The background of the slide is a photograph of a lake at sunset. The sky is filled with soft, pastel-colored clouds in shades of blue, pink, and orange. The lake's surface is calm, reflecting the colors of the sky and the surrounding green forest. The overall atmosphere is serene and natural.

# PREDICTIVE CONTROL AND ESTIMATION OF LAKE LEVELS AND STREAM FLOWS FOR THE ADAPTIVE MANAGEMENT OF COMPLEX NATURAL WATERSHEDS AND ECOSYSTEMS.

Part 1. Estimation.

Part 2. Economic Model Predictive Control.

2017 AIChE Annual Meeting

October 31, 2017

Jeffrey Kantor

University of Notre Dame

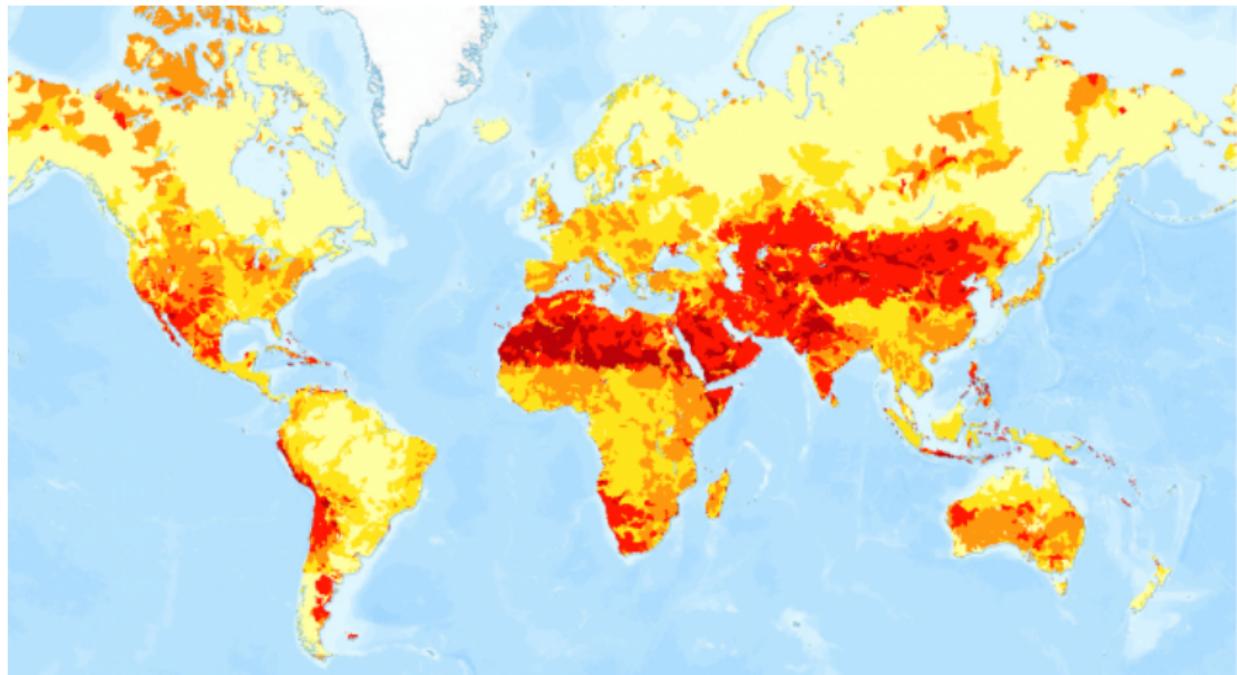
Github: <http://jckantor.github.io/Rainy-Lake-Hydrology/>

# OVERVIEW

1. Overview
2. Current Practice
3. Predictive Control 1. Implementing Rule Curves
4. Predictive Control 2. Adaptive Rule Curves
5. Predictive Control 3. Ecosystem
6. Discussion

# OVERVIEW

## OVERALL WATER RISK - WRI 2015



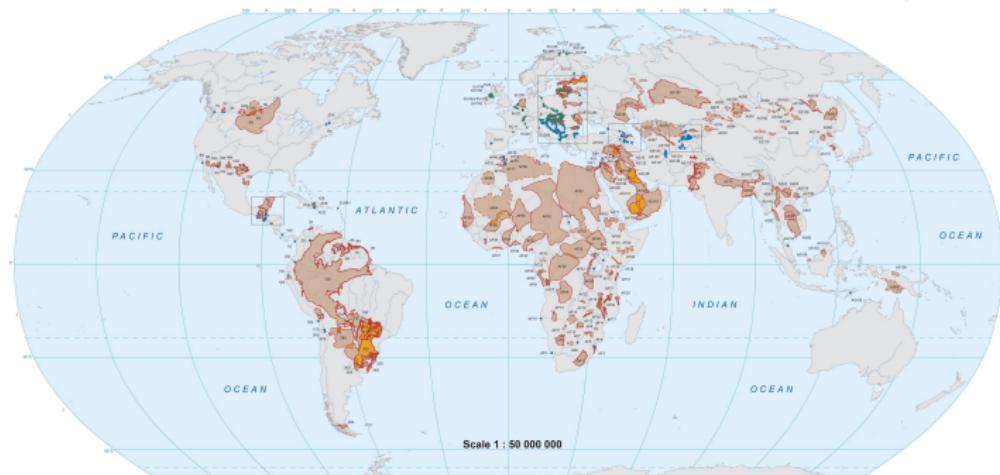
Source: World Resources Institute, Ver 2.1, 2015.

This map summarizes water risks associated with scarcity.

# TRANSBOUNDARY AQUIFERS OF THE WORLD



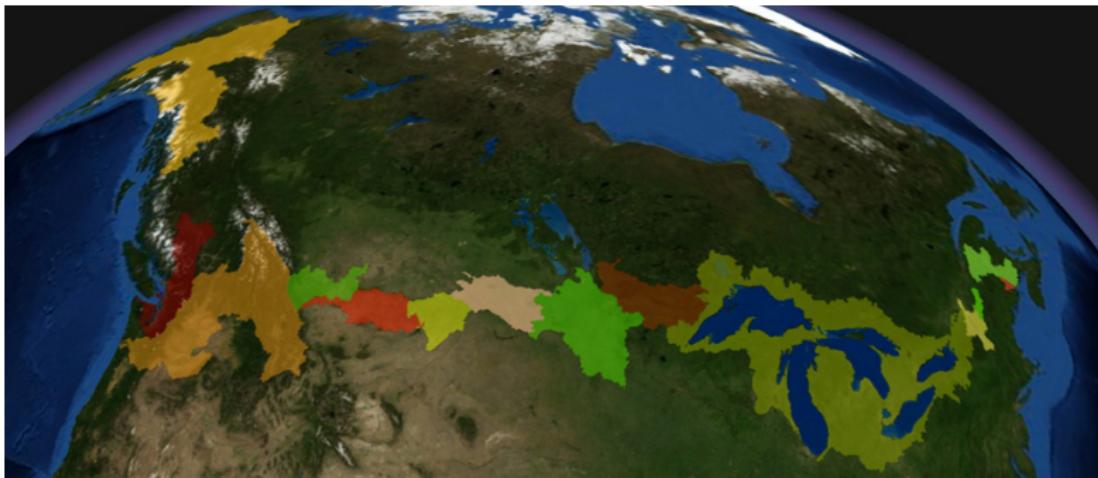
Transboundary Aquifers of the World  
Special Edition for the 7th World Water Forum 2015



Source: The International Law of Transboundary Groundwater Resources, 2017.

- Ubiquitous: 450 shared aquifers
- Strategic: 50% of global domestic needs, 40% of agriculture.
- Legal Vacuum: No global conventions
- Information Scarcity: Sovereign states with strong self-interests

# TRANSBOUNDARY WATERS OF CANADA AND THE US

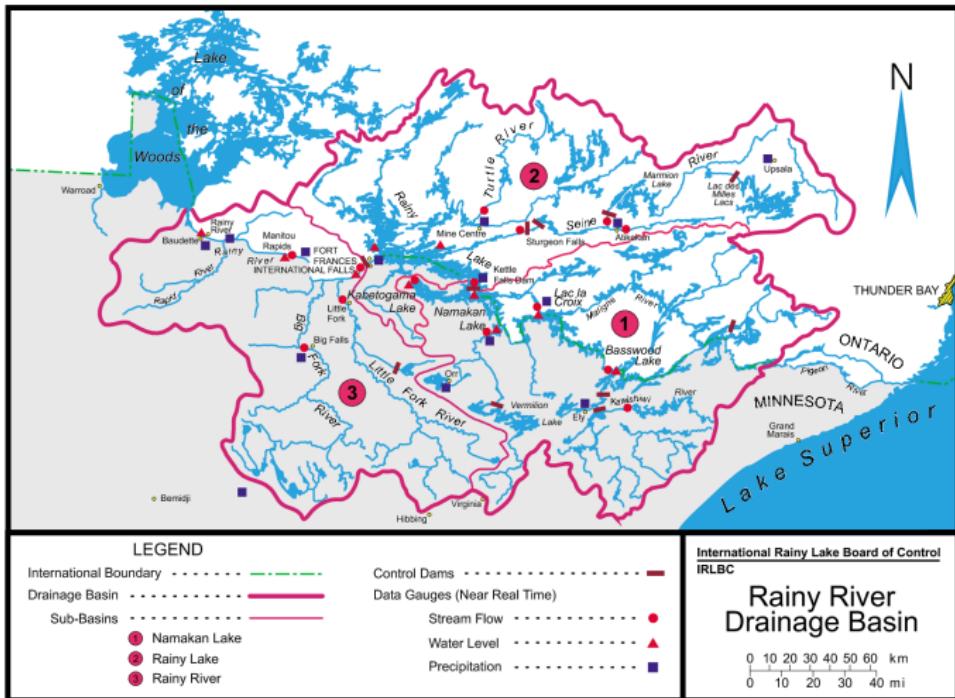


Source: Canadian Encyclopedia.

US and Canada share 8,000 km border that is 45% water with over 300 lakes and streams.

Boundary Waters Treaty of 1909 established the International Joint Commission to govern transboundary water.

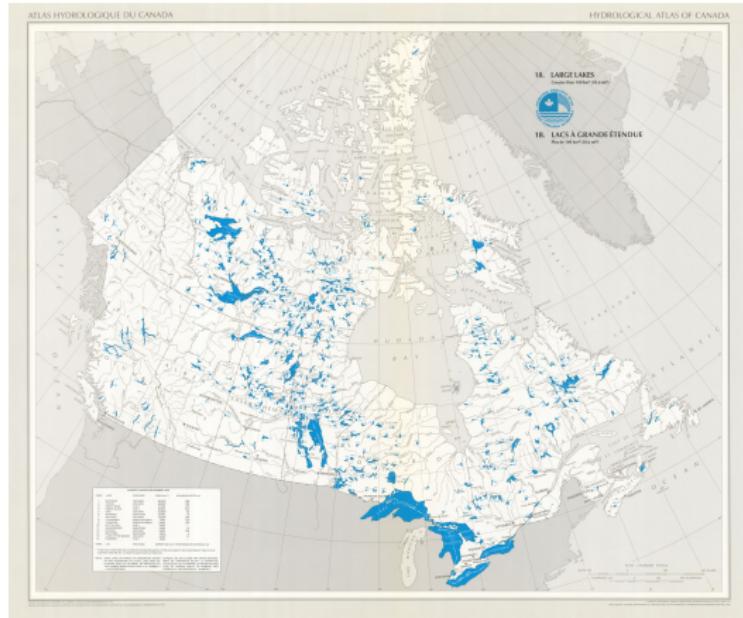
# RAINY RIVER DRAINAGE BASIN



Source: International Rainy Lake Board of Control (now IRLWWB)

50,000 km<sup>2</sup> watershed including pristine wilderness areas.

# CANADIAN SHIELD - LAKES > 100 KM<sup>2</sup>



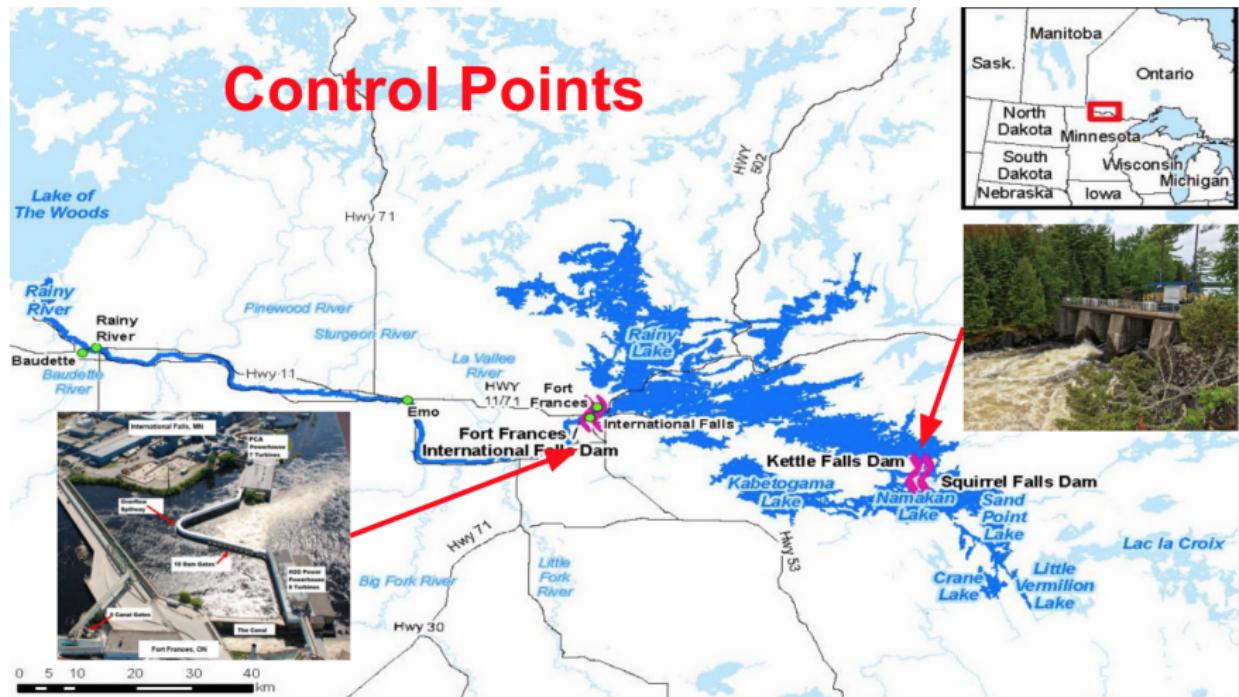
Source: [Canadian Encyclopedia](#).



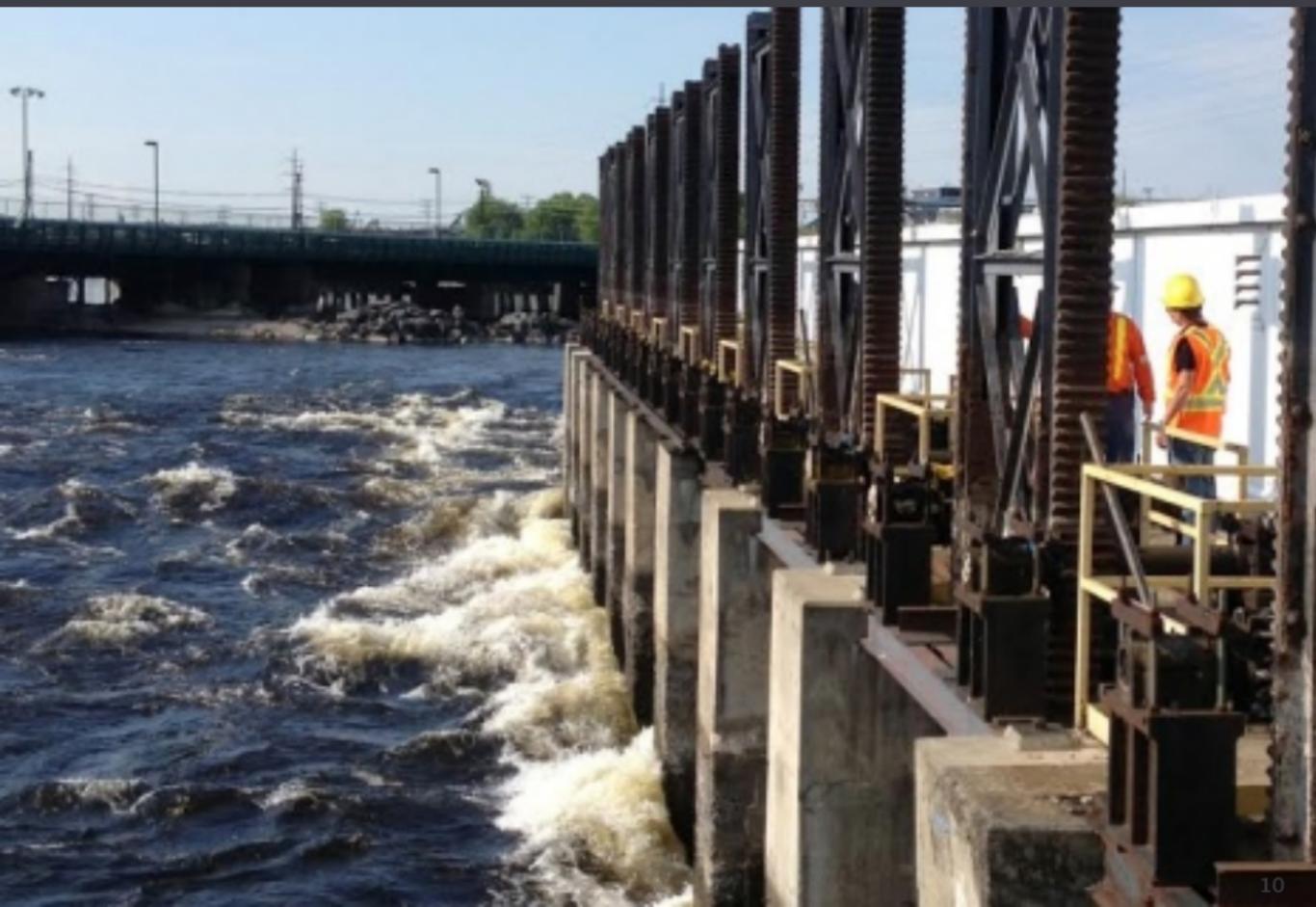
Source: [Jeff Kantor](#).

The Canadian shield is the geological core of the North American continent (the North American Craton) characterized by exposed Precambrian igneous and high-grade metamorphic rocks.

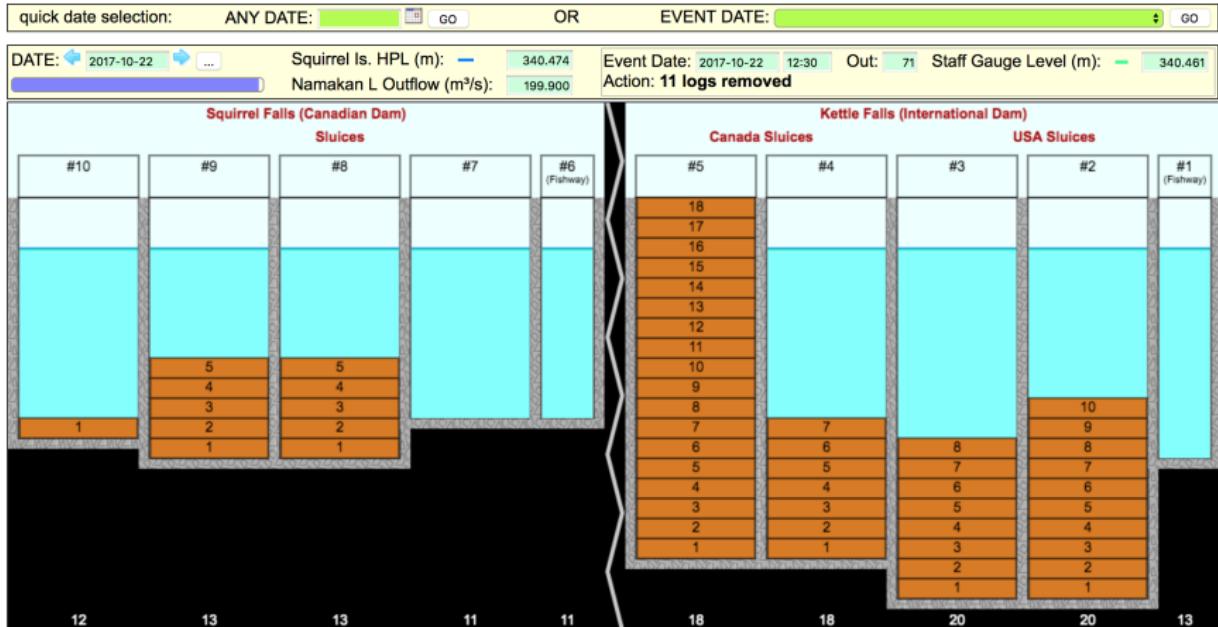
# MAJOR CONTROL POINTS



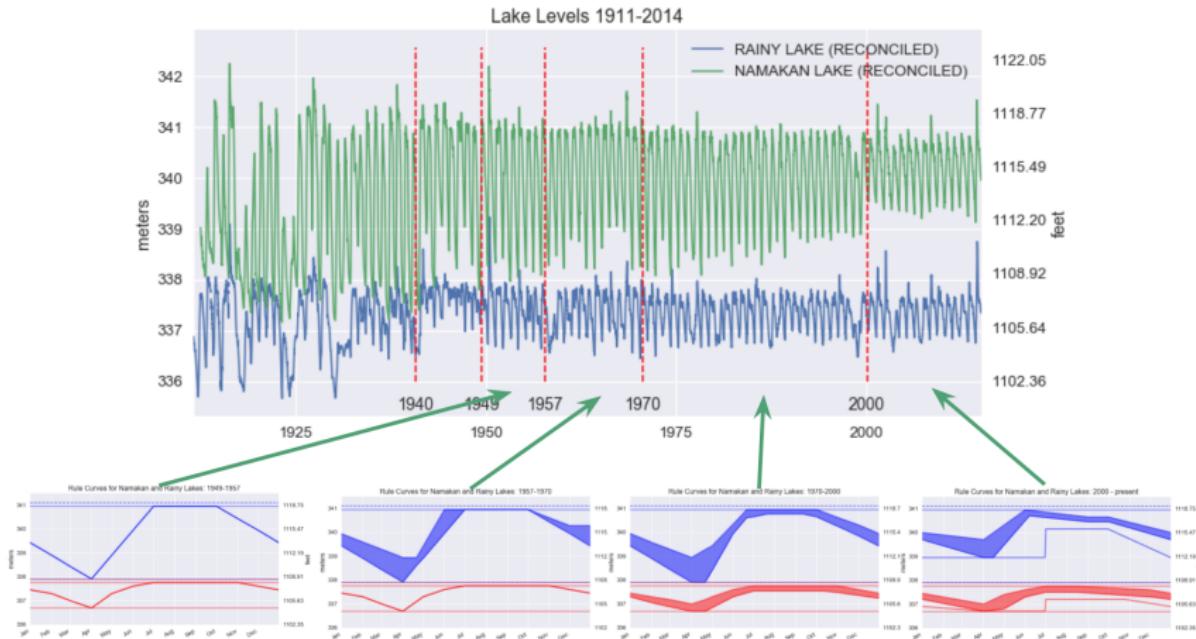
# DAM AT INTERNATIONAL FALLS, MN/FORT FRANCES, ONT



# DAM AT KETTLE/SQUIRREL FALLS



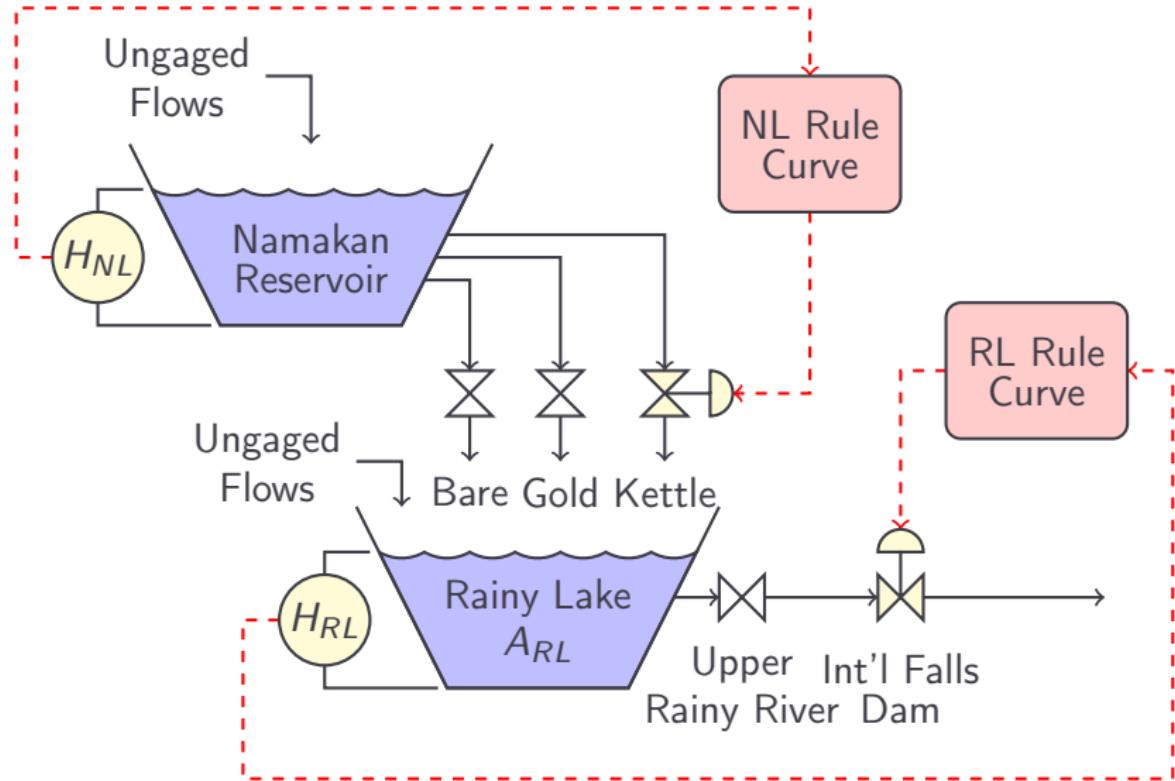
# RULE CURVES ESTABLISH CONTROL POLICY



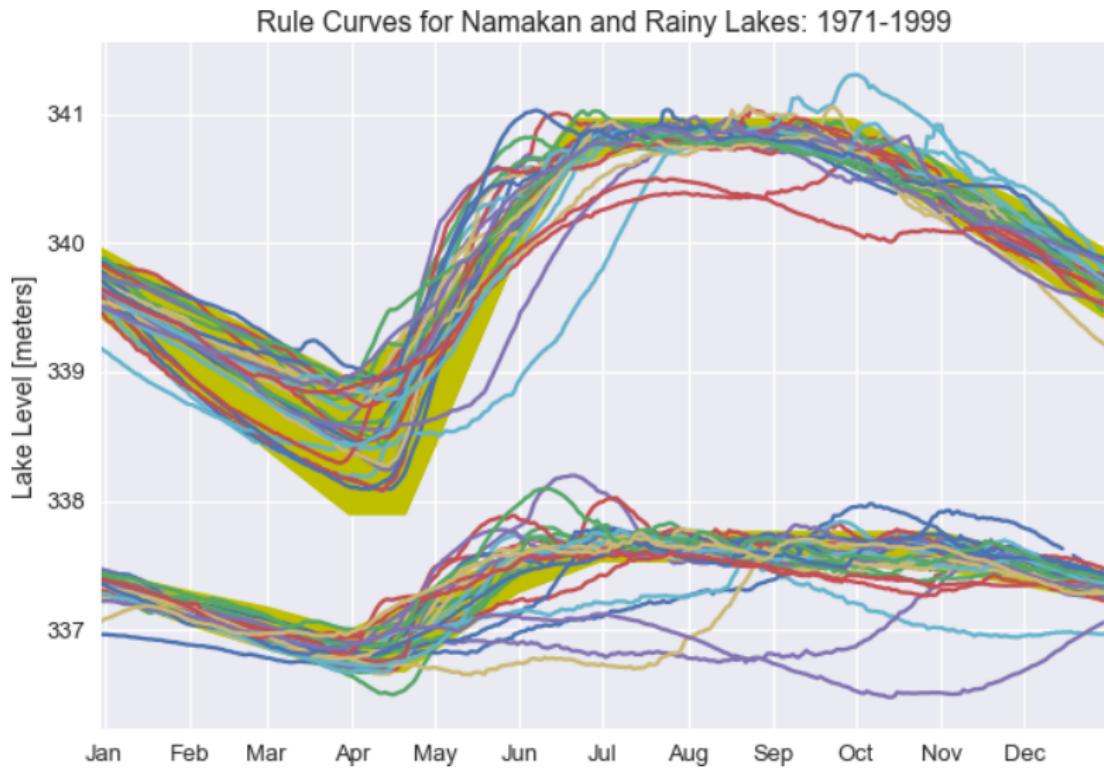
Rule Curves are established by the International Joint Commission by authority of the Boundary Waters Treaty of 1909.

# CURRENT PRACTICE

# RULE CURVES

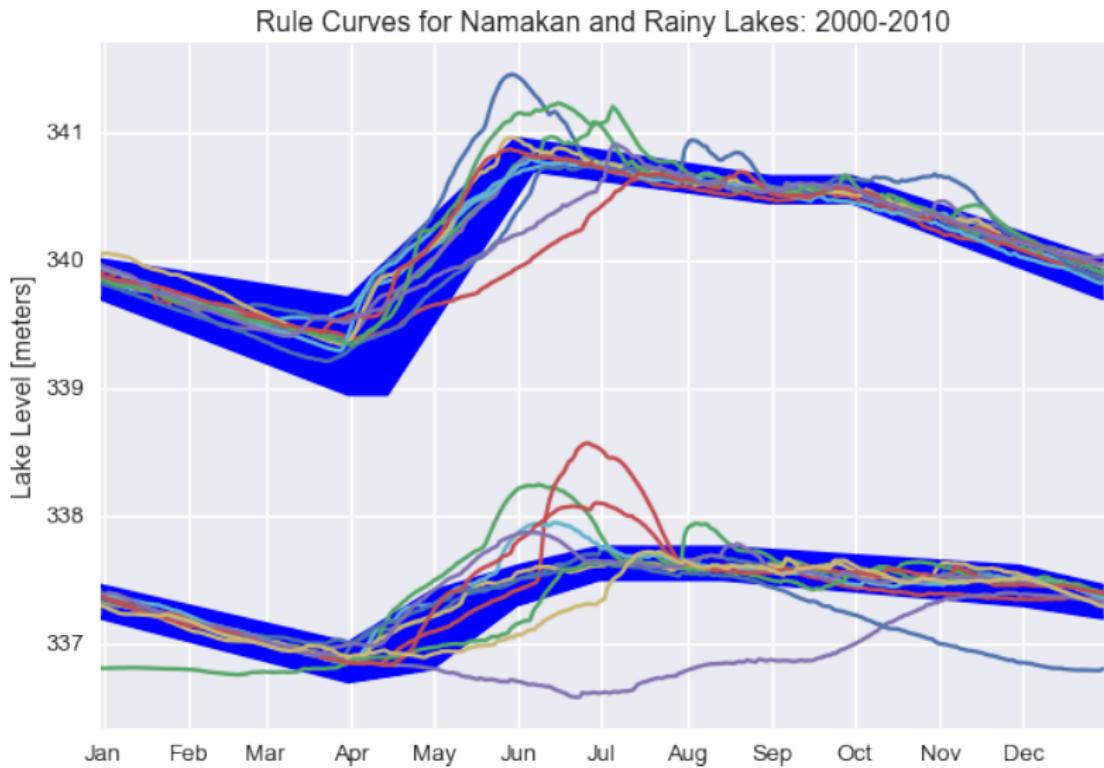


# RULE CURVE PERFORMANCE 1970–1999



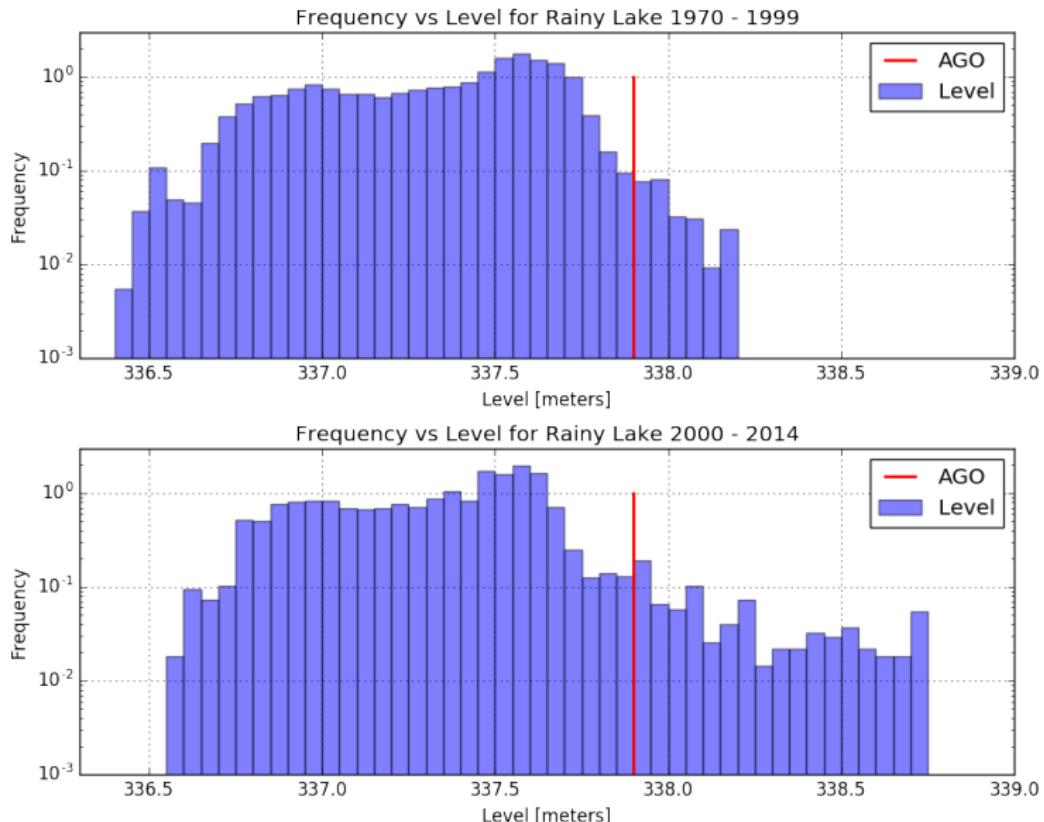
Source: [Github Repository for this paper.](#)

# RULE CURVE PERFORMANCE 2000–2014



Source: [Github Repository for this paper.](#)

# RULE CURVE PERFORMANCE - RAINY LAKE LEVELS



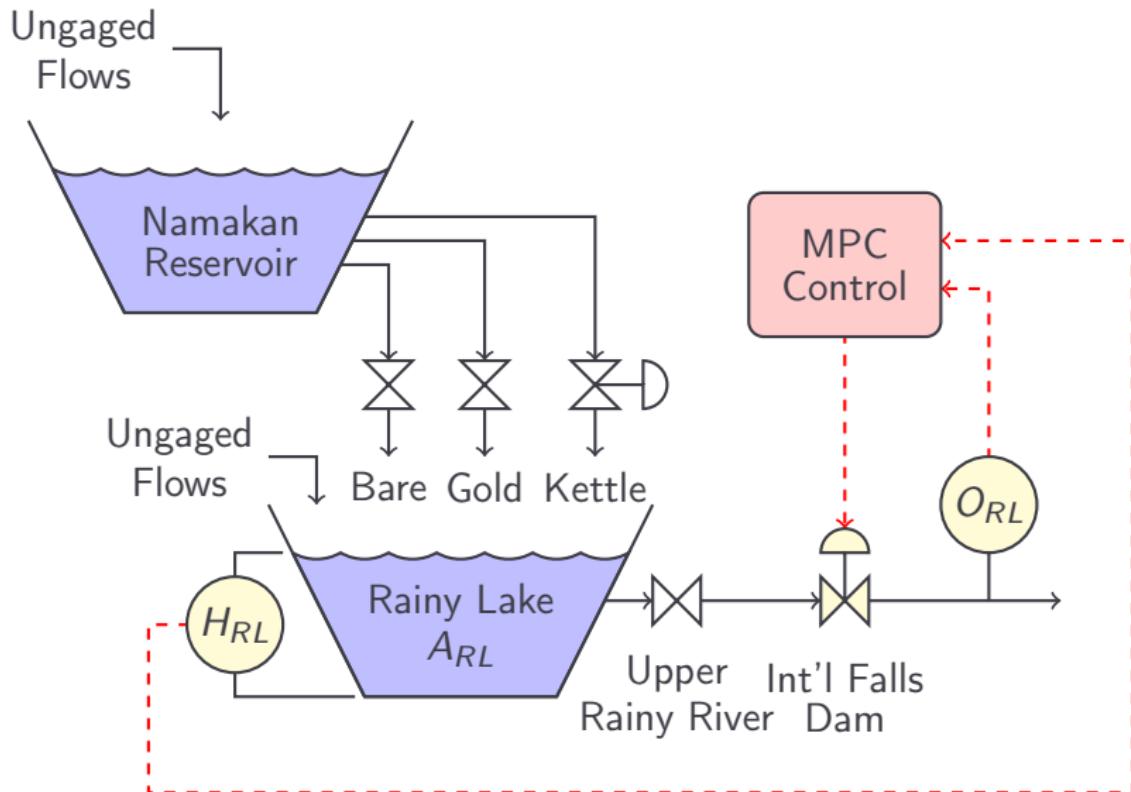
Source: [Github Repository for this paper.](#)

## INCREASING FREQUENCY OF FLOODING EVENTS



# PREDICTIVE CONTROL 1. IMPLEMENTING RULE CURVES

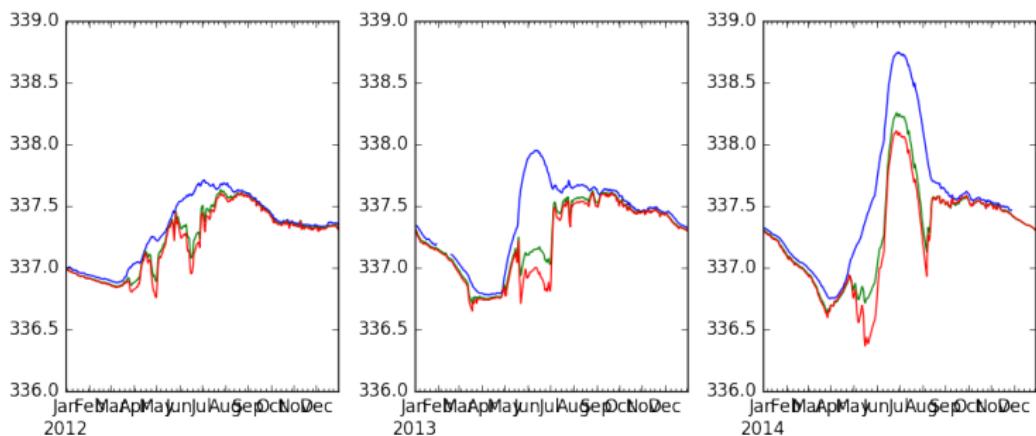
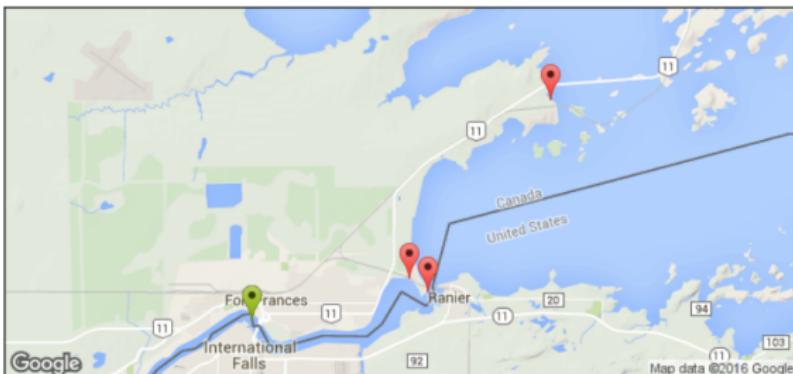
# MODEL PREDICTIVE CONTROL FOR RAINY LAKE



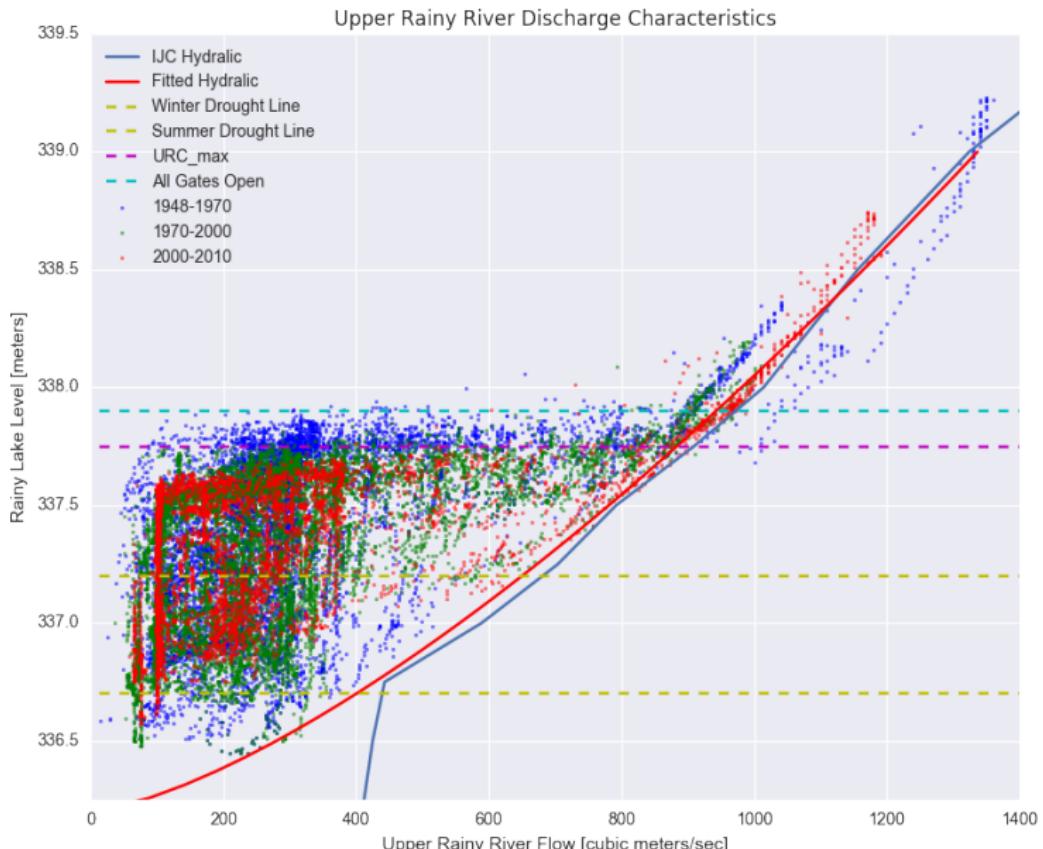
## UPPER RAINY RIVER DISCHARGE CHARACTERISTICS



# UPPER RAINY RIVER DISCHARGE CHARACTERISTICS

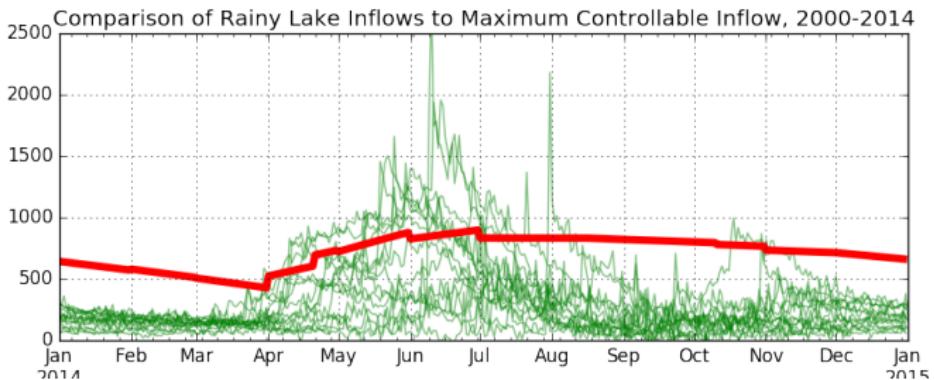
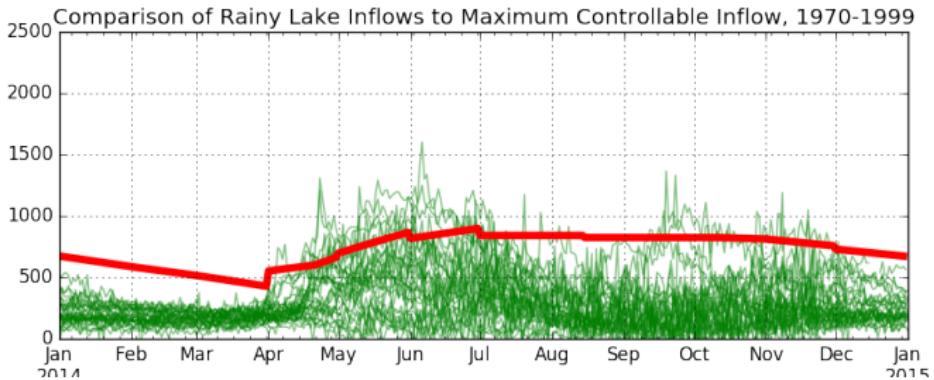


# UPPER RAINY RIVER DISCHARGE CHARACTERISTICS



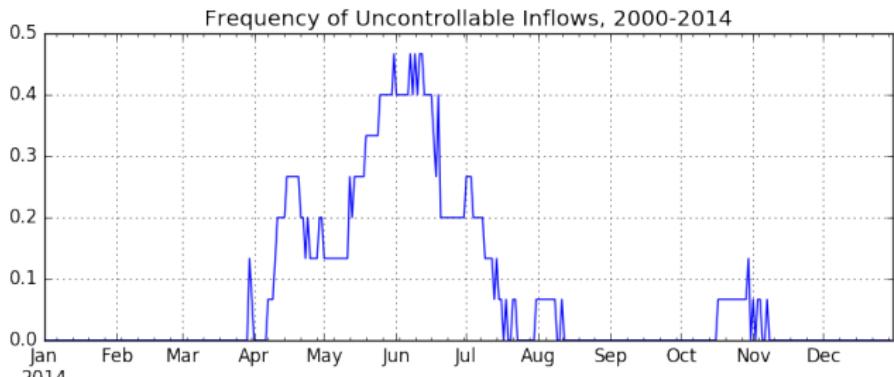
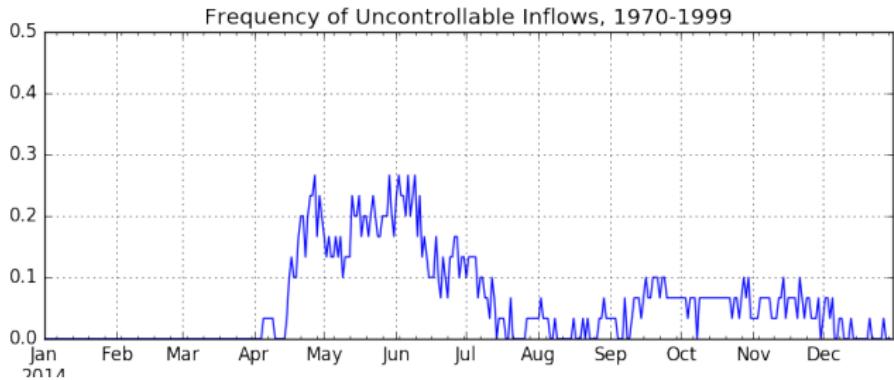
Source: [Github Repository for this paper.](#)

# MAXIMUM CONTROLLABLE INFLOWS



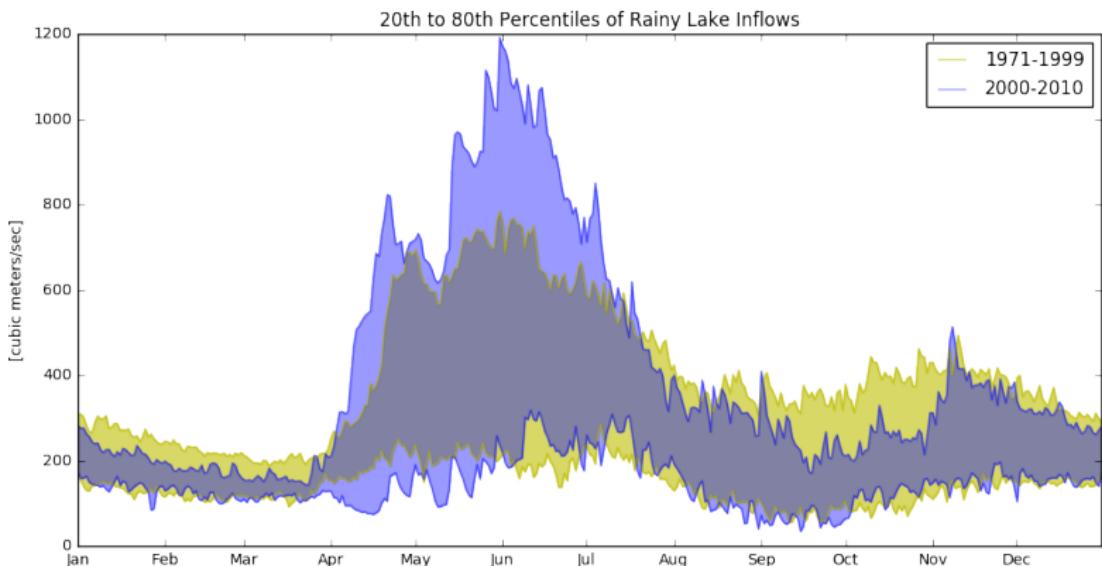
Source: [Github Repository for this paper.](#)

# UNCONTROLLABLE INFLOW FREQUENCY



Source: [Github Repository for this paper.](#)

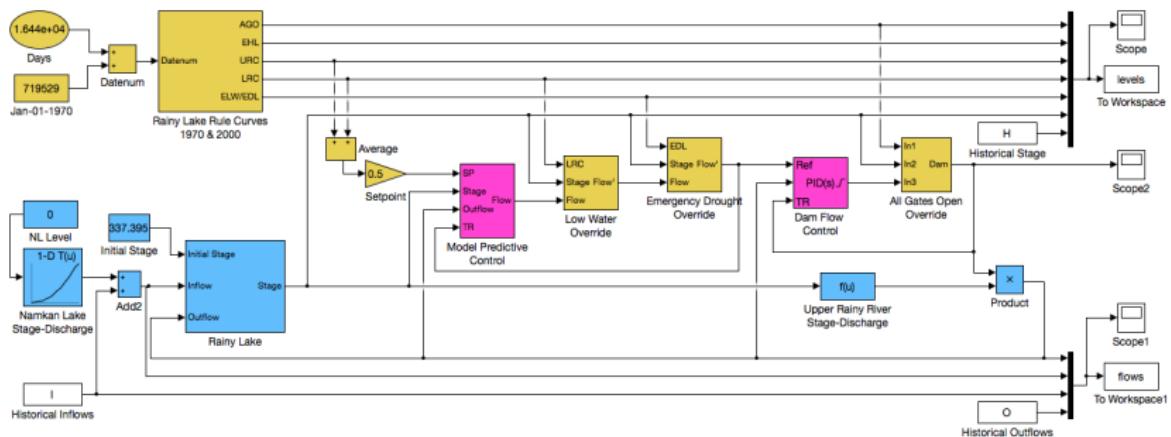
# INFLOW ESTIMATION



Source: [Github Repository for this paper.](#)

# MATLAB/SIMULINK IMPLEMENTATION

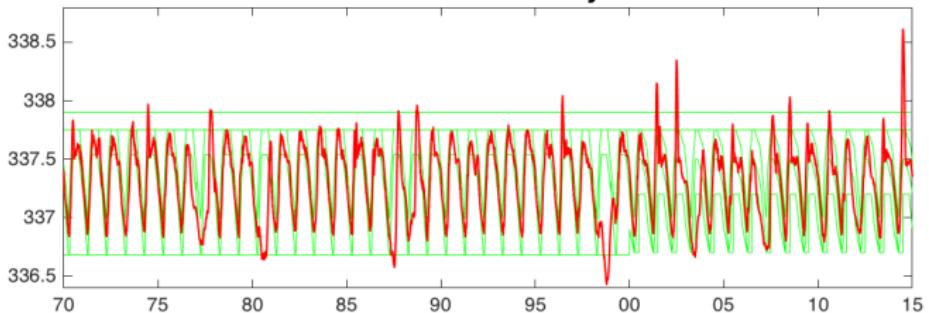
## Implementation of 1970-2014 Rule Curves for Rainy Lake by Model Predictive Control



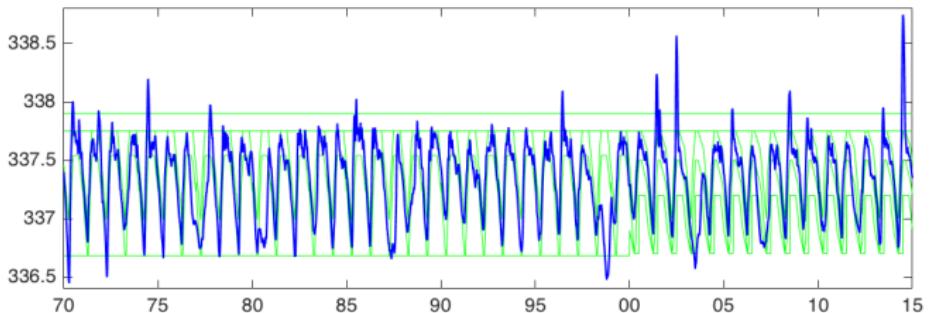
Source: Github Repository for this paper.

# SIMULATION RESULTS

**Control Simulation for Rainy Lake Levels**

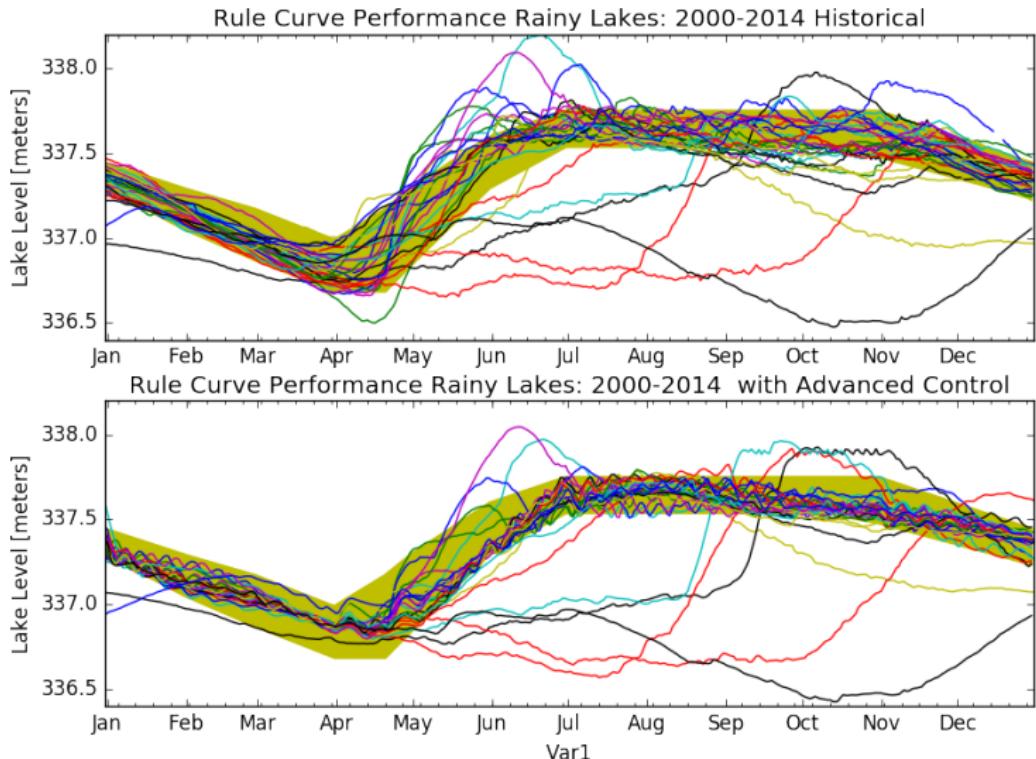


**Historical Levels**



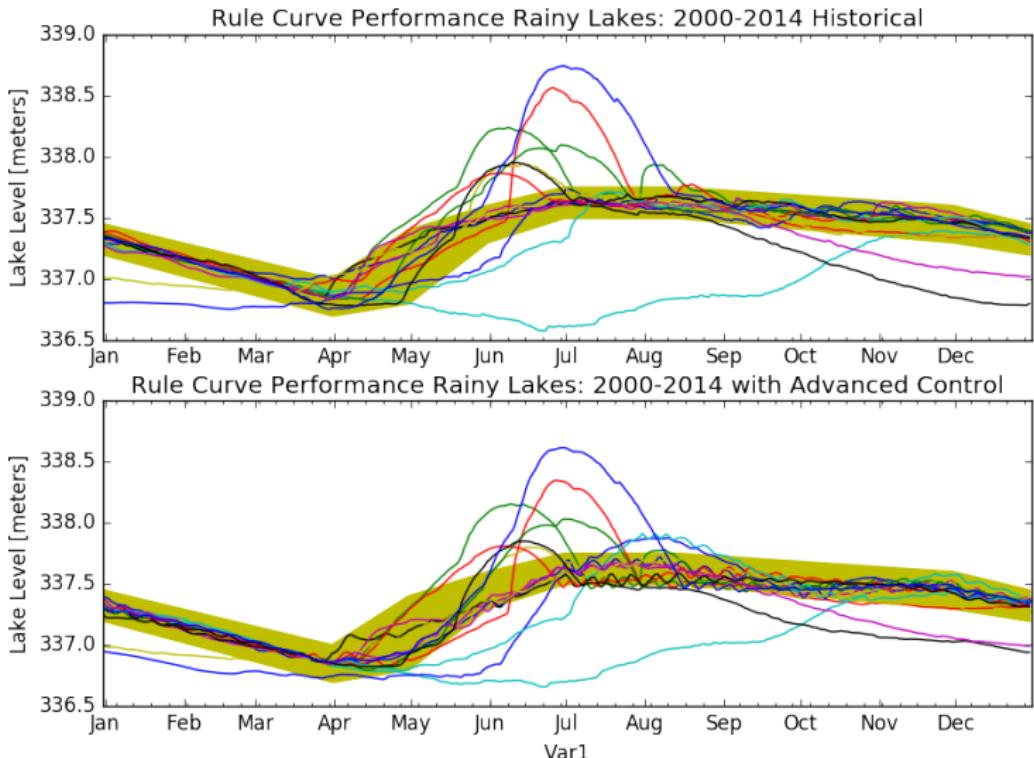
Source: Github Repository for this paper.

# SIMULATION RESULTS



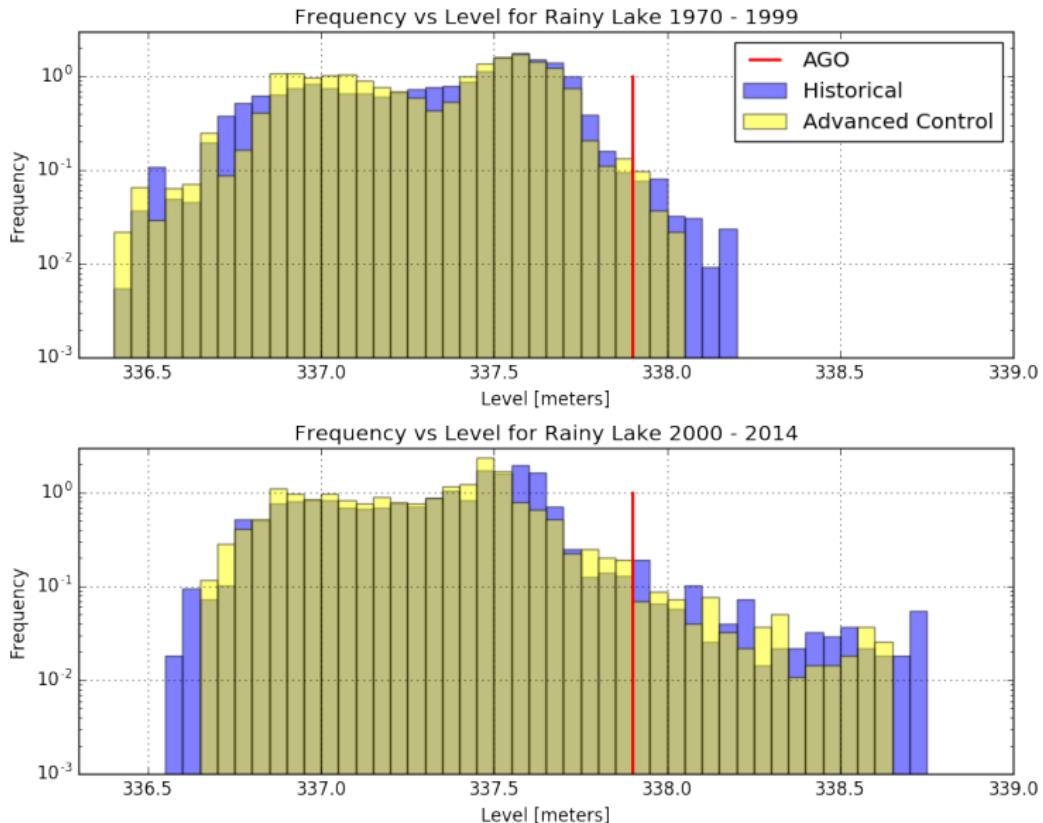
Source: [Github Repository for this paper.](#)

# SIMULATION RESULTS



Source: [Github Repository for this paper.](#)

# SIMULATION RESULTS - RAINY LAKE LEVELS



Source: [Github Repository for this paper.](#)

In 2015, Dam Operators committed to more careful control using feedback principles augmented with inflow and level forecasting information.

One outcome was a record crop of wild rice



Other outcomes were increased downstream bank erosion.

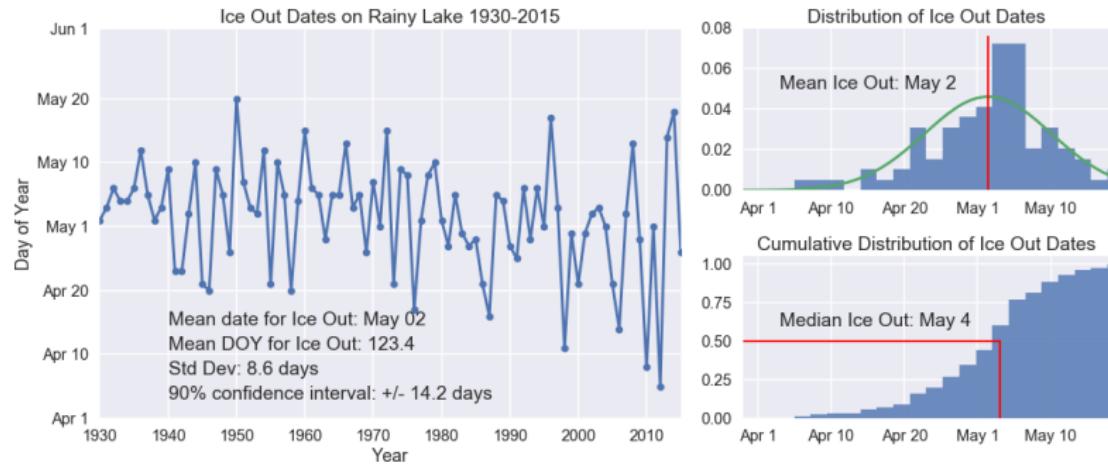
# PREDICTIVE CONTROL 2. ADAPTIVE RULE CURVES

## FRESHET AND ICE OUT



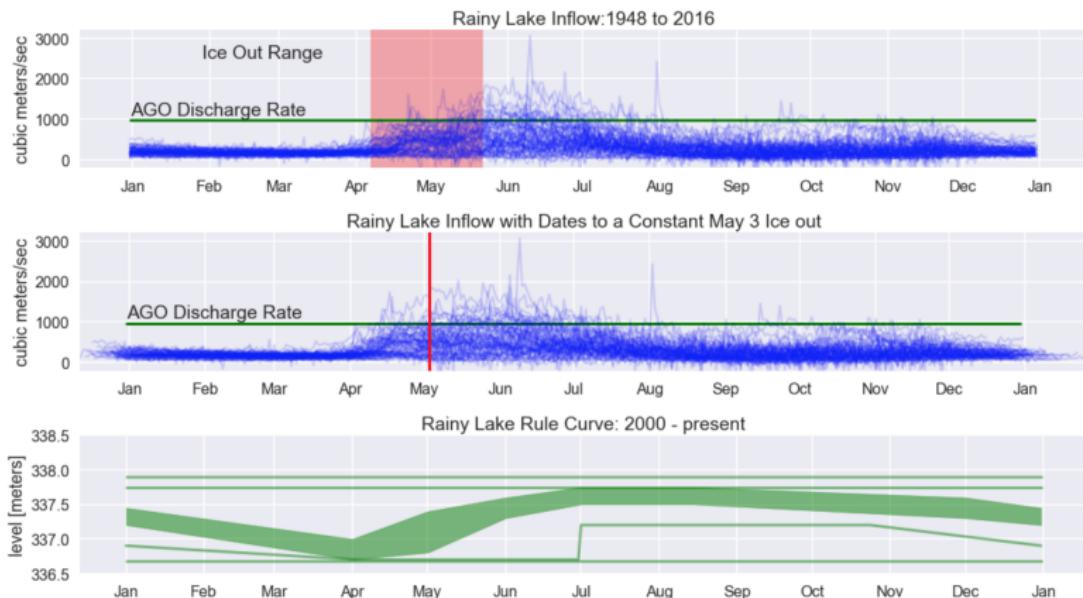
The Spring Freshet followed by Ice Out is the start of the annual fill cycle.

# SIGNIFICANCE OF VARIABLE ICE OUT

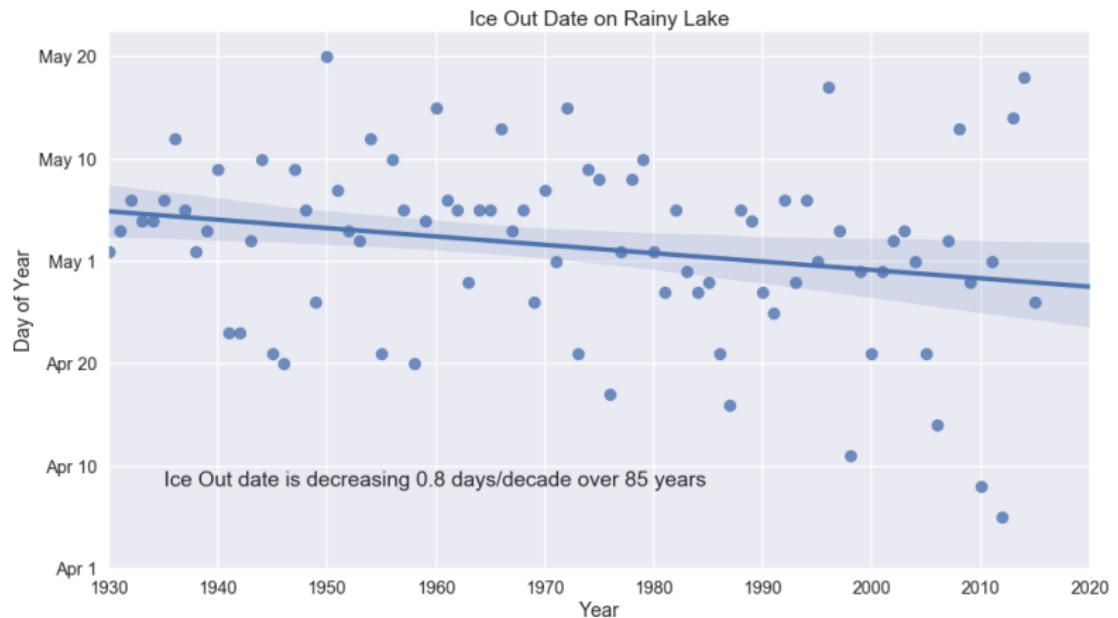


Ice out is correlated with the Spring inflows of water.

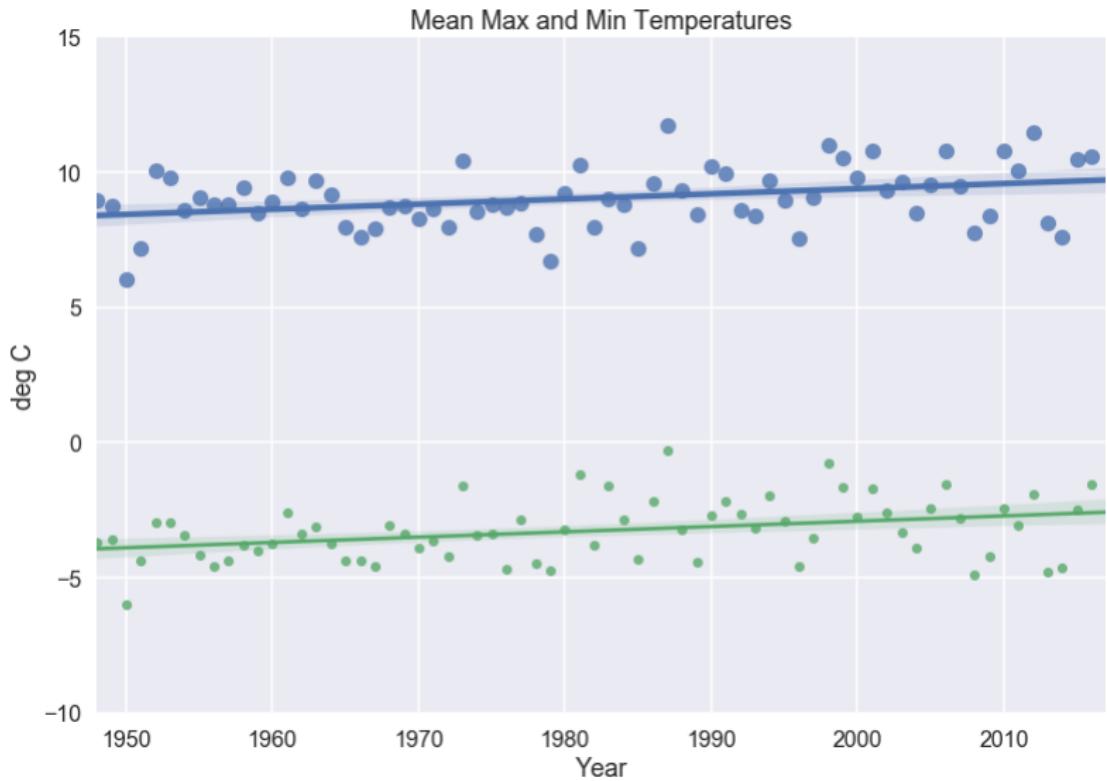
# SIGNIFICANCE OF VARIABLE ICE OUT



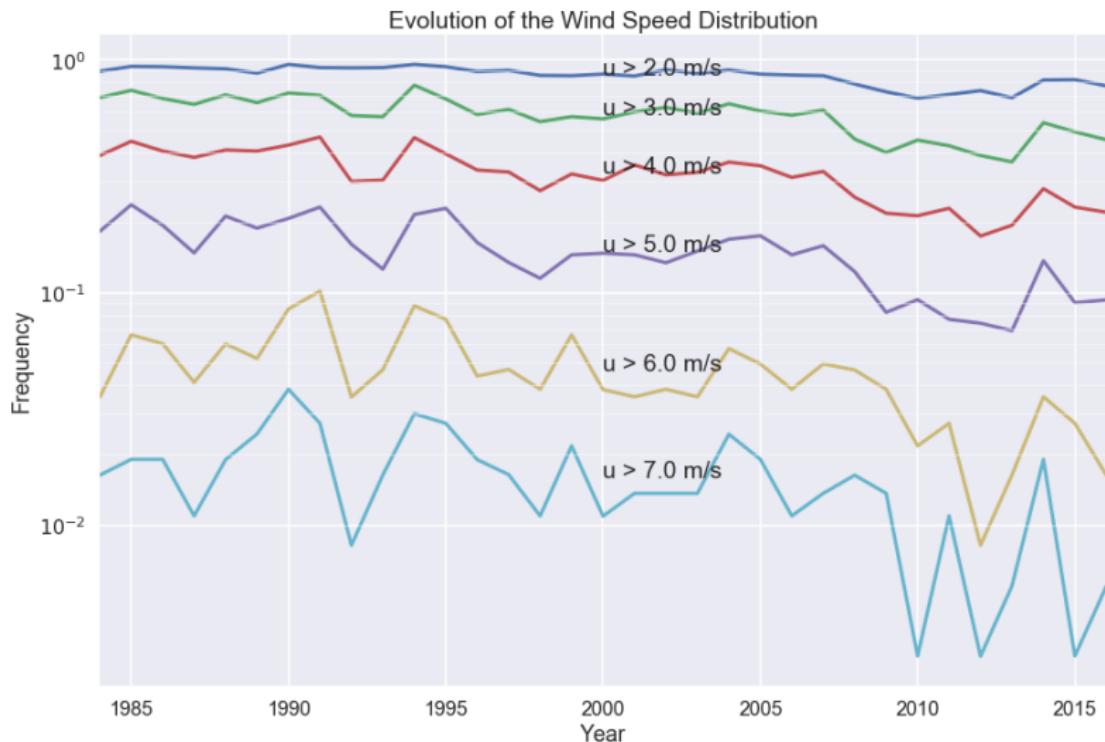
# TRENDLINES



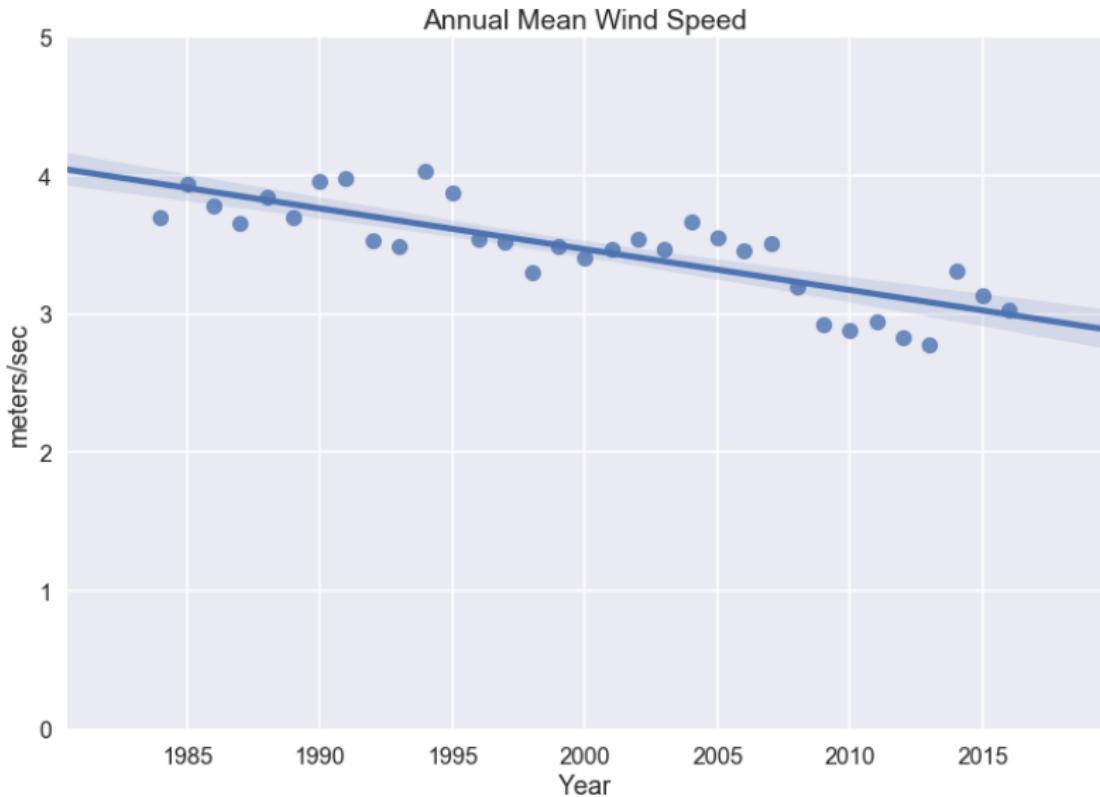
# CONSISTENT WITH GLOBAL WARMING



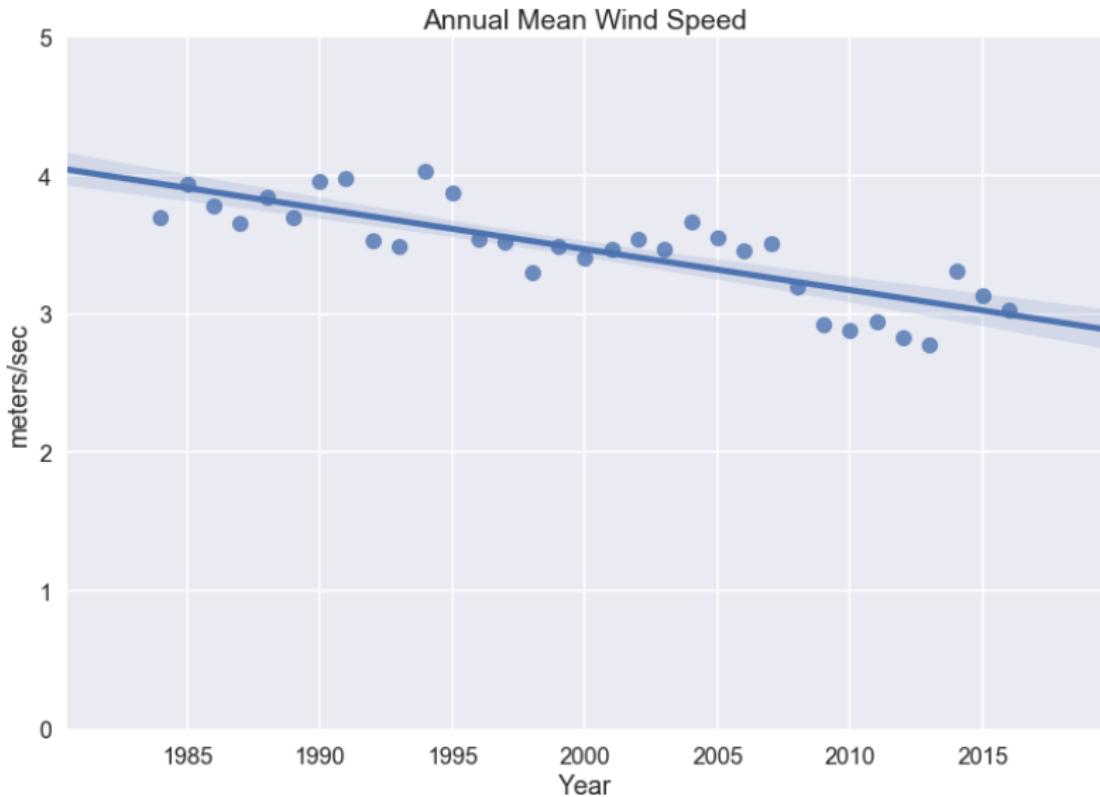
# WIND DISTRIBUTION IS CHANGING



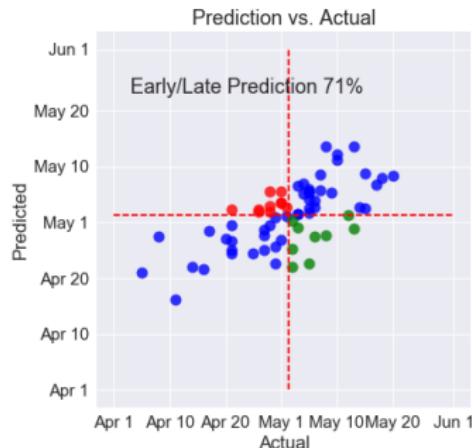
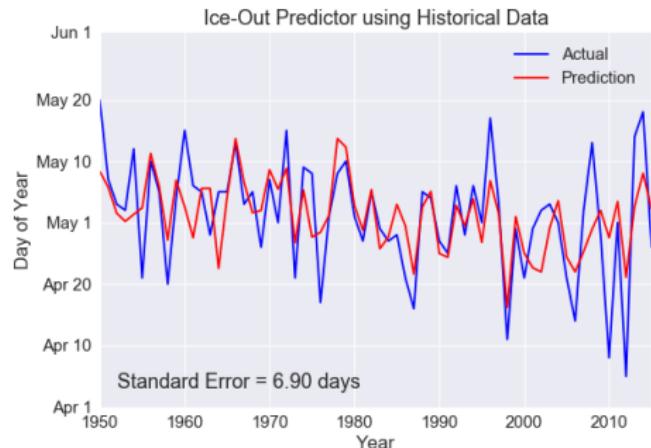
# CONSISTENT WITH GLOBAL STILLING



# CONSISTENT WITH GLOBAL STILLING



# MARCH 1 PREDICTOR



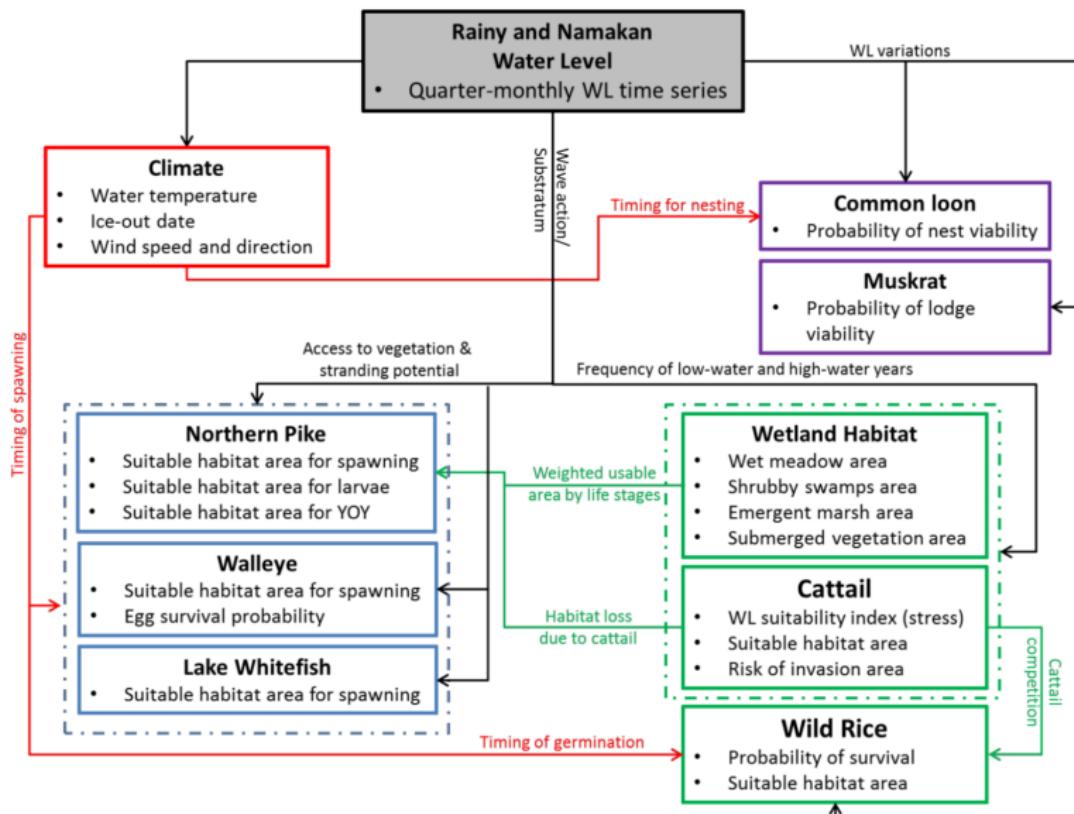
Source: [Github Repository for this paper.](#)

Predictor fitted using Elastic Net Regression with ENSO, PDO, local weather station temperature data for preceding 3 months.

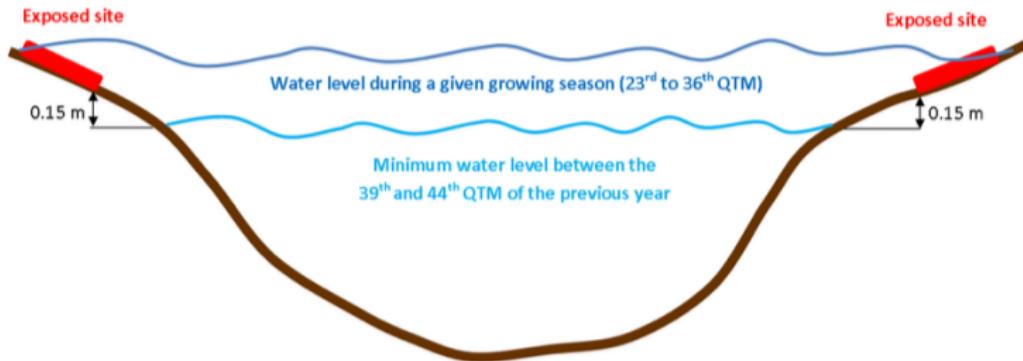
Formal recommendation to the International Joint Commission for Adaptive Management of the Rainy Lake Basin.

# PREDICTIVE CONTROL 3. ECOSYSTEM

# KEY ECOLOGICAL CONSIDERATIONS



# SUBMERGED VEGETATION



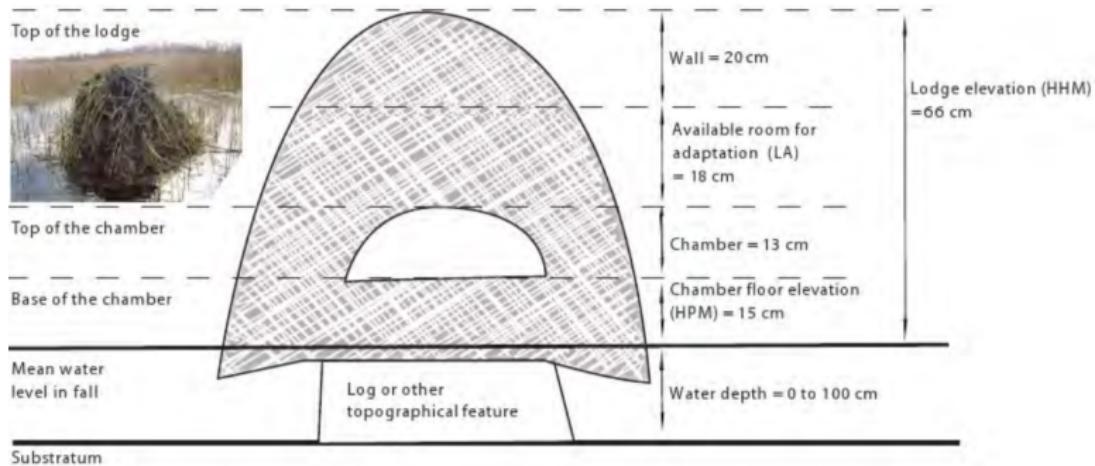
# LOONS



# MUSKRAT



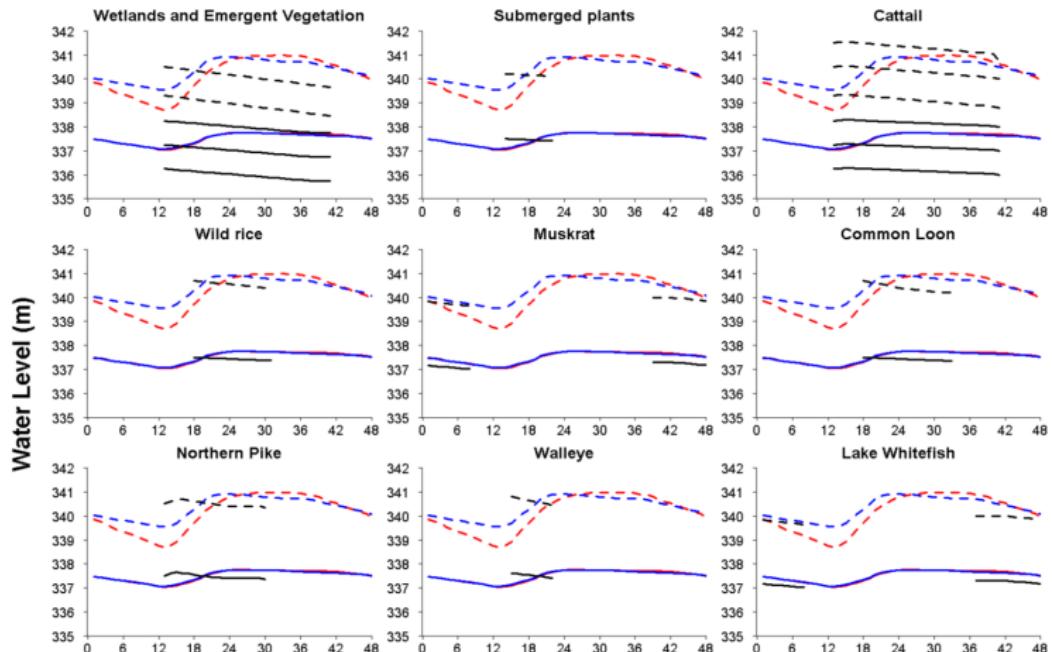
# MUSKRAT



# WILD RICE

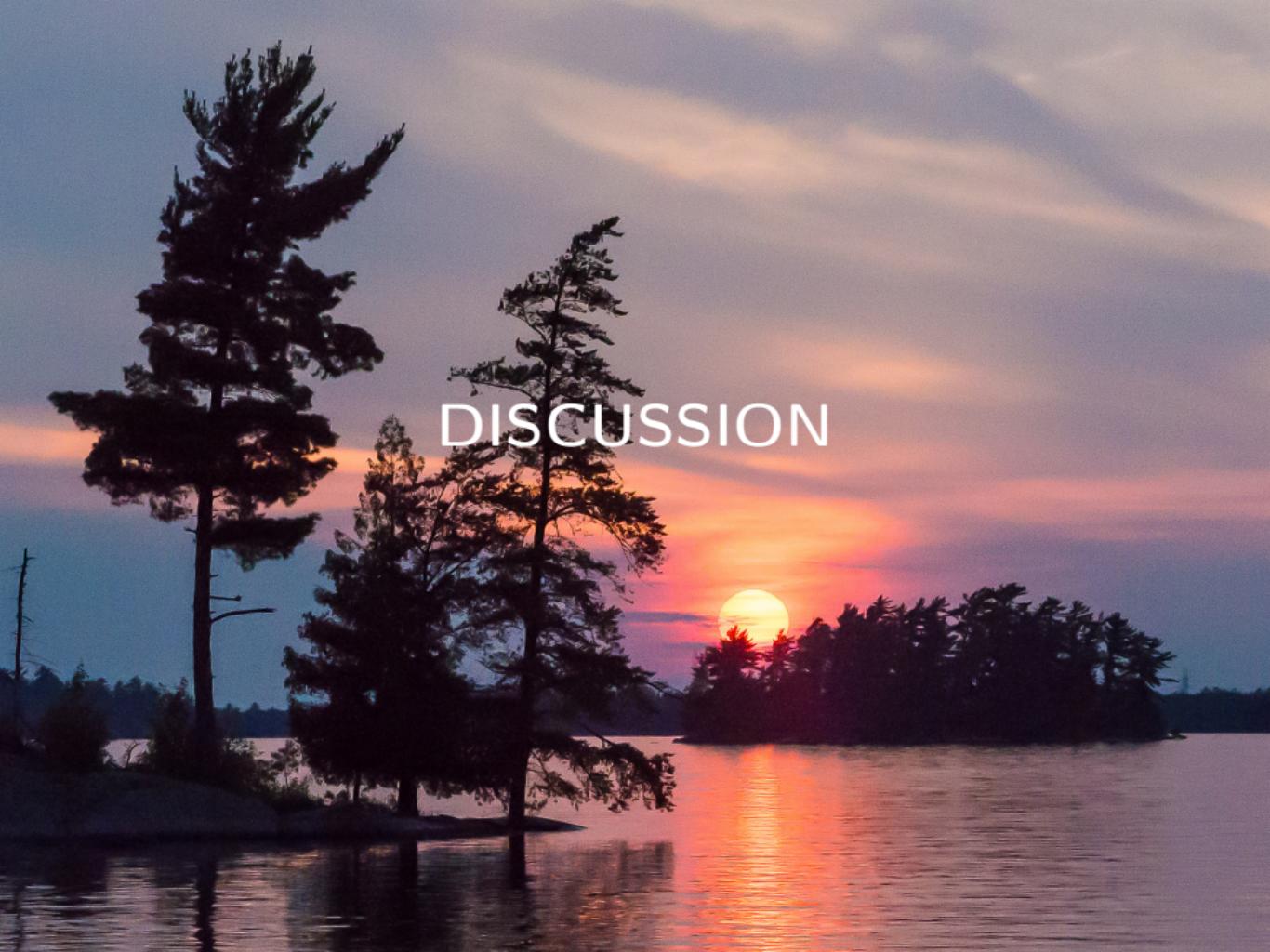


# PREDICTIVE CONTROL CONSIDERATIONS



## ACKNOWLEDGEMENTS

- UG Research Assistants:
  - Nicole Mejias
  - Michele Pham
  - Kelly McGarry
  - Usa Wongsanguan
  - Emmy
- Alan Hamlet, CEEES, Notre Dame
- Marc Muller, CEEES, Notre Dame
- Aaron Thompson, Directorate Environment Canada
- Jean Morin, Environment and Climate Change Canada
- RLPOA Research and Technology Committee

A photograph of a sunset over a body of water. In the foreground, several tall, silhouetted pine trees stand on a dark shoreline. The water reflects the warm colors of the setting sun. In the background, a large, bright sun sits low on the horizon, casting a golden glow across the sky. The sky is filled with soft, pastel-colored clouds.

# DISCUSSION