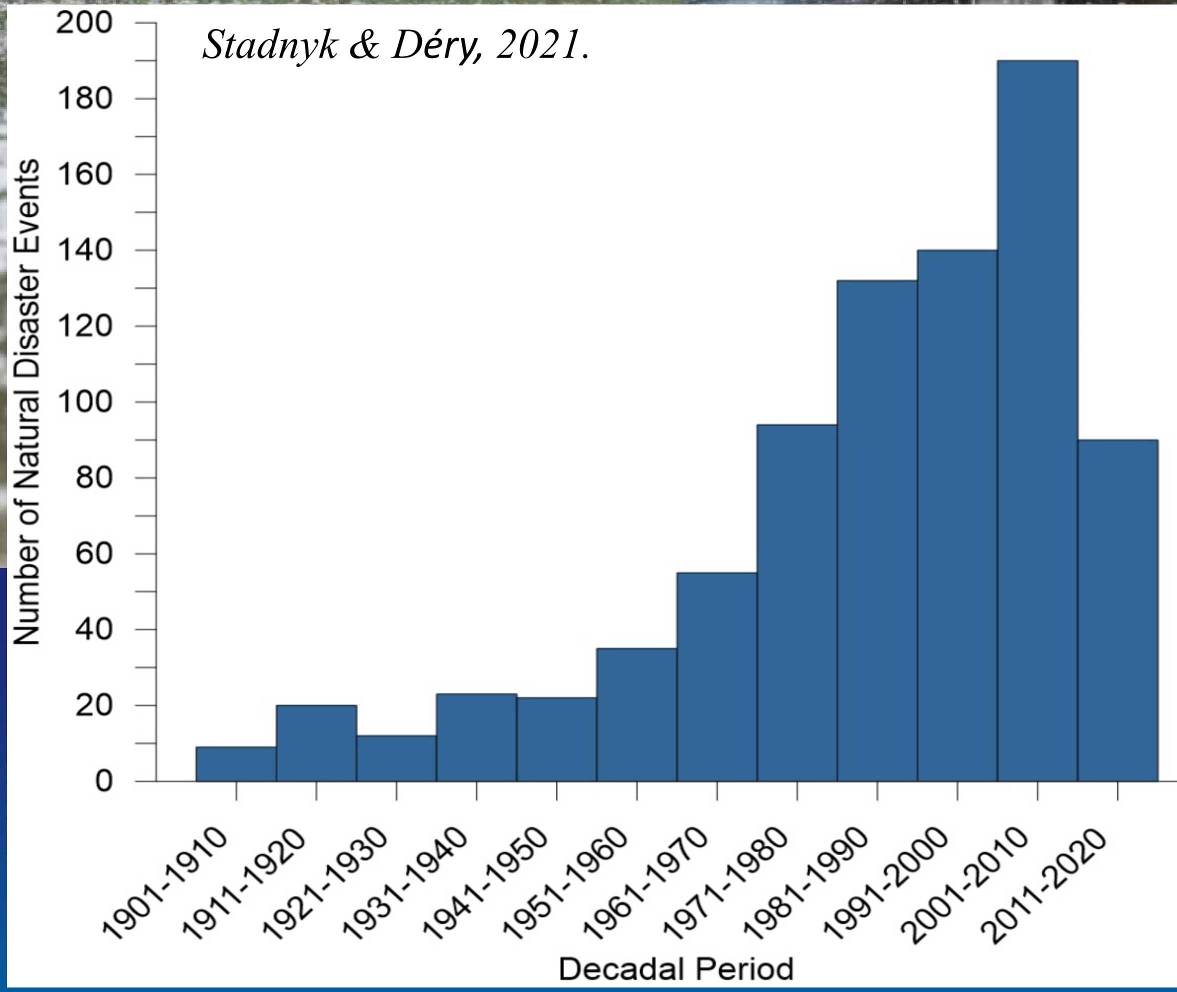
- Increase in natural disasters (ND) in recent decades in Canada
- Significant number of ND associated with hydrological events





GENEROUSLY SUPPORTED BY:

Feltmate, Moudrak, and Bakos 2020.

HYdrological Predictions for the Environment (HYPE)

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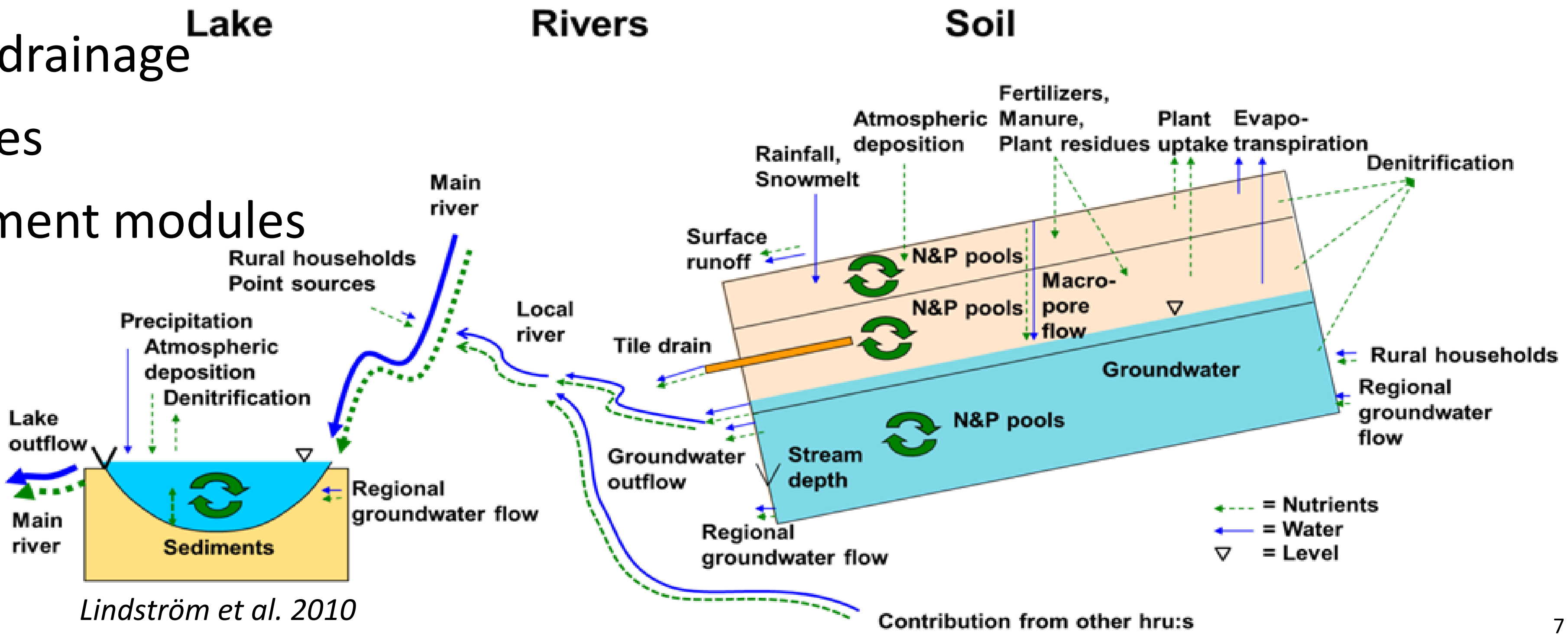
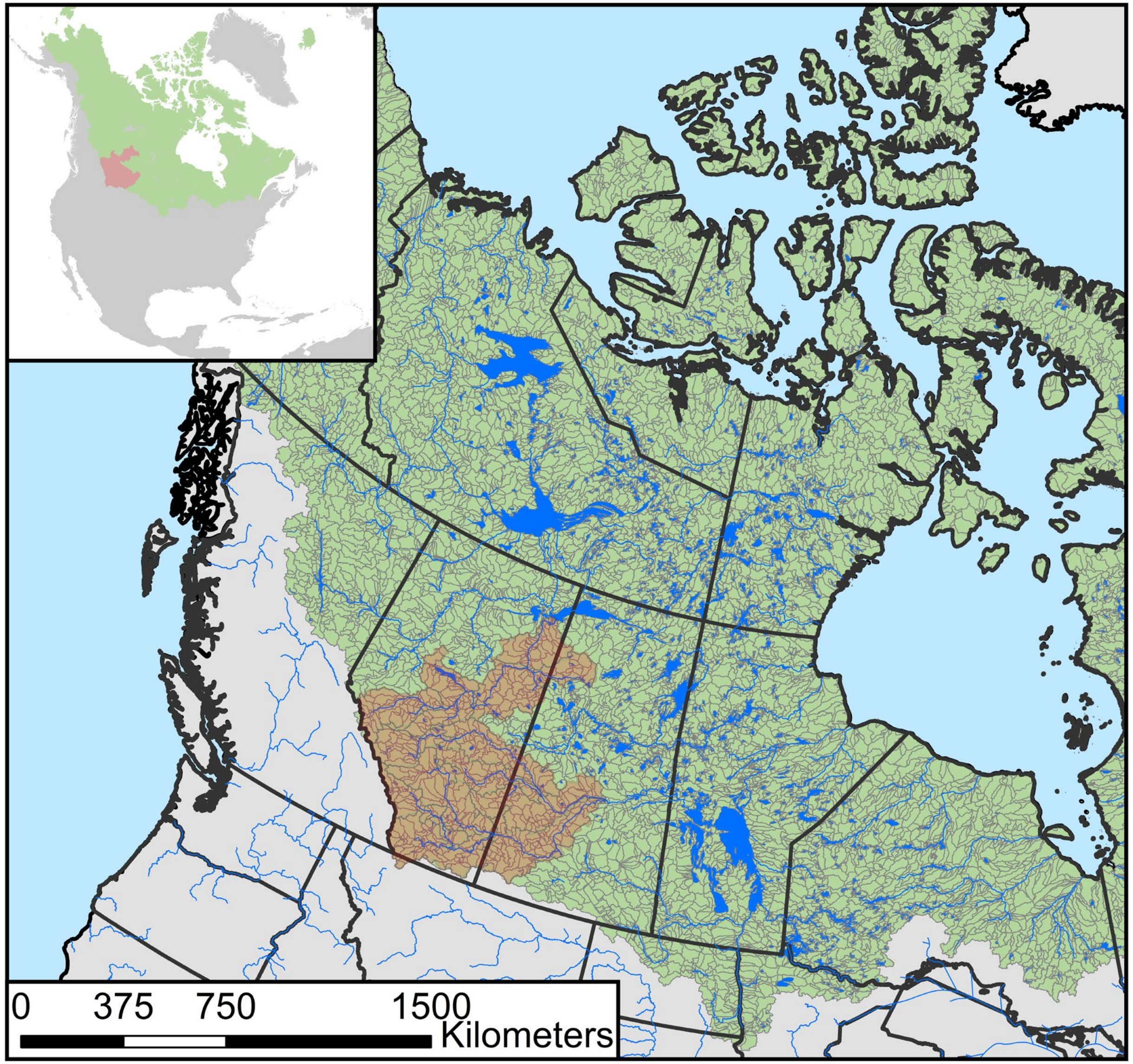
- Developed by the Swedish Meteorological and Hydrologic Institute (SMHI)
- Semi-distributed sub-basin model
- Landcover and soils
- Lakes, wetlands, tile drainage
- Cold regions processes
- Water quality + sediment modules

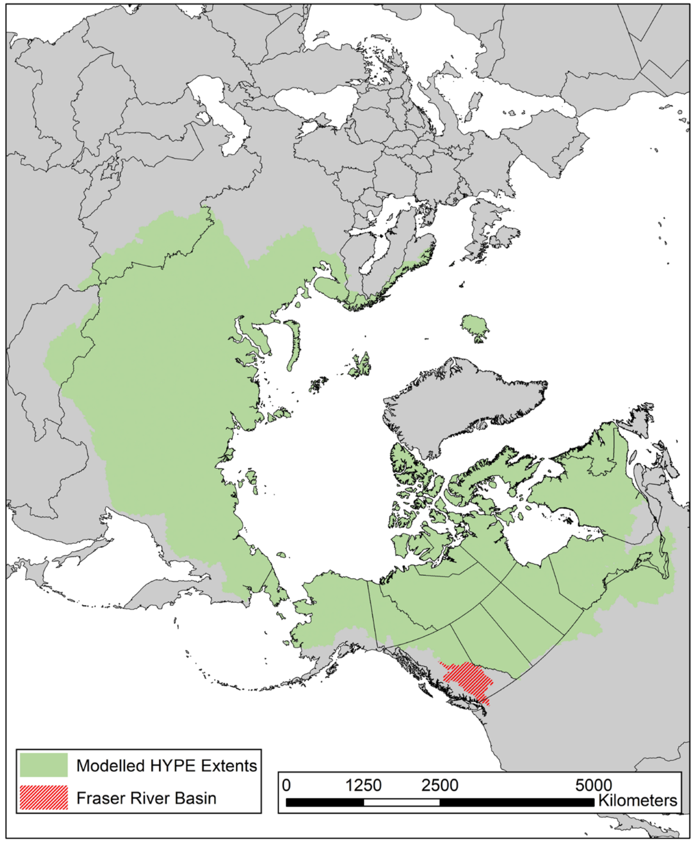
- Future developments
  - Frozen soils
  - Water temperature
  - River ice
  - Isotope-enabled

Agreement with SMHI on model development (2020 – 2025)



Lindström et al. 2010





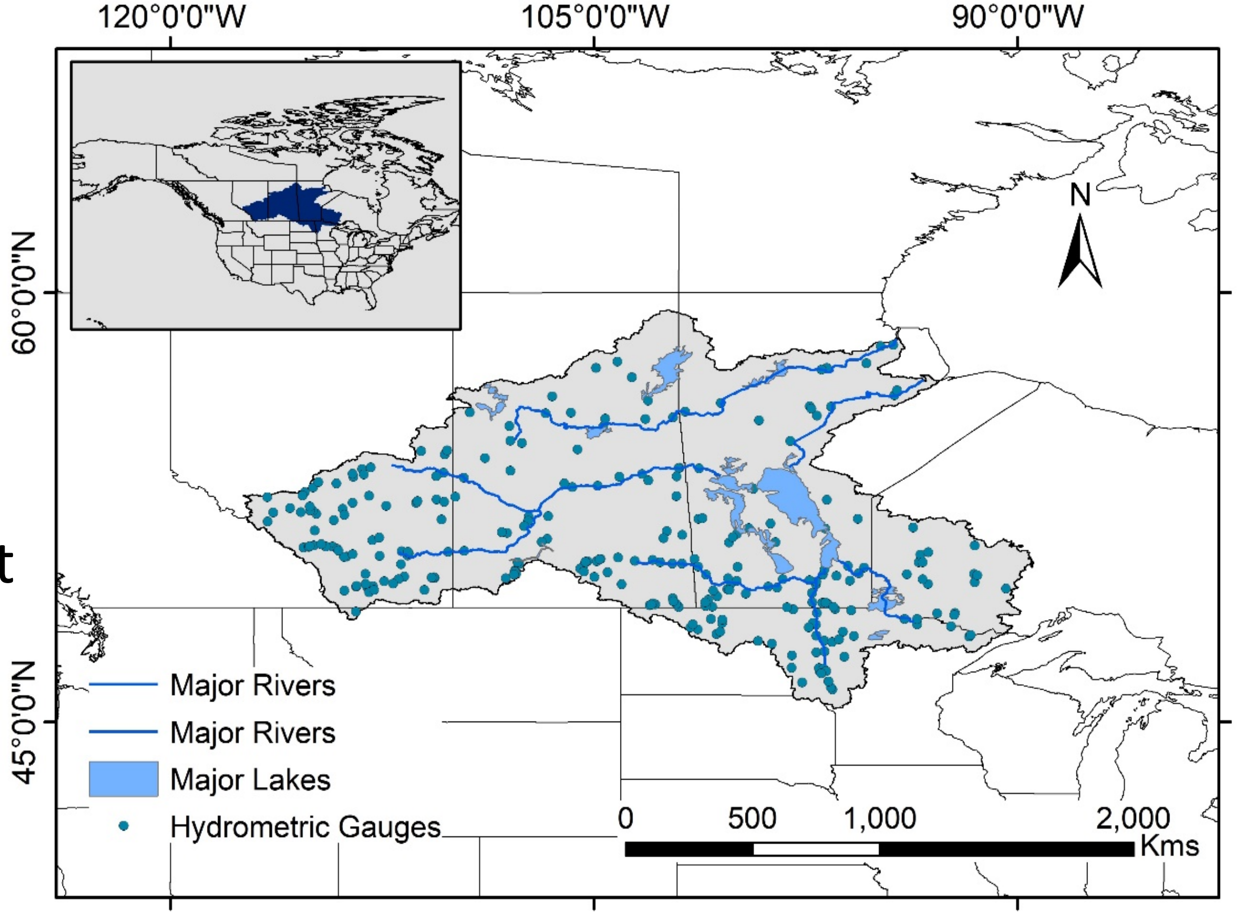
Modelled extents

Under development

Modelling Domain

Nelson-Churchill River Basin (NCRB)

- ~1.4 M km^2 of Canada's continental interior
  - Canadian Boreal and Prairie landscape
  - High-latitude, within permafrost zone
- Highly regulated
  - Agricultural drainage and withdrawal, flood control, hydropower development
- Transboundary, inter-jurisdictional management
  - 4 Provinces in Canada and 3 United States



Influence of River Regulation

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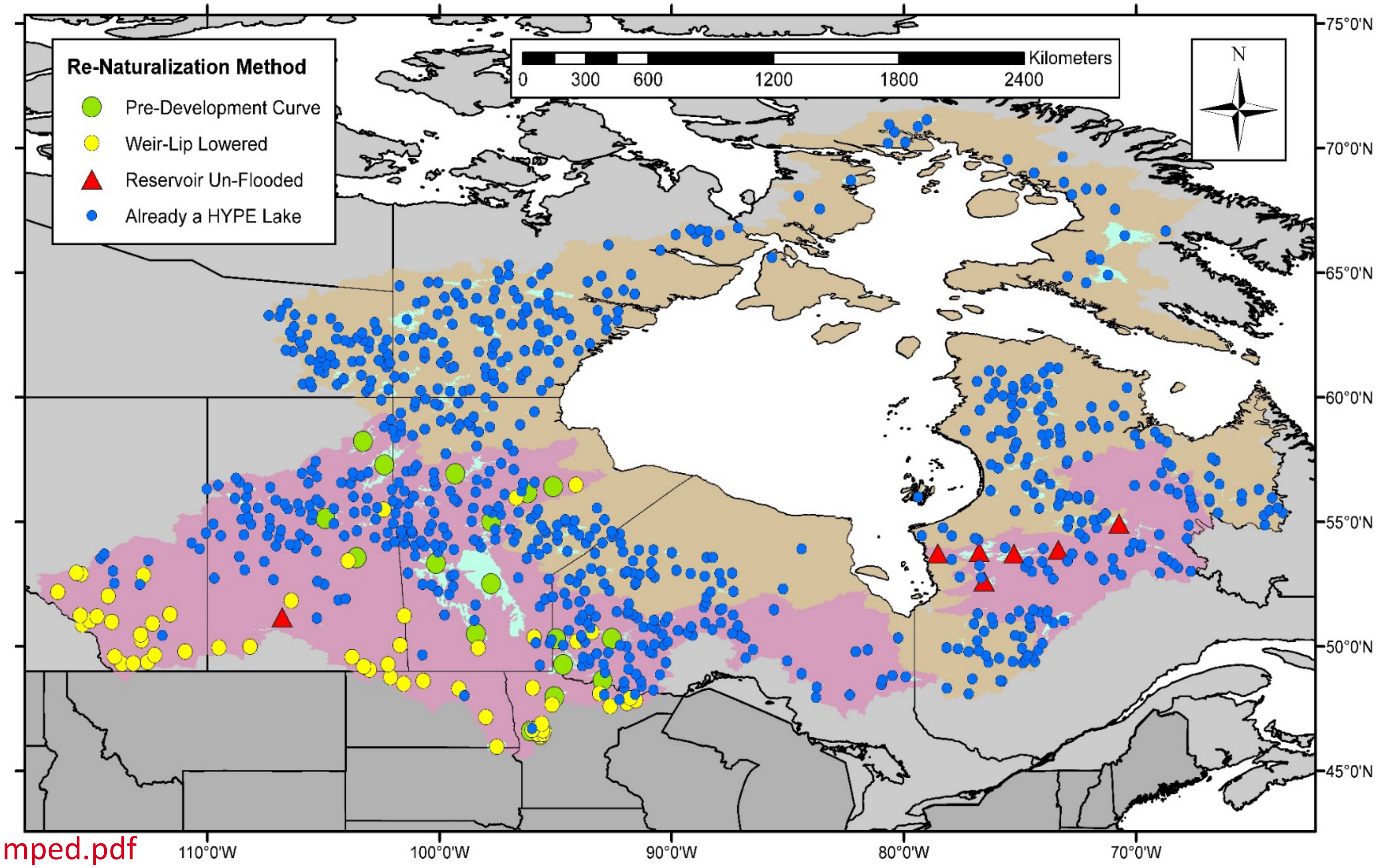
>70% of total annual discharge entering Hudson Bay is regulated; 47% being intensely regulated

Tefs et al. 2021

- Most models are not equipped to simulate human alteration of flow
  - Lakes, wetlands and reservoirs
  - Diversions, dams and irrigation
  - Infrastructure operations and decision-making

- Hydropower/hydropeaking impacts significant
  - New metric to track 'degree of regulation'



https://assets.researchsquare.com/files/rs-441563/v1_stamped.pdf

Modelling Reservoir Operations in HYPE

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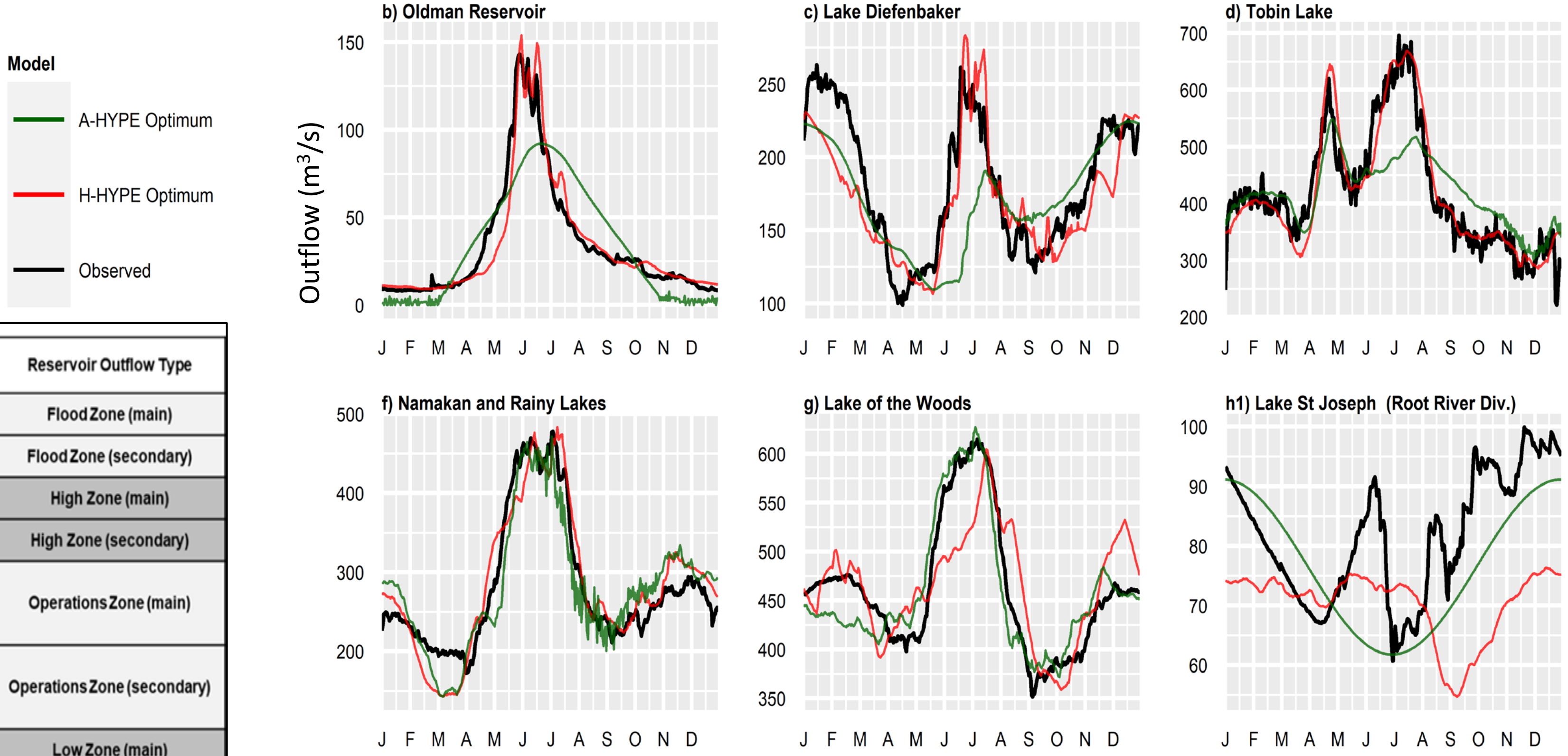
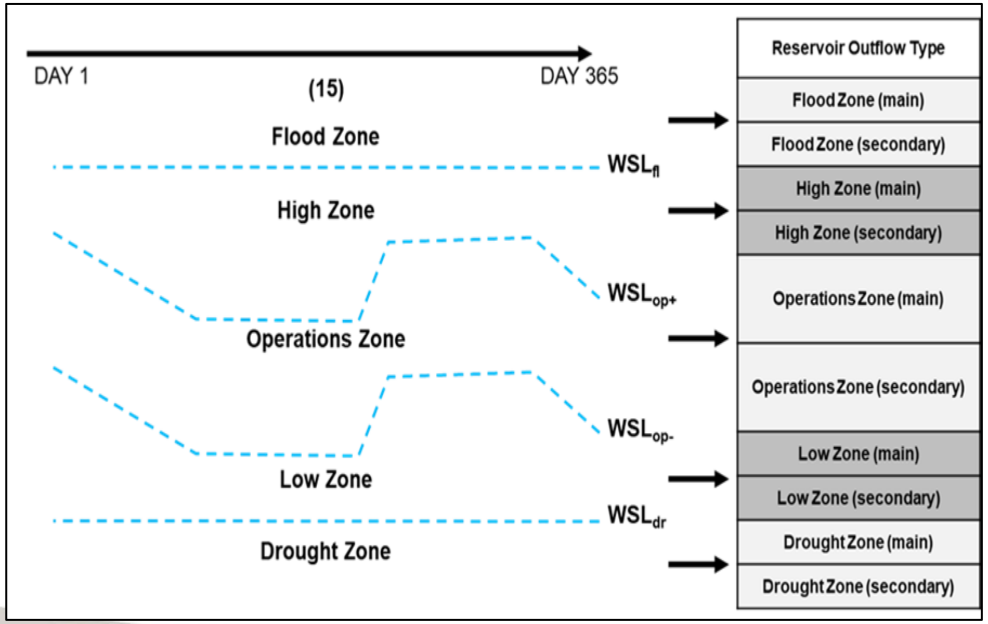
Tefs et al. 2021

- Multiple operational functions
  - 1 or 2 outlets
- Operations zones
  - Wide/thin & high/low
  - Monthly, conditional or unrestricted





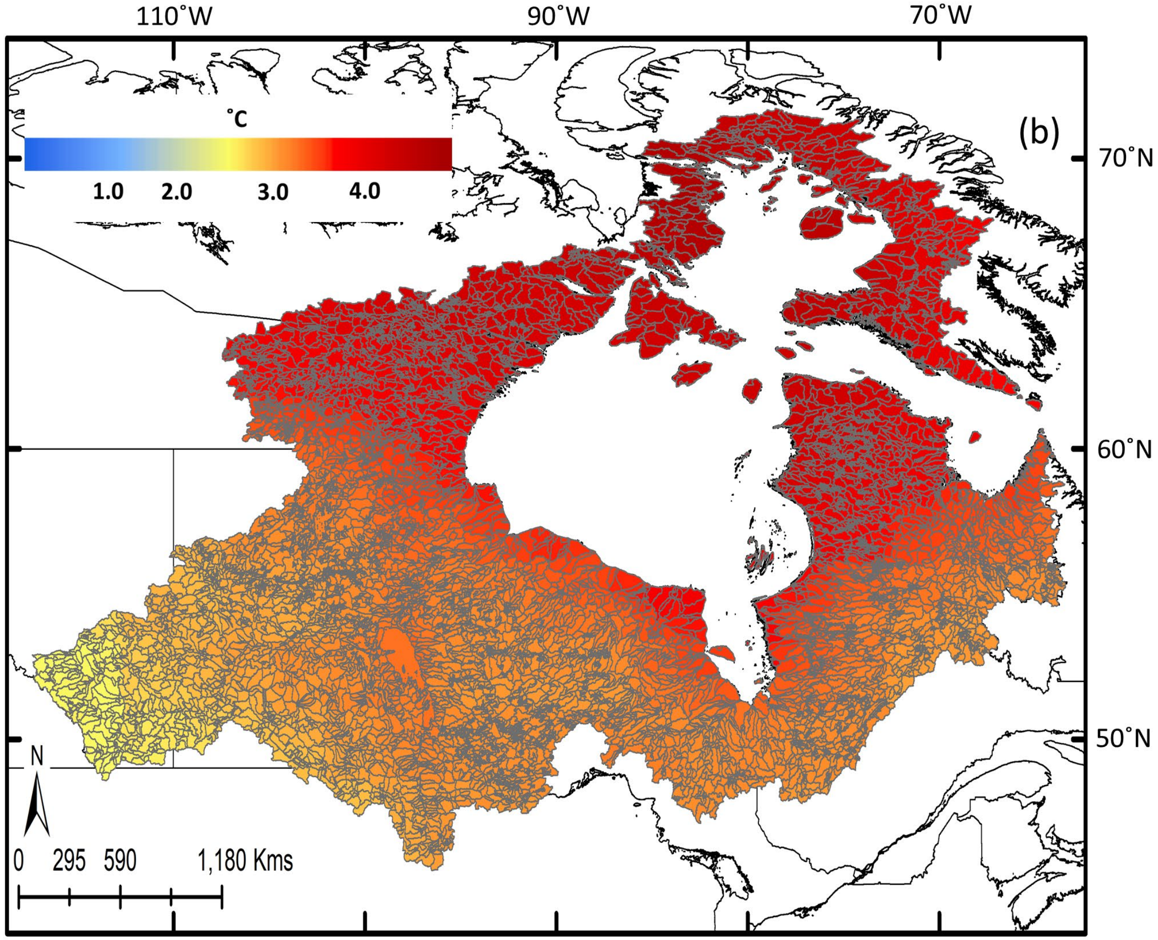
- Uses publicly available inputs

  Daily flow, Inflow, Mean surface area

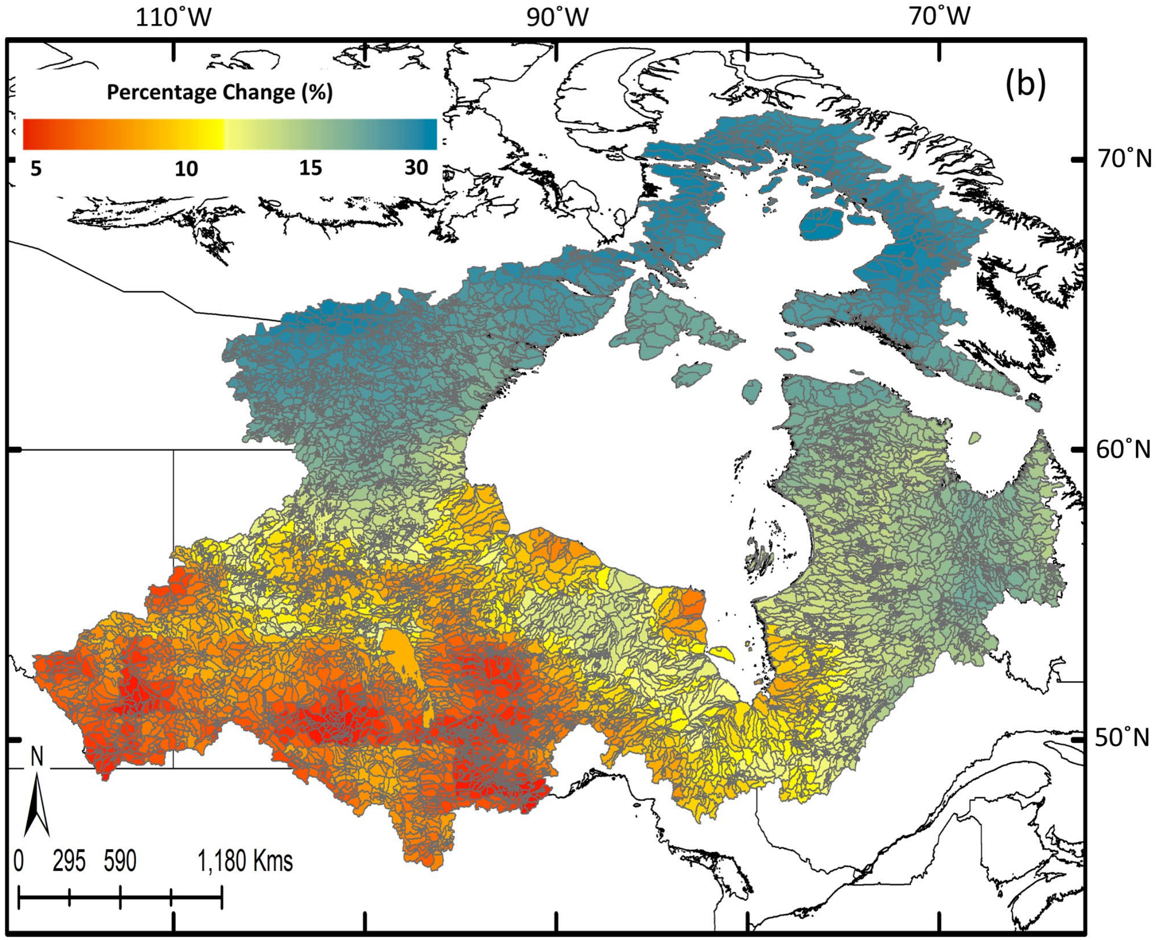
Climate Change Projections 2050's (2031-2070)

Stadnyk et al. 2019
Braun et al. submitted

Its getting warmer…



and wetter.



Derived from an ensemble of 19 CMIP5 simulations (RCP 4.5, 8.5)

Long-term Water Supply Projections

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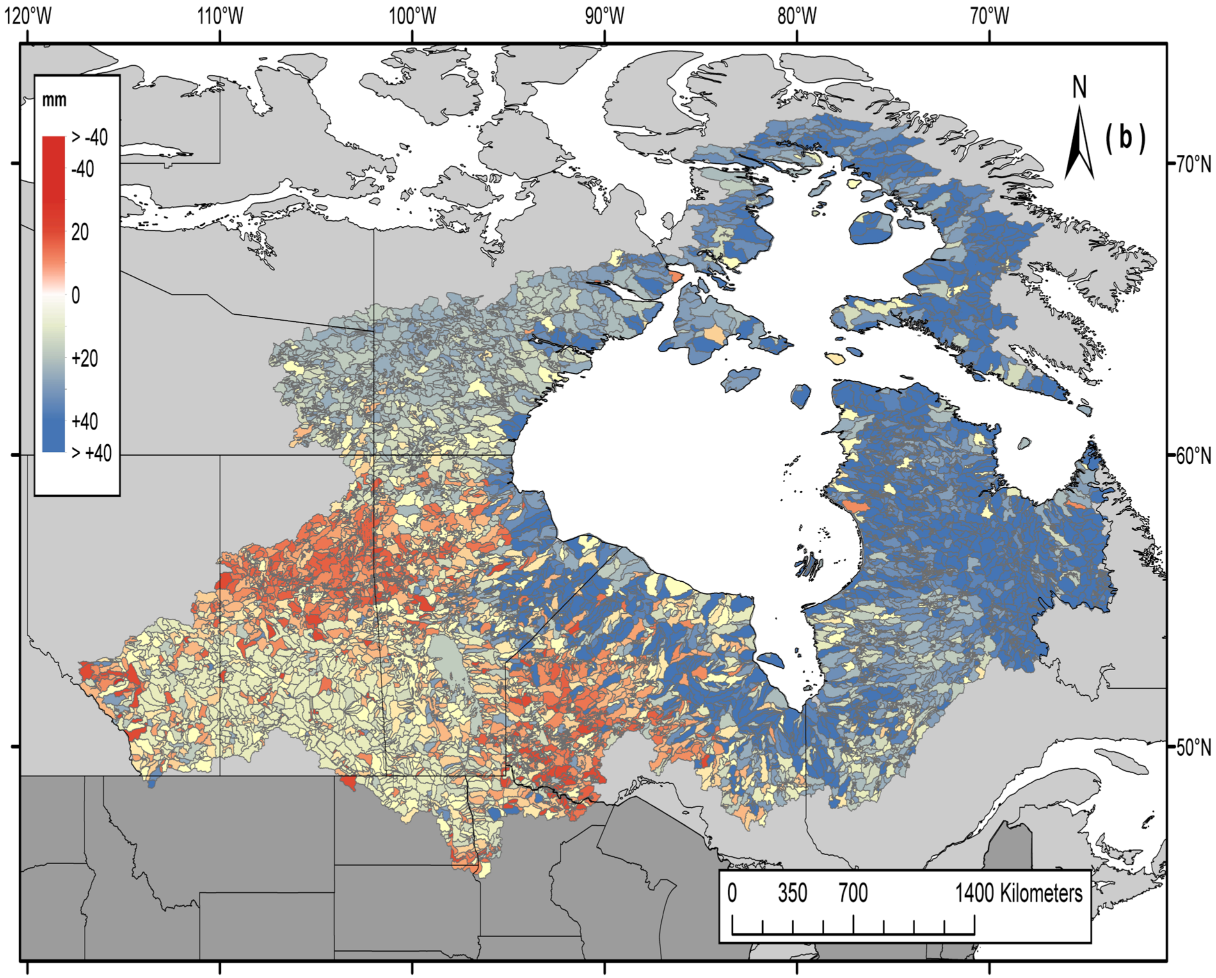
- Couple climate and hydrologic models to produce large ensembles of future hydrology
  - Identify 'hot spots'
  - Discharge increasing on average, driven by higher winter flows
  - Prairies likely to see decreasing runoff; longer dry periods
  - In the future (2021-2070), could see increases of up to 20% in the North

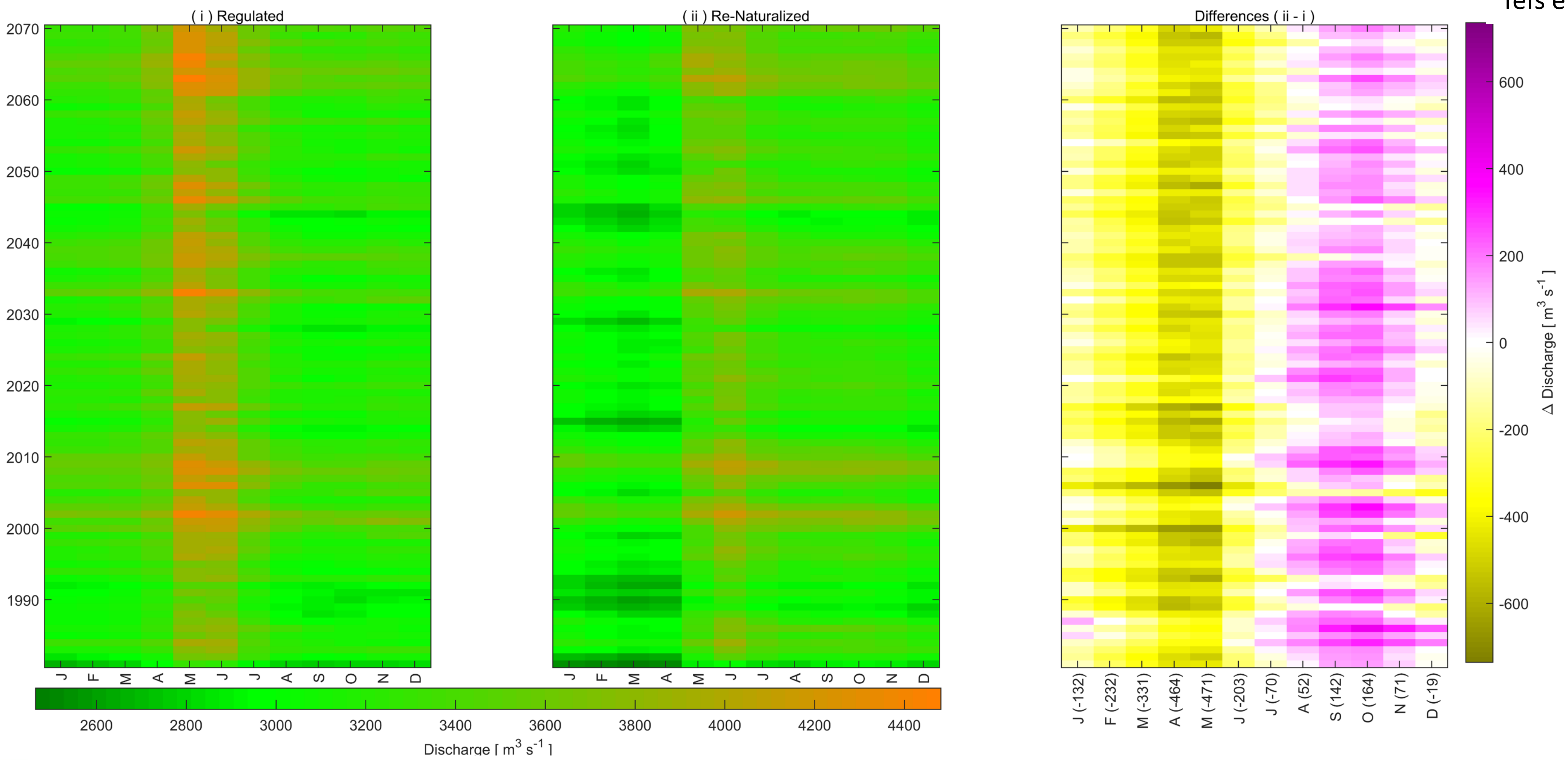
Projected change in mean annual runoff (mm) 2021-2070



Stadnyk et al. 2019

On the Impact of Regulation

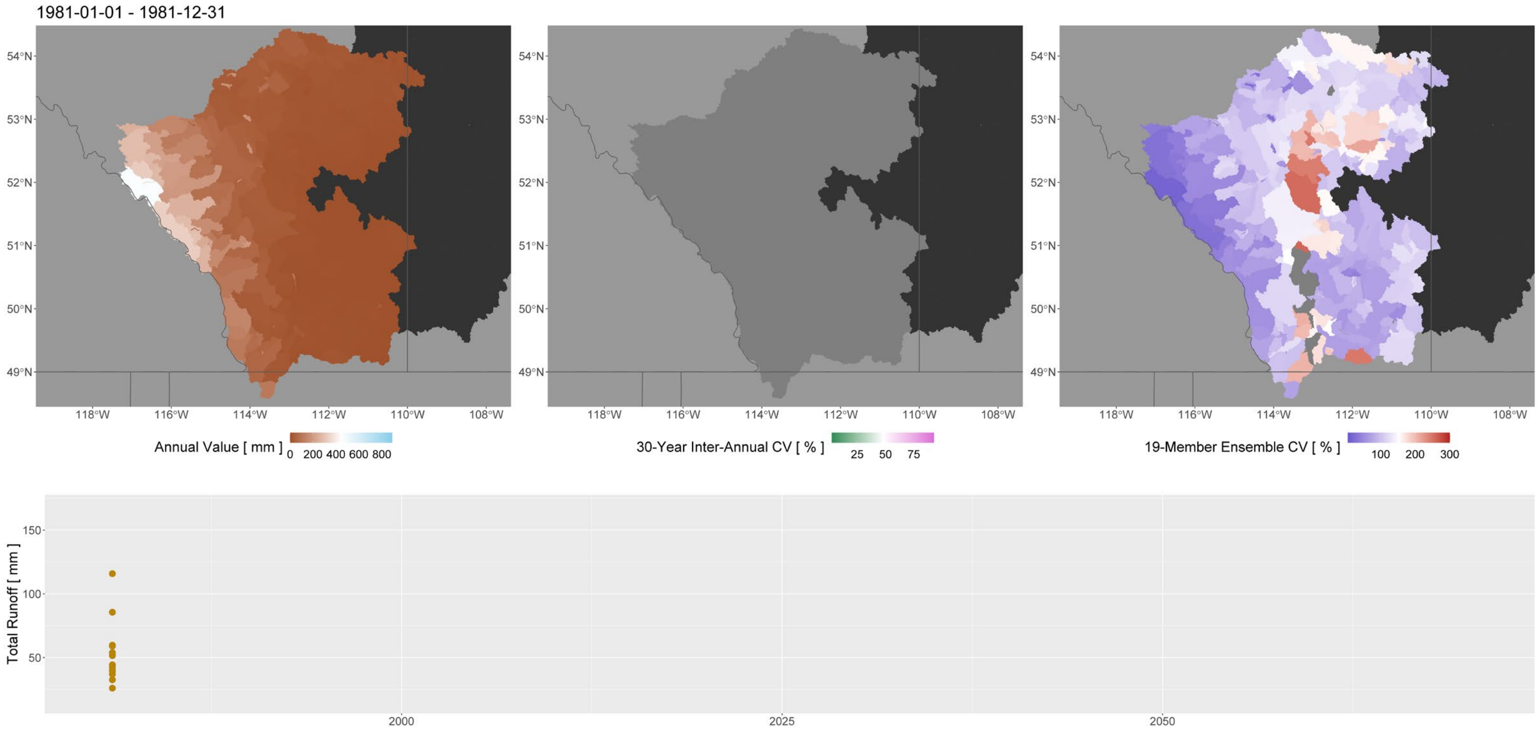
Tefs et al. in prep



Uncertainty in the Modelling Chain

Tefs et al. in prep

- Large uncertainties in climate projections
  - Particularly over the Prairies
- Include uncertainty due to
  - Input data
  - Model structure
  - Model parameterization
  - Output data
  - Future water management



Ensemble Projected Runoff for the Saskatchewan River Basin headwaters (1981-2070)

Input Data Uncertainty

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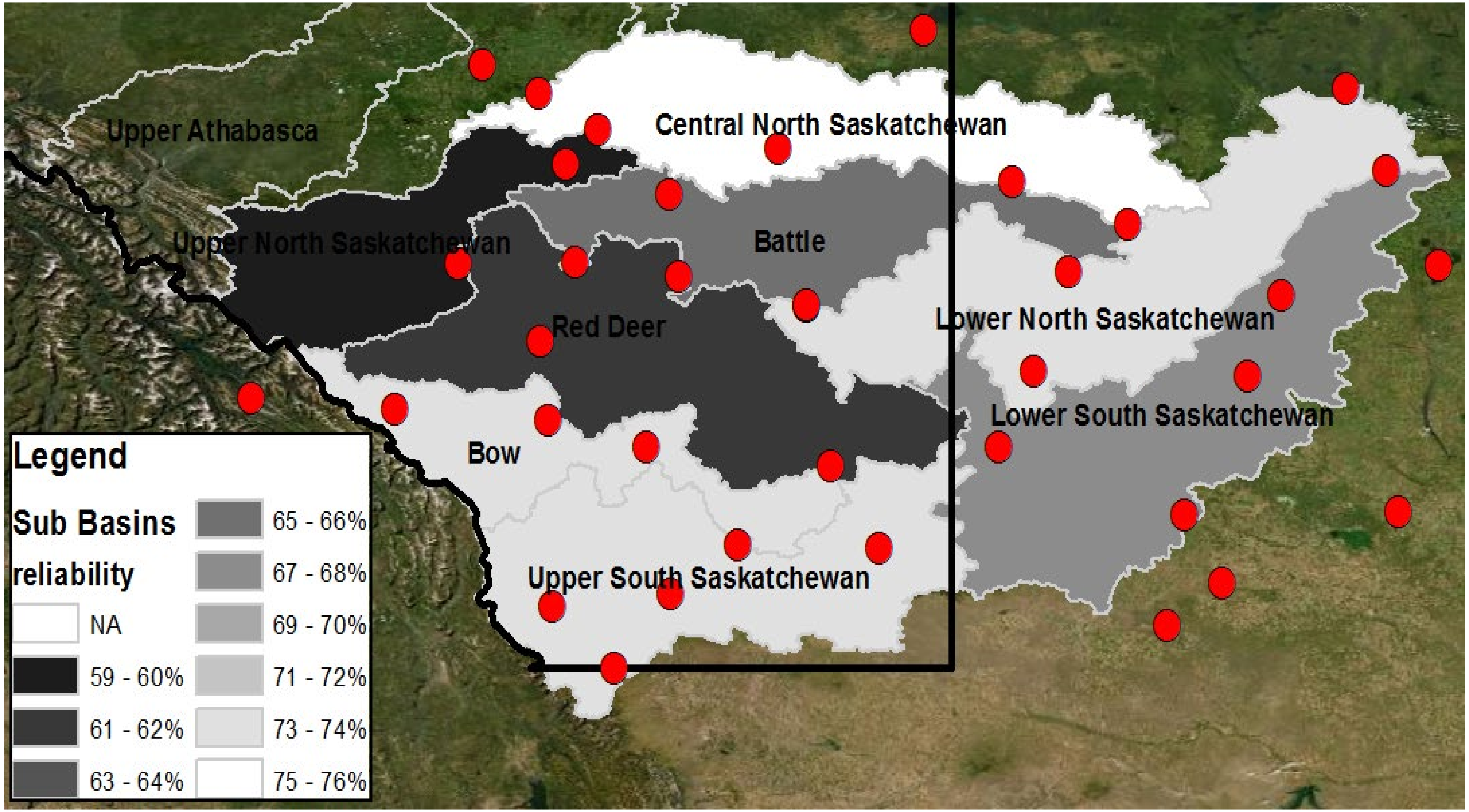
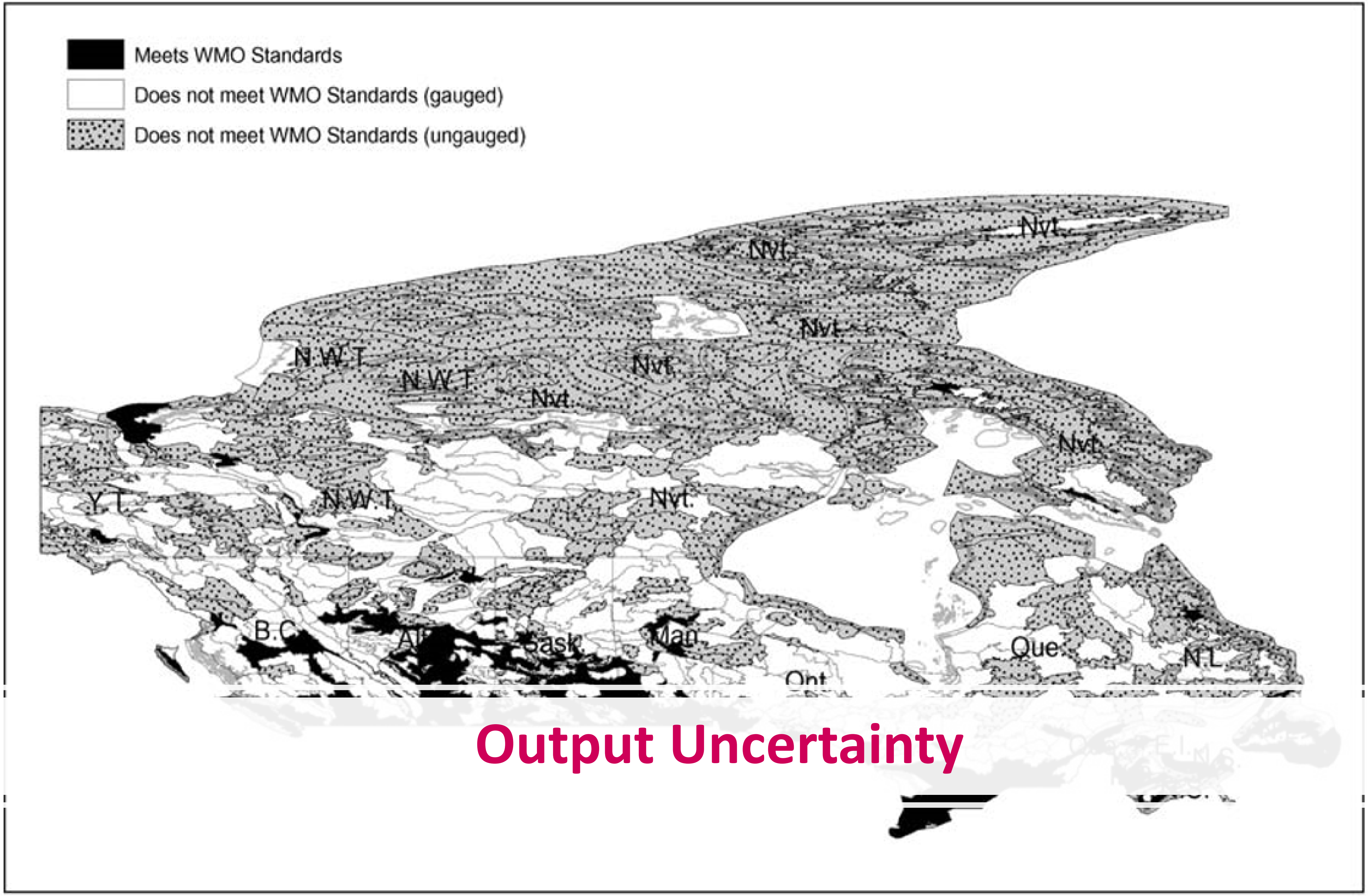
Pokorny et al. 2020
Lilhare et al. 2019



- Input data significantly impacts model reliability
- Compared 5 inputs at the subbasin scale (1981-2010)
  - ANUSPLIN, NARR, HydroGFD, WFDEI, ERA-I
- Ensemble leverages strengths/dimishes weaknesses



Output Uncertainty

Climate v. Regulation Uncertainty

Pokorny et al. (2020)
Tefs et al. (submitted)

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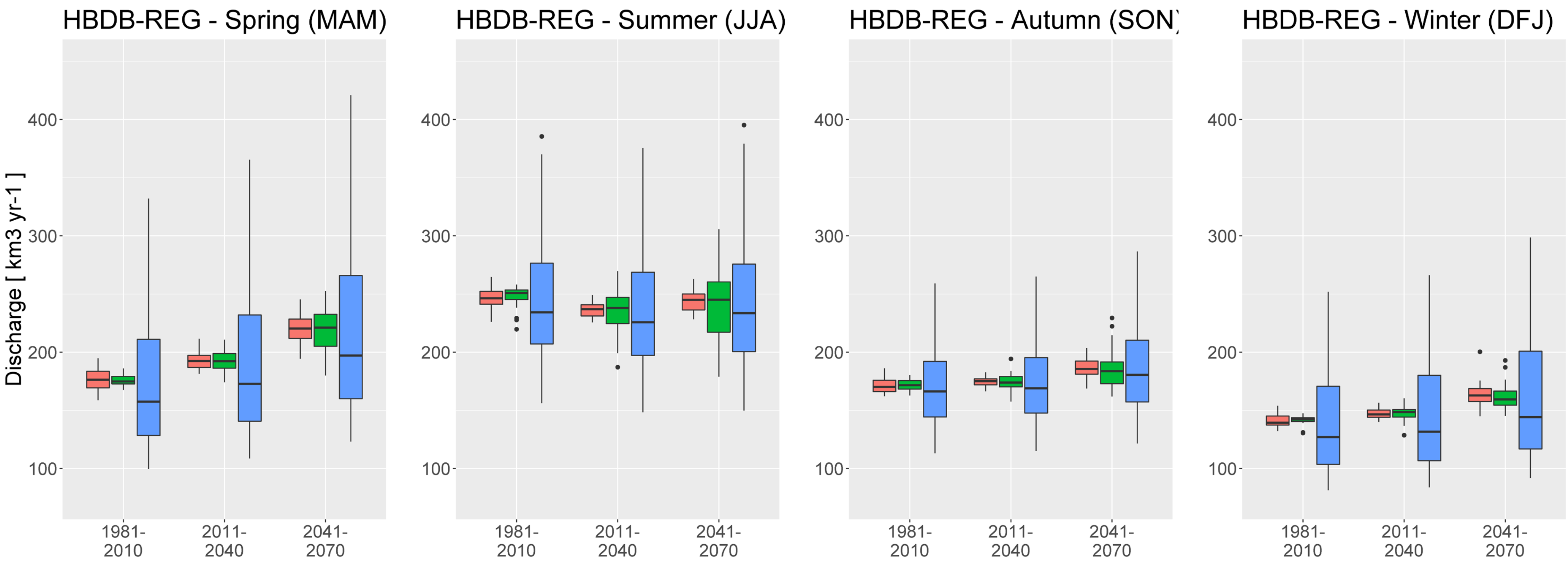


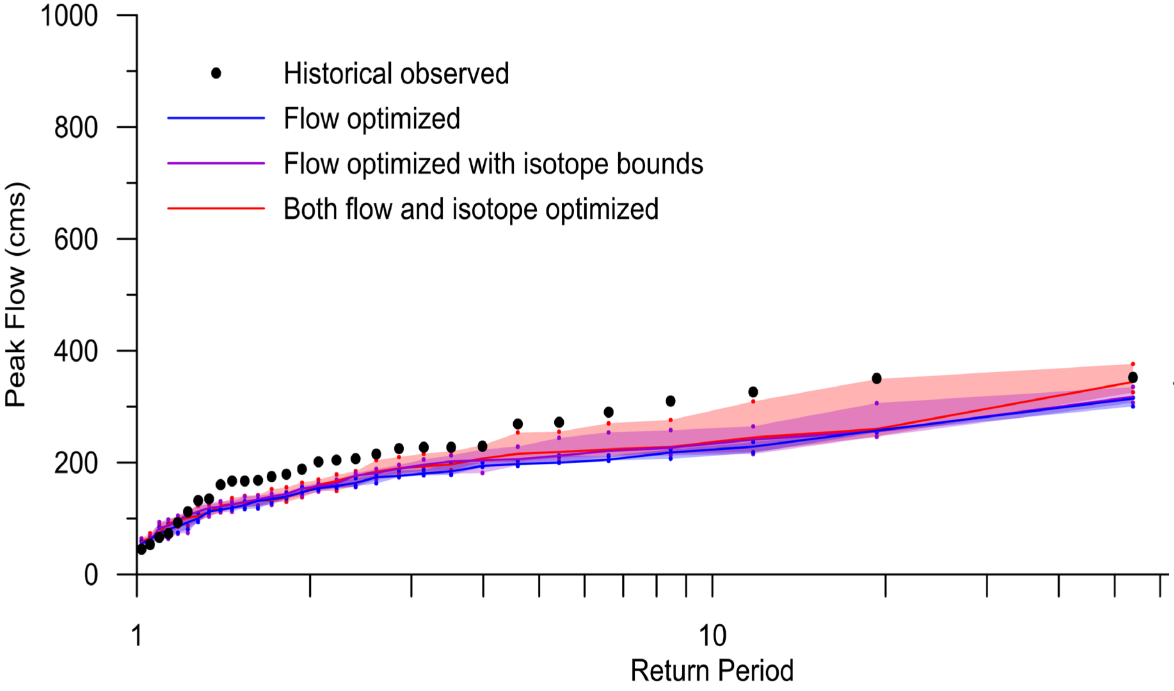
Red = annual variability of 30-year ensemble mean (inter-annual climate)

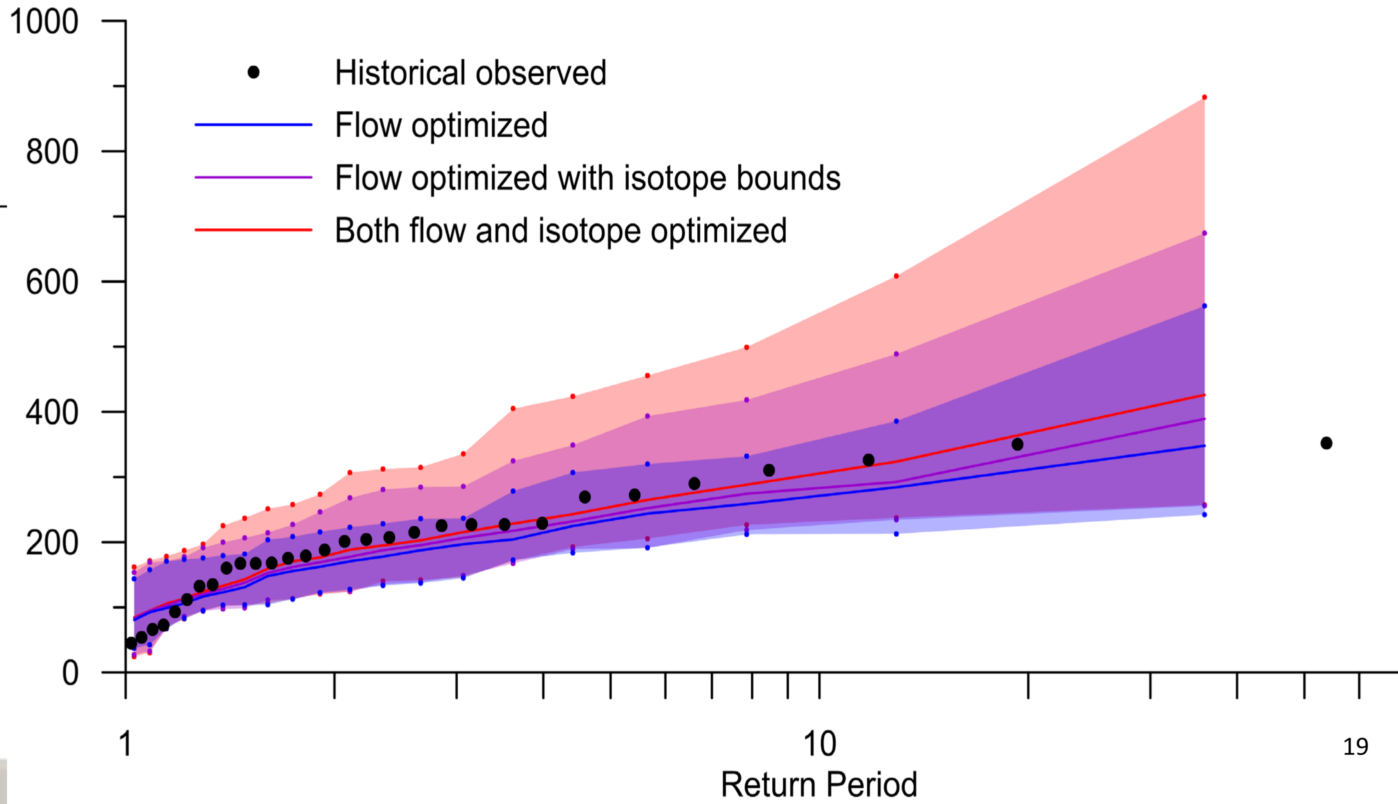
Green = annual ensemble variability (intra-annual climate)

Blue = variability under different hydrologic 'storylines' (climate + model structure)

Parameter Uncertainty: Accuracy v. Fidelity

Holmes et al. (in prep)



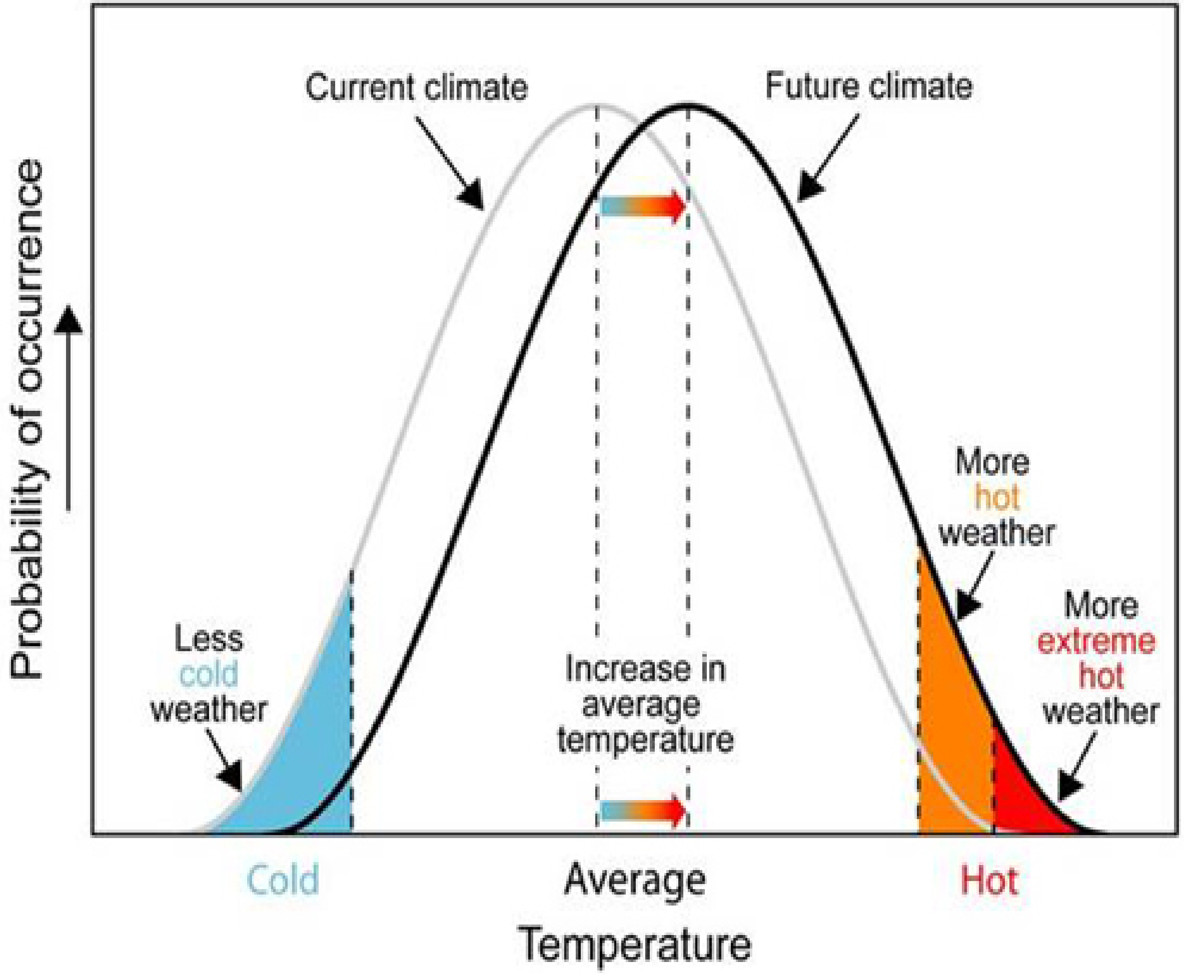


Flow duration curves generated from SO and MO optimizations (2009-2015) with and without isotope tracers v. future period (2051-2070) under RCP 8.5

Planning for the Future

- “Risk” to society
  - “Design” events are historically those that occur over shorter time scales, with high intensity and therefore with lower frequency
  - Mean may shift, but more impact to tails of the distribution (i.e., extremes)

Adapted from Kodra & Ganguly, 2014

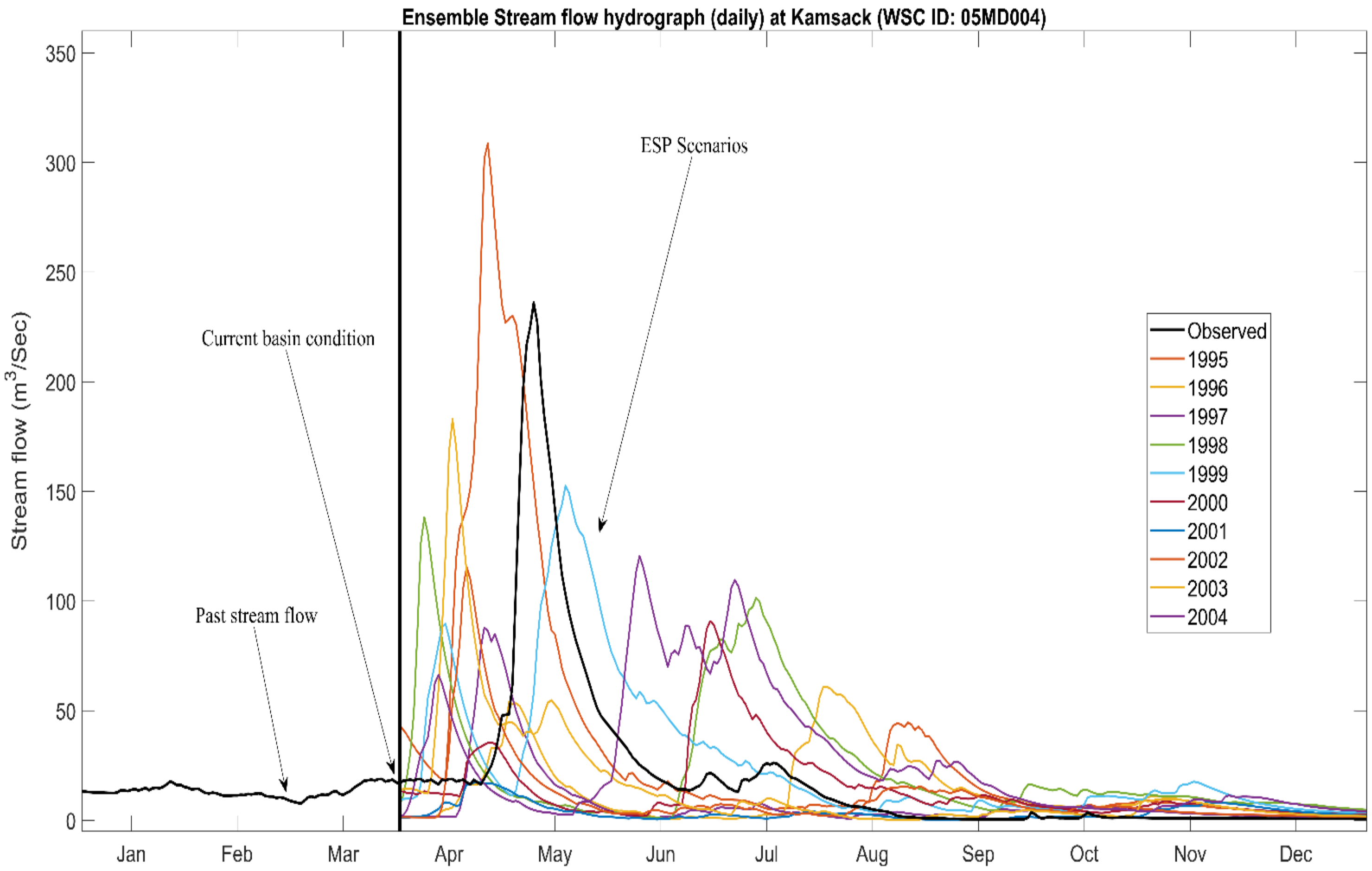


Dealing with Uncertainty in Operations

- Models are different possible representations of reality

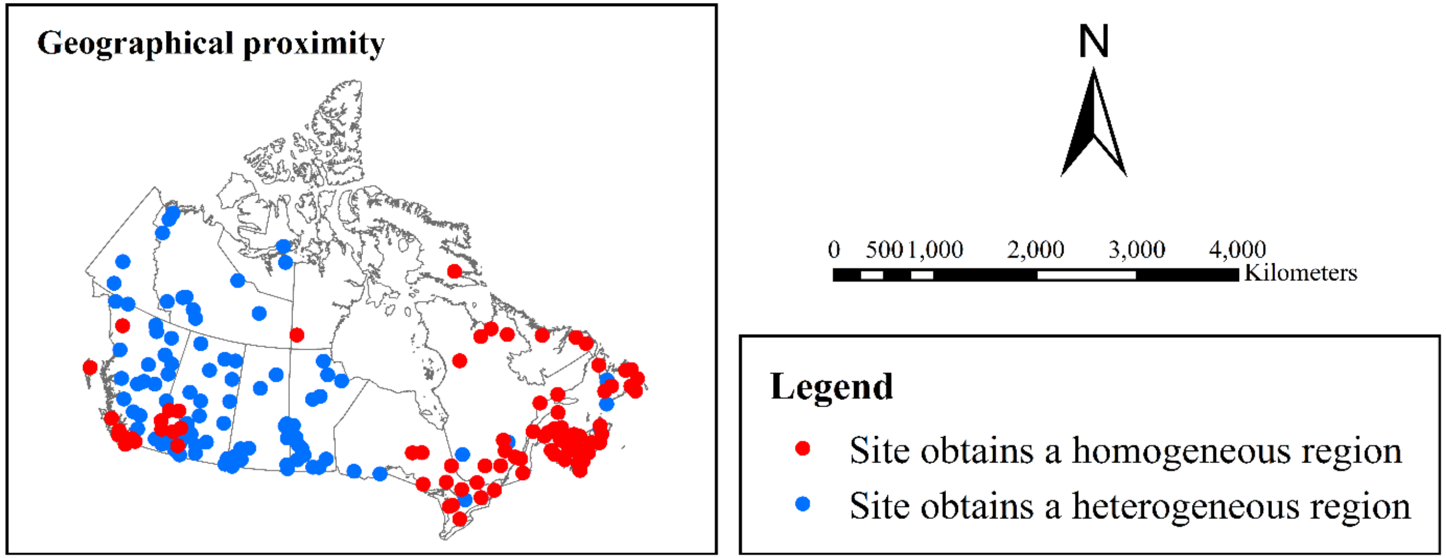
"All models are wrong, some are useful"
[Box, 1976]

- Leverage multiple models and scenarios to obtain a distribution of flow
    - Quantify risk and reliability
    - Increase likelihood of *accurate* predictions



Flood Frequency Analysis In Canada

- Zhang et al. (2020) showed hydrometric records in Canada are insufficient for accurate FFA
  - Too short to estimate extreme quantiles (i.e., >Q_{50})



- Developed regionalization procedure to group hydrometric gauges based on hydrologic similarity measures
  - Increases station record length to estimate >Q_{100} for all sites across Canada

Ensemble Flood Forecasting

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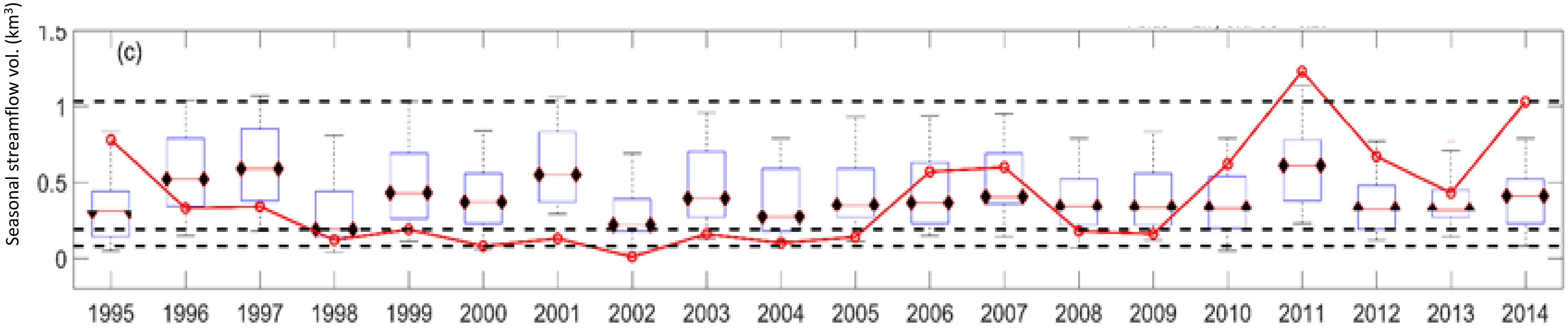
Muhammad et al (2018)

- Post-processing tools required for Canadian Hydrologic Forecasters
  - Ensemble methods leverage the best of all models and diminish individual weakness
  - Determine uncertainty in forecast
  - Translate uncertainty into probability and risk



Seasonal forecast for Manitoba Infrastructure, City of Winnipeg

Hydropower Production and Climate Change

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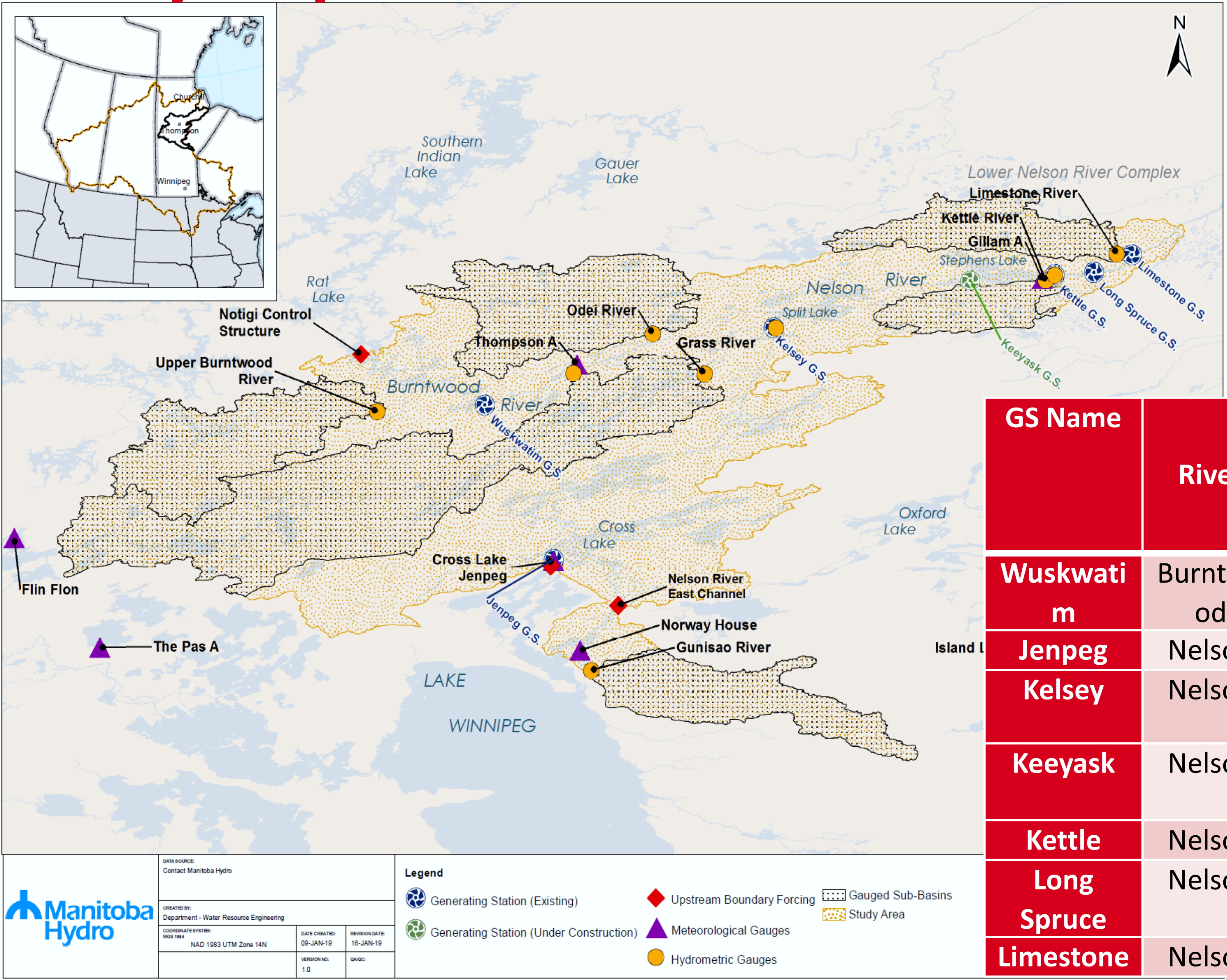

GS Name	River	Completion Year	Power Generation Capacity [MW]	Generating Station Type
Wuskwatim	Burntwood	2012	211	ROR
Jenpeg	Nelson	1979	115	CS
Kelsey	Nelson	1957	464	Storage[1] (limited: ~ 1 month)
Keeyask	Nelson	Expected 2022	695	ROR
Kettle	Nelson	1970	1, 220	ROR
Long Spruce	Nelson	1977	980	ROR
Limestone	Nelson	1990	1, 350	ROR

Sagan et al., 2019

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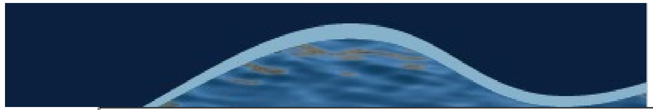
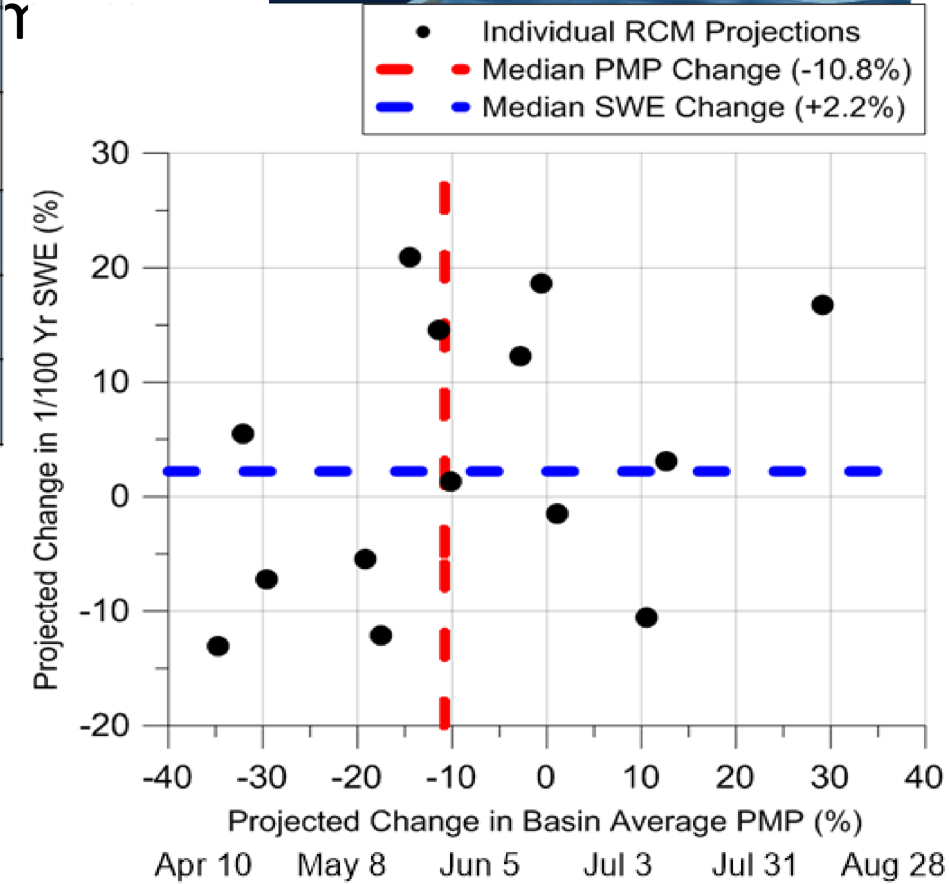
Infrastructure Design: Probable Maximum Flood

	Change from SSARR PMF (%)	Projected Climate Change Impacts		
		Minimum (%)	Median (%)	Maximum (%)
Basin Outlet				
SSARR	N/A	-11.7	0.0	19.7
HEC-HMS	-12.1	-9.3	0.6	12.2
WATFLOOD	2.5	-14.4	-3.2	13.0





- Method:
    1. Produce baseline PMF using different models
    2. Perturb with future climate scenarios
    3. Evaluate future climate-affected PMF sensitivity

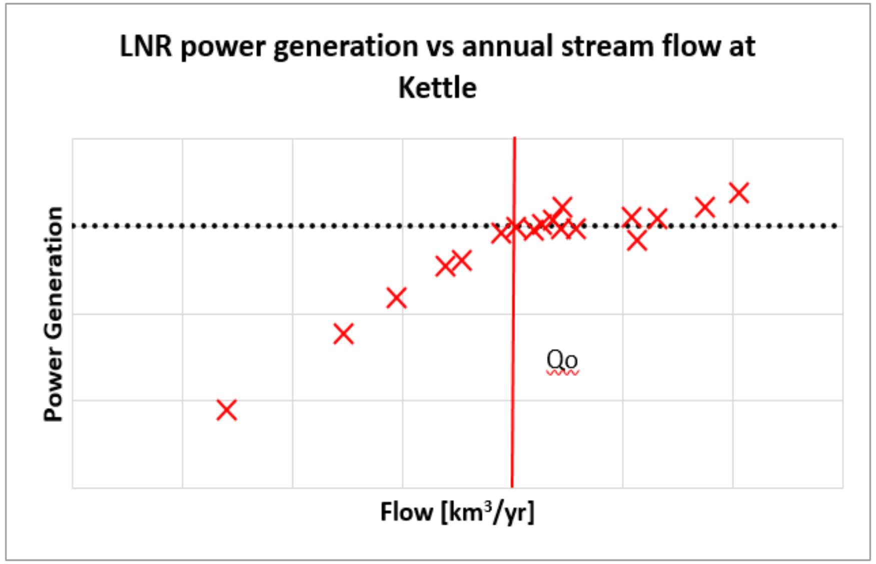
[1]Canadian Dam Association. Dam Safety Guidelines, revised 2013

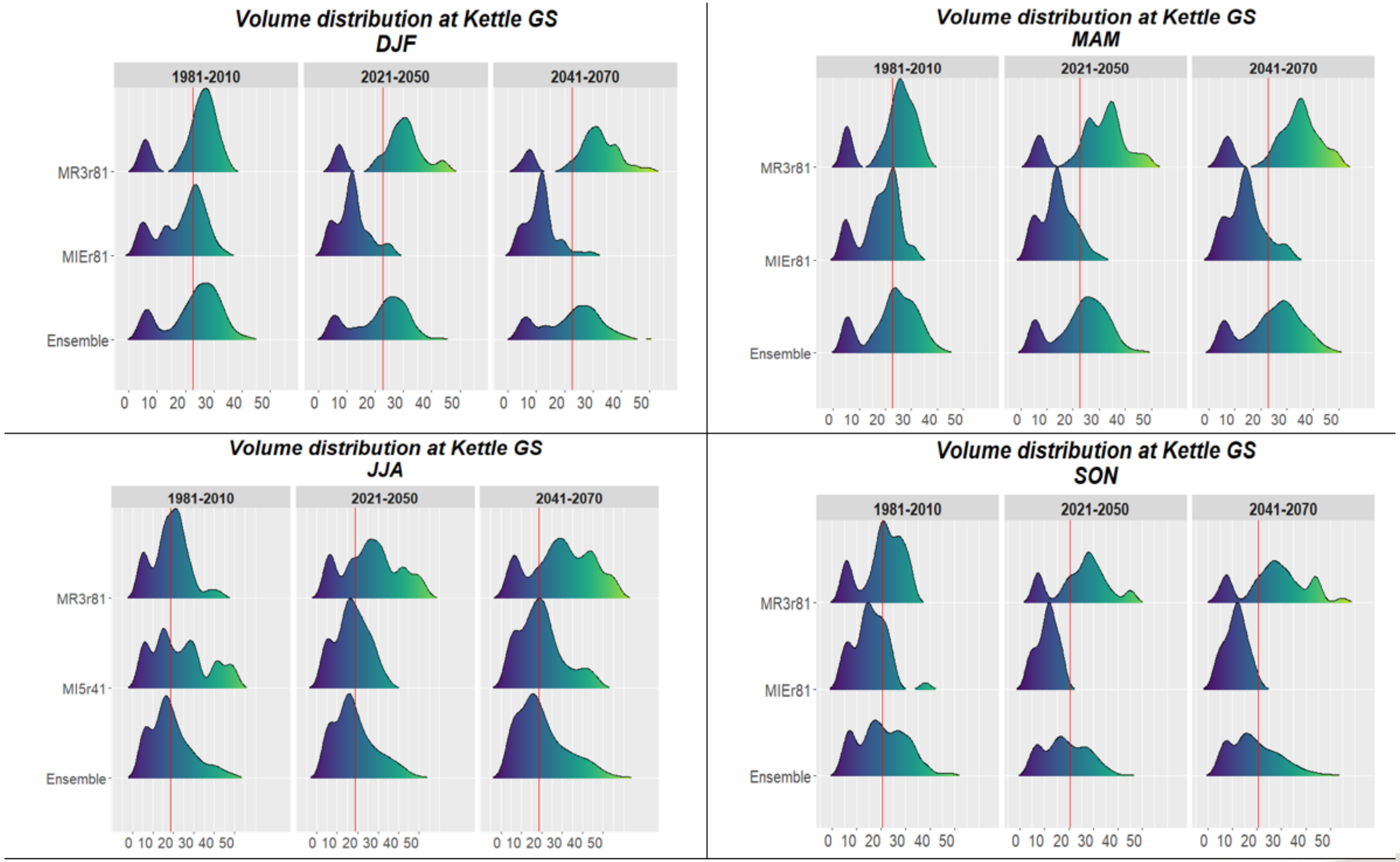
Ouranos. (2015). Probable Maximum Floods and Dam Safety in the 21st Century Climate. Report submit-ted to Climate Change Impacts and Adaptation Division, Natural Resources Canada, 39 p.

Net Energy Production under Changing Climates

Kim et al., submitted

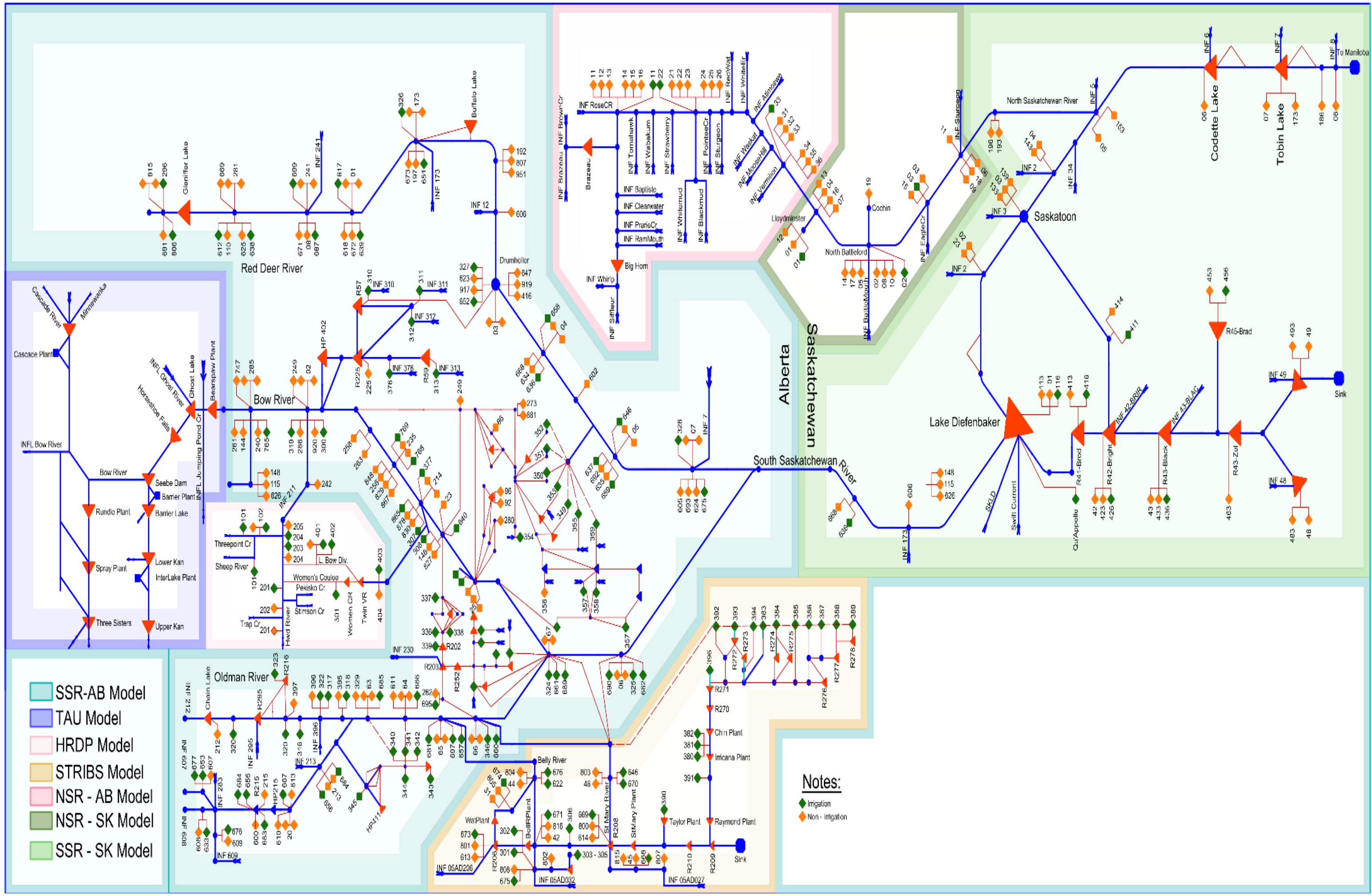
- High flows becoming more common
- Energy production plateaus at higher flows
  - Spill increases tailwater and decreases head



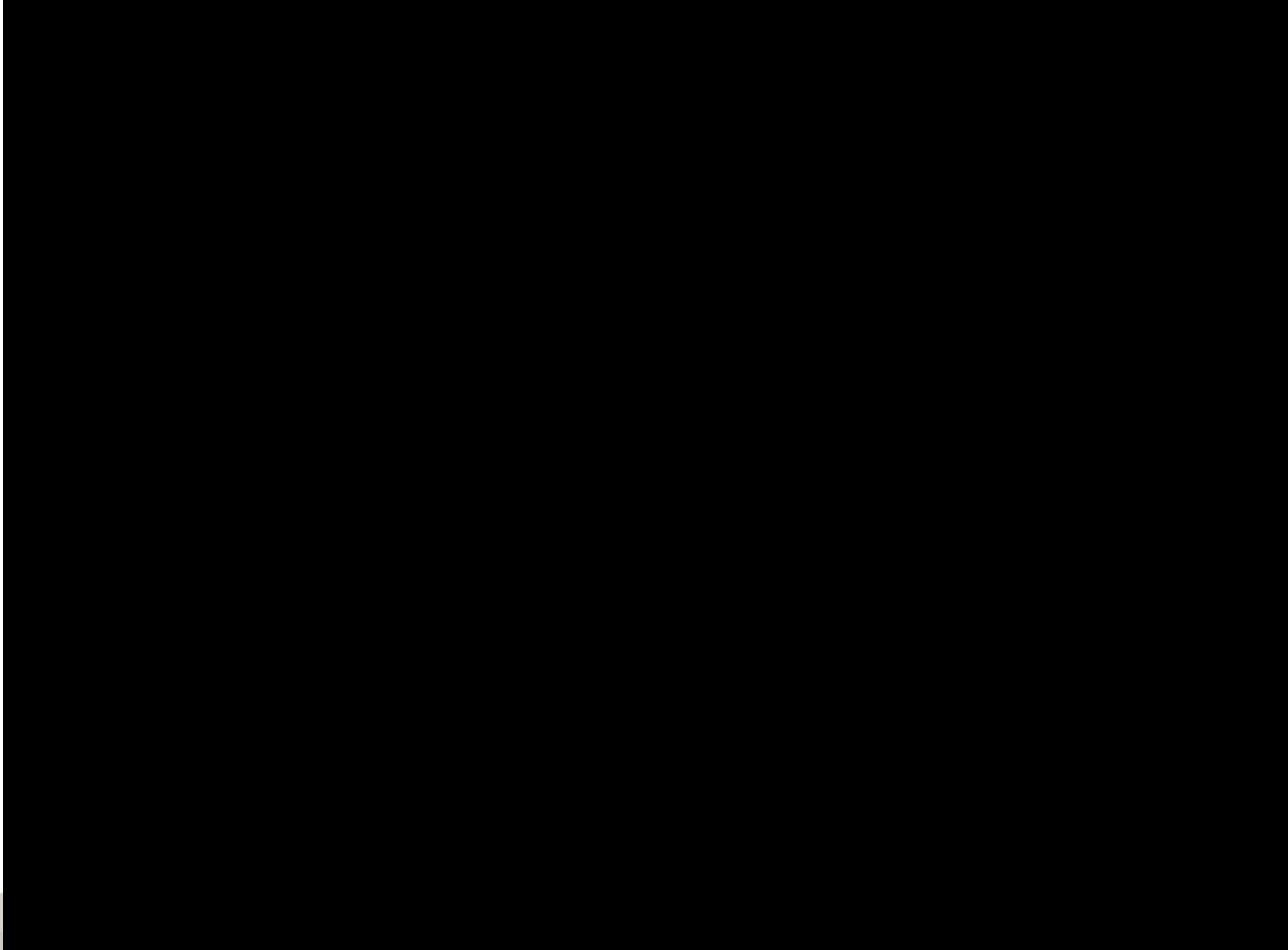


Future Water Management Decisions

- Couple hydrology with Integrated Water Resource Management (IWRM)
  - Incorporate human decisions at system nodes
  - Add climate-driven hydrological response
  - Evaluate inter-jurisdictional water use
  - Define cost/benefit of decisions



Decision-Support for Practitioners



MODSIM visualization (Gutwin et al., Computer Science, UofS)

Risks to Infrastructure and Energy Industry

1. Infrastructure largely designed for *spring freshet* flood protection
   - Higher winter flows possible; icing in culverts lowers conveyance
   - Rain on snow events becoming more common; earlier spring flood risk
   - Lower spring freshet puts recreational and agricultural storages at risk
   - More frequent summer floods mean conveying shorter duration, higher volumes
2. Changing PMP/PMF Conditions and Extreme Events
   - Shift to shorter duration rainfall flood events means less warning time, requiring more accurate forecasting systems
   - Inadequacy of flow conveyance infrastructure
     - Increasing low quantile events in winter; high quantile summer events

Risks (cont'd…)

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3. Seasonality is changing
   - Management of diversions, flood channels and outlet structures will need to be adapted, particularly in terms of timing of rating curves
   - Ice-on rating curves will be significantly impacted as ice thickness changes
4. Management of ecological and environmental flow needs
   - Difficulty maintaining low flow requirements and appropriate stream temperature
   - Impact on water quality and physical properties likely significant
5. Increasing long-term drought risk
   - Vulnerability of water supply under current water share agreements
   - Increasing socio-economic risk

The Way Forward

- ‘Best’ model input data
  - Driving an ensemble of hydrologic models with ensemble inputs offers more robust performance (Pokorny et al. 2020; Lilhare et al 2020)
- Leverage ensemble approaches to modelling
  - Ensemble of *meteorologic* inputs to drive an ensemble *hydrologic models*
  - Facilitates critical evaluation of model uncertainty and reliability (risk)
- Evaluation of model fidelity vs. accuracy
  - Leverage tracers to evaluate soil-based processes and T/ET
- Cumulative Effects assessment
  - Risk is only accurately depicted if we consider *all* system impacts and changes

“

…All models are wrong, but some are useful

”

Box, 1976

For more information

https://ucalgary.ca/labs/hydrological-analysis/home

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