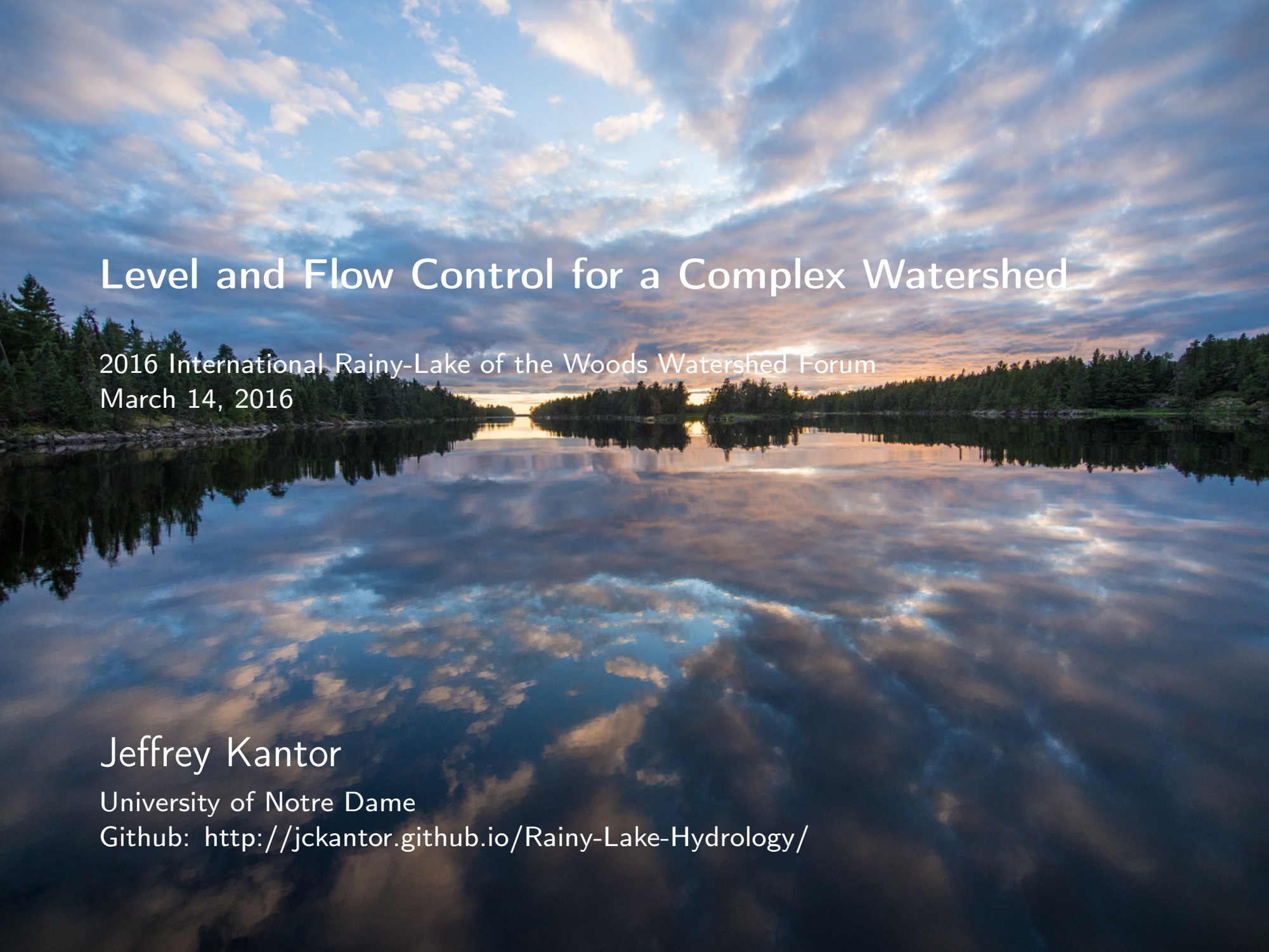
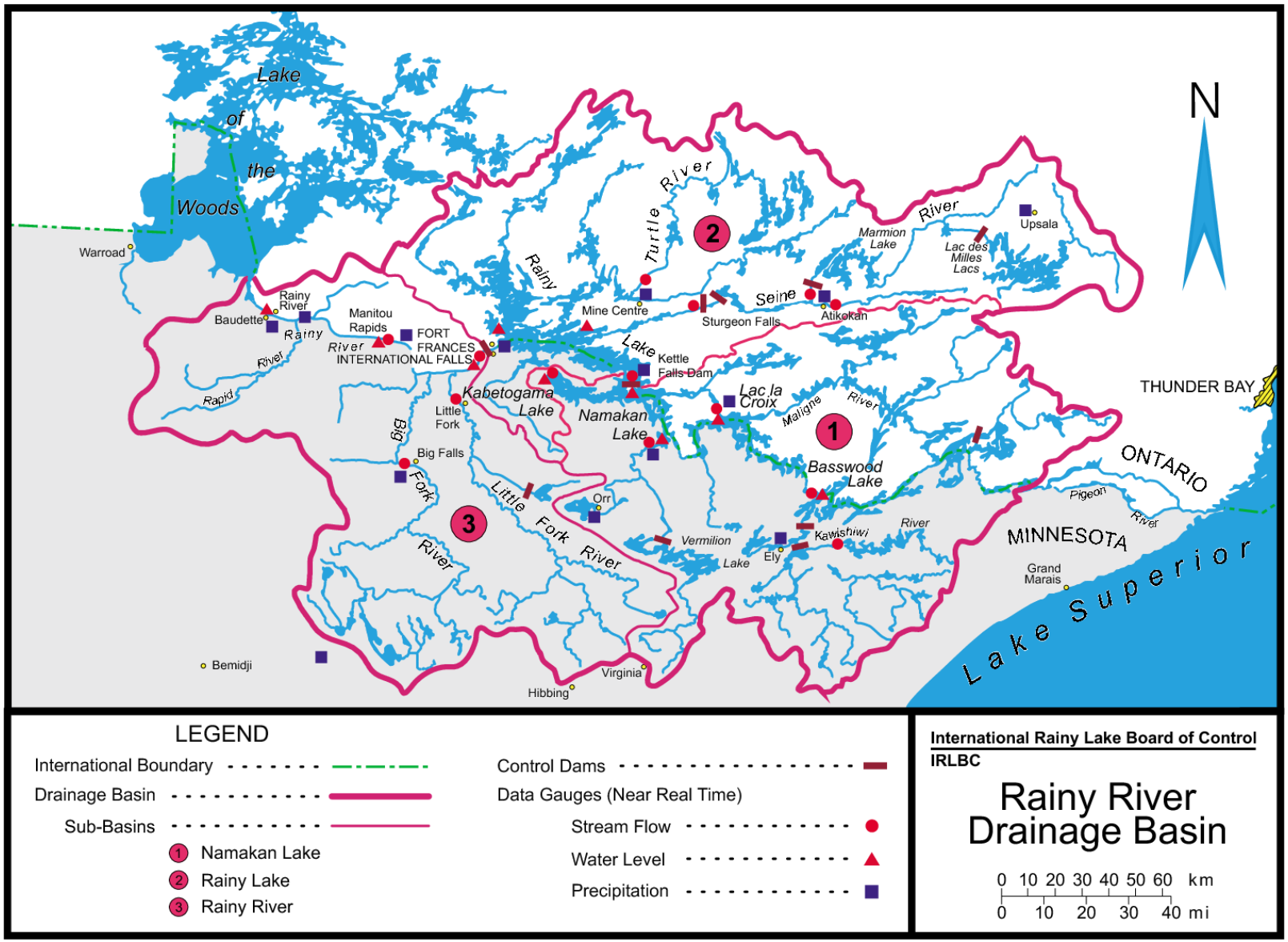


# Level and Flow Control for a Complex Watershed

2016 International Rainy-Lake of the Woods Watershed Forum
March 14, 2016

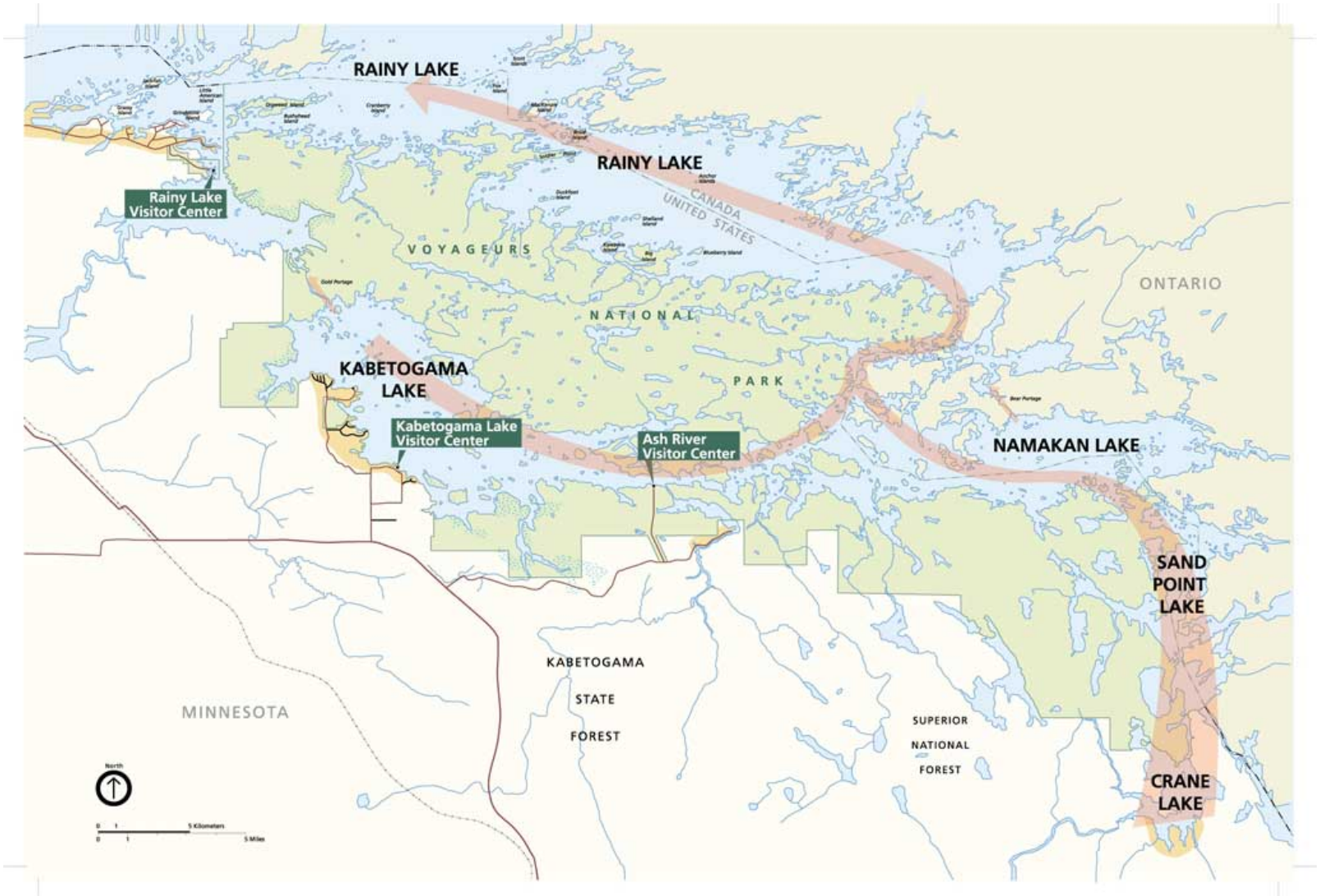
Jeffrey Kantor
University of Notre Dame
Github: http://jckantor.github.io/Rainy-Lake-Hydrology/

# RAINY RIVER DRAINAGE BASIN



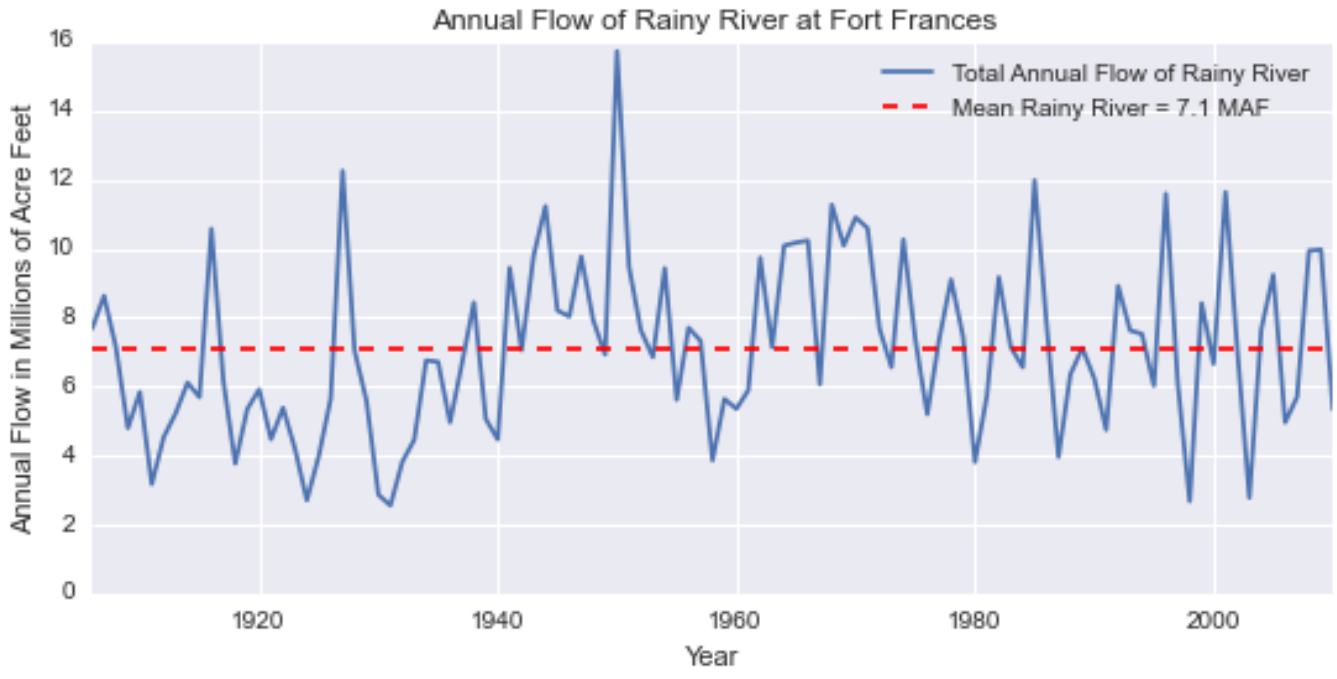

Source: International Rainy Lake Board of Control (now IRLWWB)

# WATER FLOW NAMAKAN RESERVOIR THROUGH RAINY LAKE




Source: US National Park Service

# RAINY RIVER MEAN ANNUAL FLOW

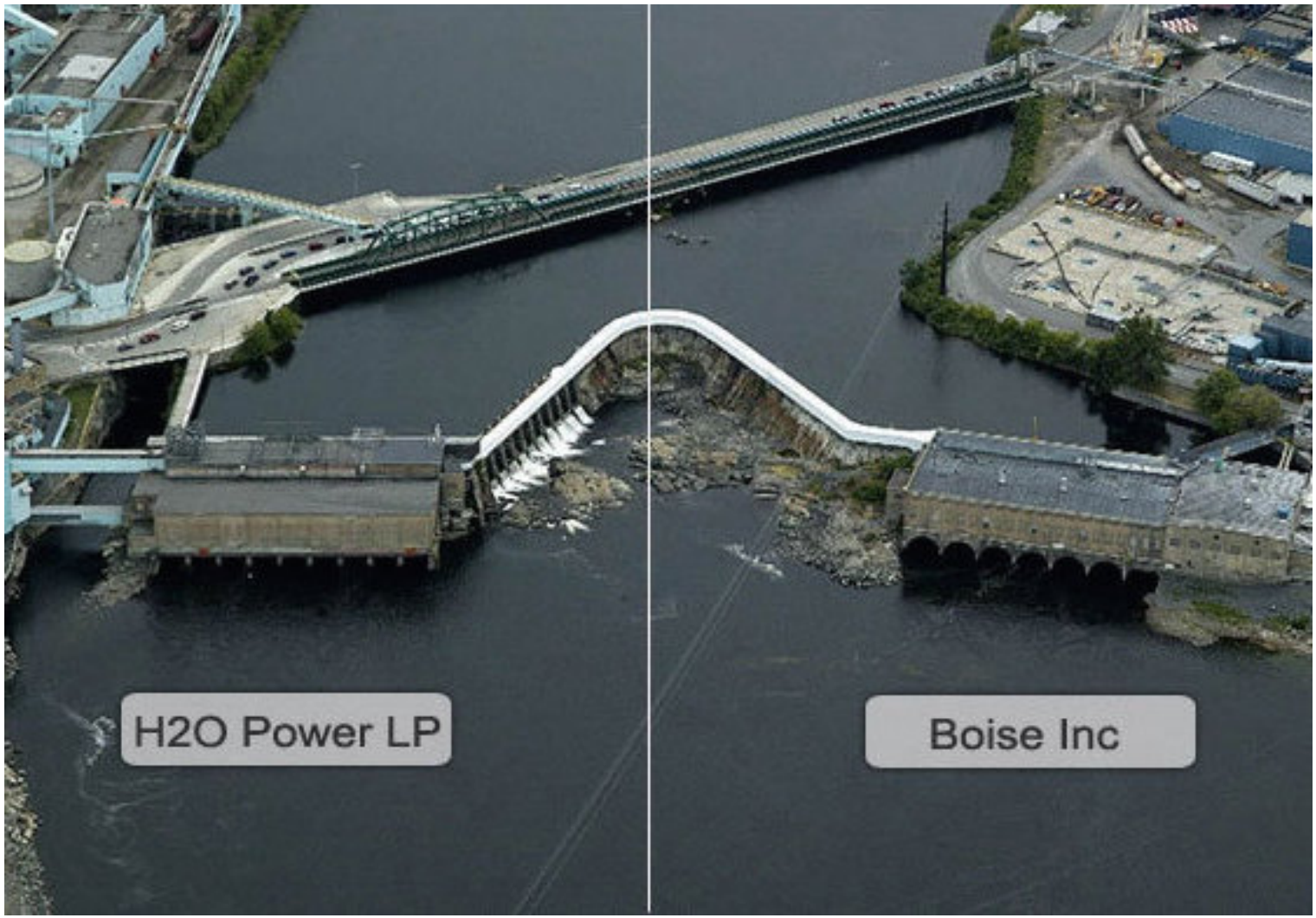



Source: Github Repository for this paper.

| | Million Acre-Feet/year |
|---|---|
| Rainy River at Fort Frances | 7.1 |
| Mississippi at St. Anthony Falls | 8.7 |
| Lake Mead Release at Hoover Dam | 9.6 |
| California, All managed Water | 40 |

# BOTTLENECK AT RAINY RIVER

# BOTTLENECK AT RAINY RIVER



# SUMMER FLOODING 2014

[0] Photo by Bob King (rking@duluthnews.com)

[0]Photo by WCCO, CBS Minnesota

[0]Photo by John Meyers, Duluth News Tribune

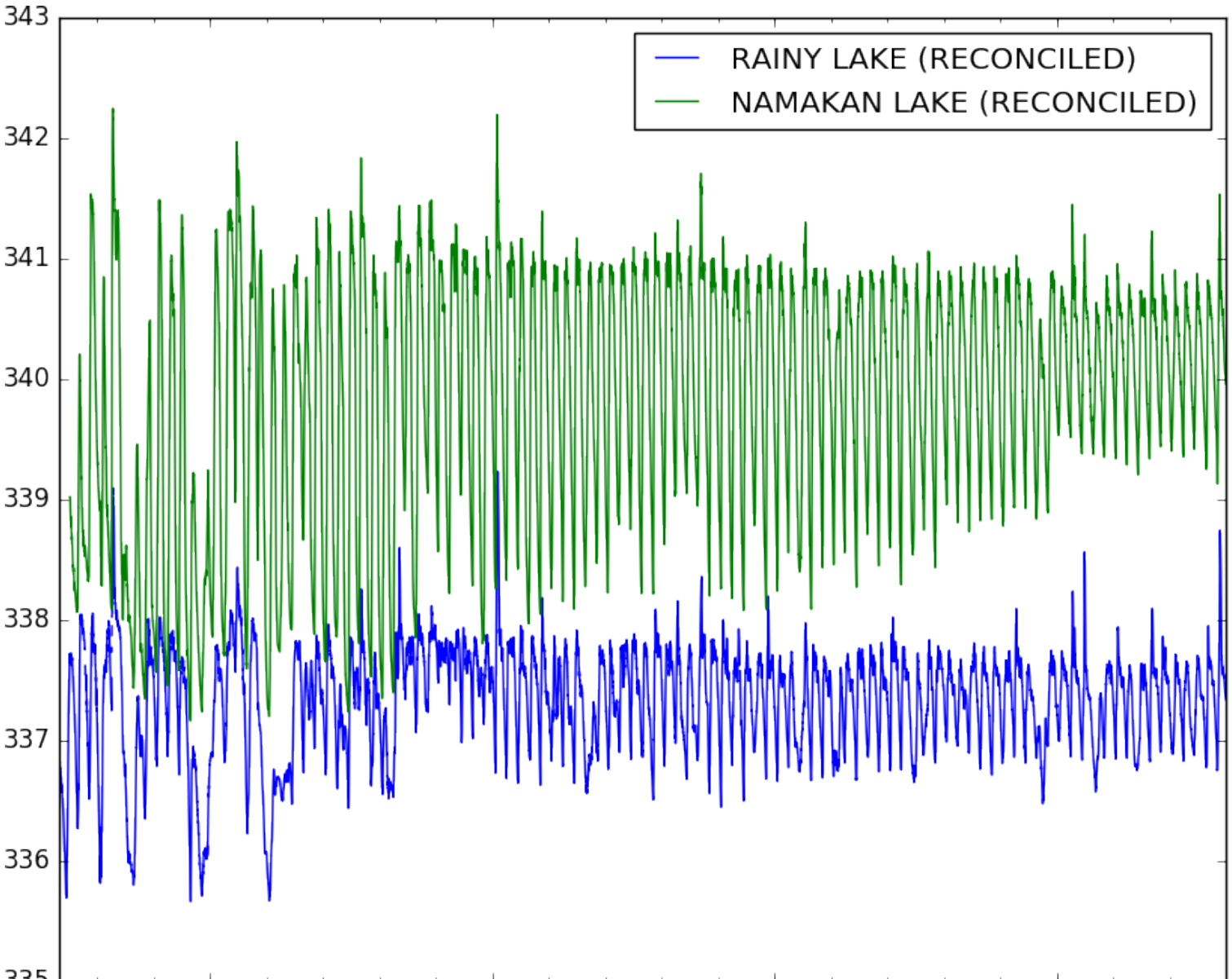
# 1987 LOW WATER YEAR

[0]Photo by Larry Kec

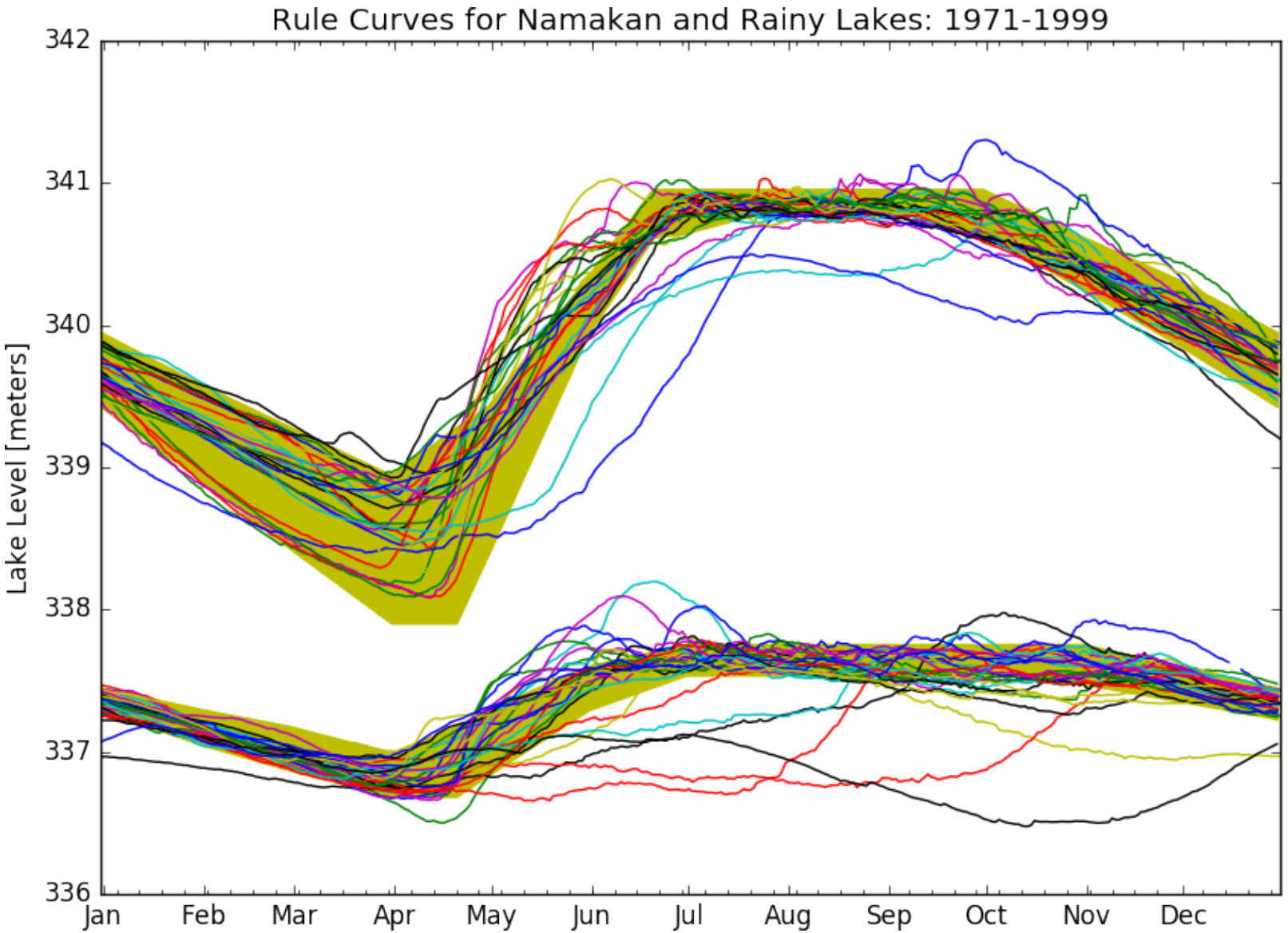
# IMPACT ON 2015 WILD RICE PRODUCTION

# RAINY LAKE AND NAMAKAN LAKE LEVELS 1911–

Clearly see three rule curve regimes ...

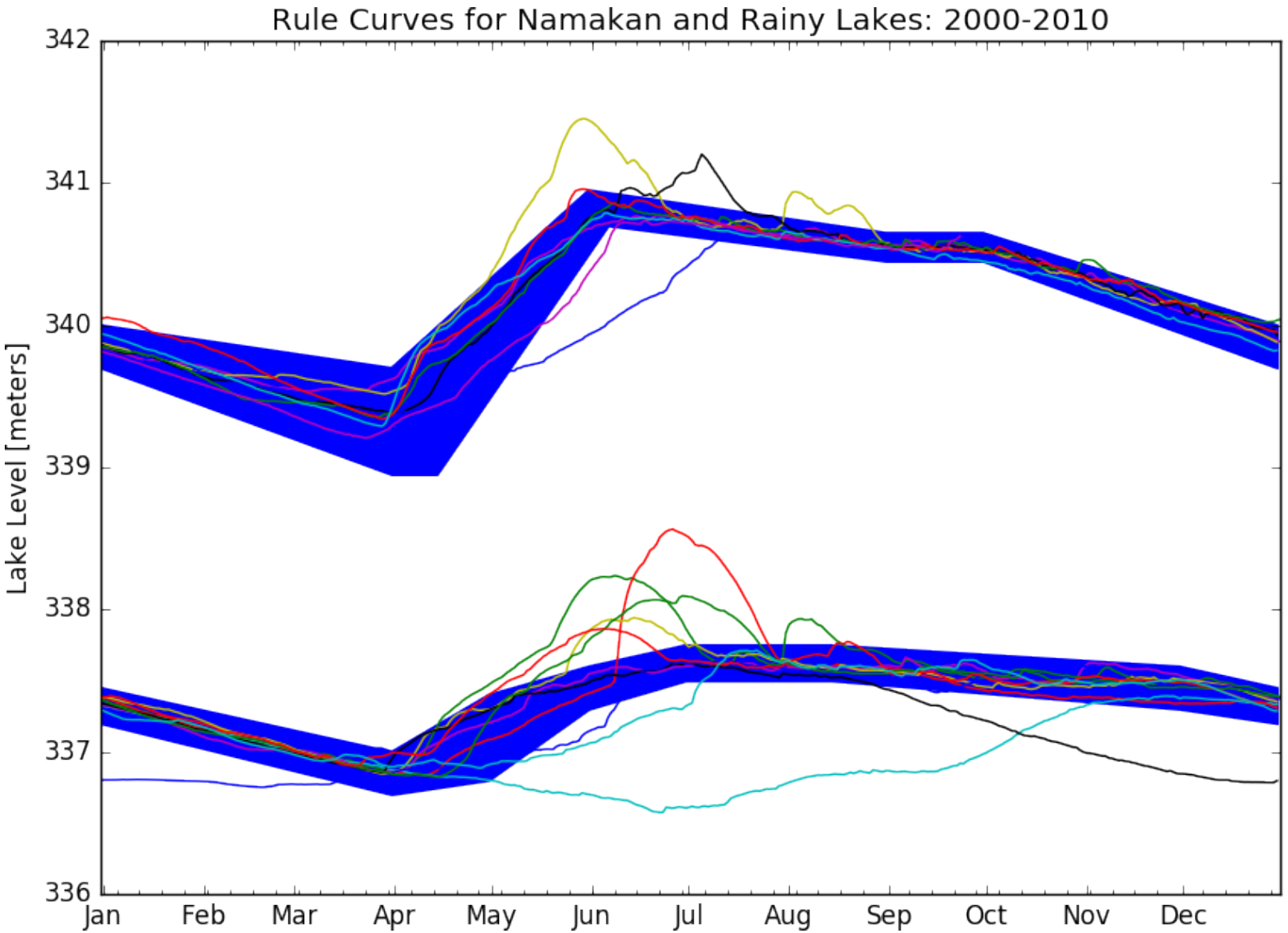


# RULE CURVE PERFORMANCE 1970–1999




Source: Github Repository for this paper.

# RULE CURVE PERFORMANCE 2000–2010




Source: Github Repository for this paper.

# SUMMER HIGH WATER EVENTS (MAY–SEPTEMBER)

| | | 1971–1999<br>4437 days | 2000–2010<br>1683 days |
|---|---|---|---|
| Rule Curve Exceeded | | | |
| | Frequency | 14.8% | 17.8% |
| | Median | 0.07 m | 0.23 m |
| | 95th Percentile | 0.38 m | 0.70 m |
| Emergency High Water | | | |
| | Frequency | 7.6% | 13.7% |
| | Median | 0.05 m | 0.19 m |
| | 95th Percentile | 0.36 m | 0.71 m |
| All Gates Open | | | |
| | Frequency | 1.9% | 8.7% |
| | Median | 0.12 m | 0.17 m |
| | 95th Percentile | 0.29 m | 0.62 m |

Source: Github Repository for this paper.

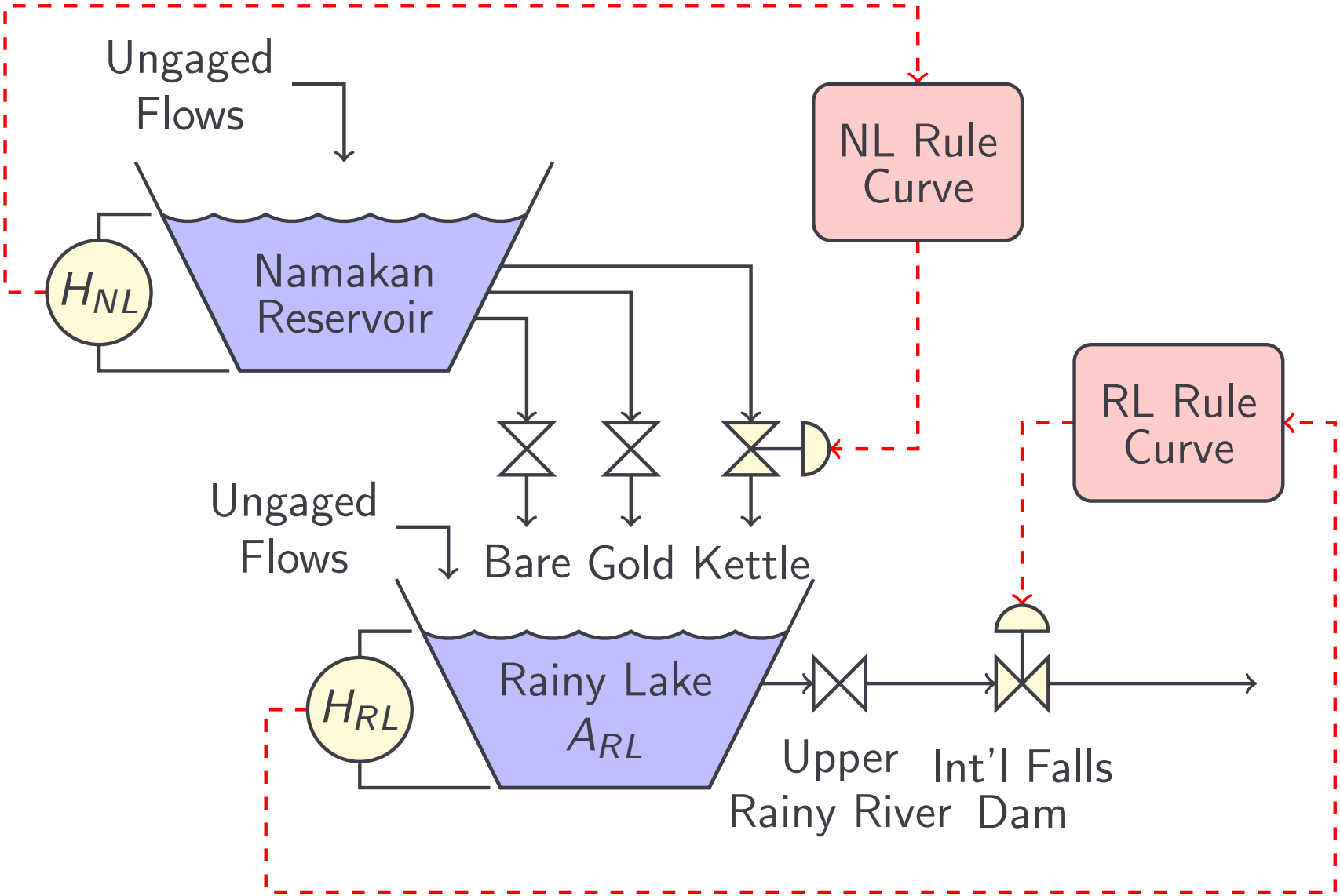
# 1993 FINAL REPORT AND RECOMMENDATIONS

"To offset the potential for the proposed rule curve modifications to increase the frequency of spring flood events, the IJC should enforce the provision of its 1970 Supplemental Order requiring the dam operators to anticipate inflows and maximize the discharge capabilities of the dams to prevent emergency water levels.

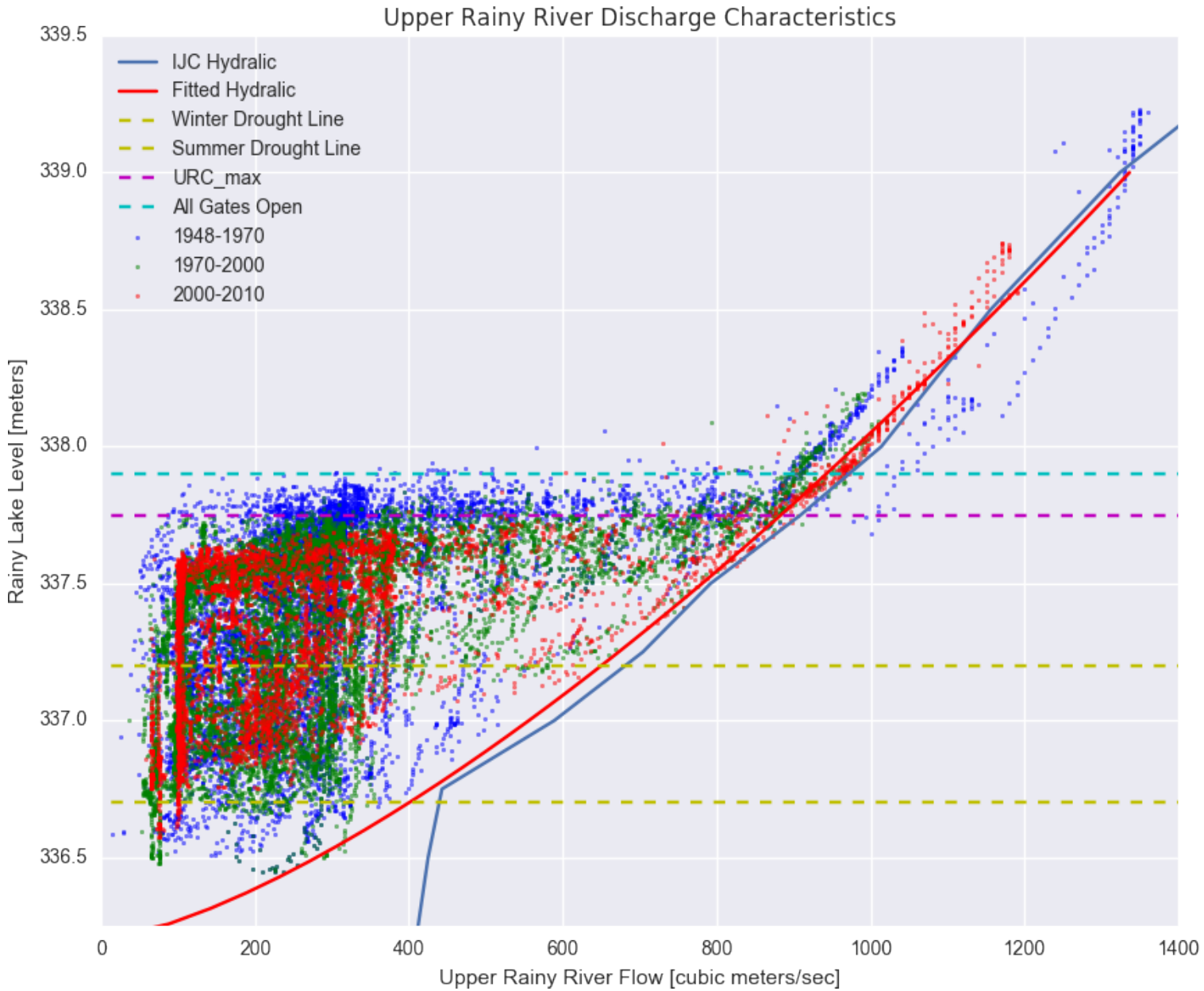
"The Steering Committee believes that diligent use of the existing network of upstream lake level gauges and currently available hydrologic models can make this IJC mandate a reality and improve the accuracy and reliability of reservoir level control."

Source: Rainy Lake & Namakan Reservoir Water Level International Steering Committee, Final Report and Recommendations, November, 1993.

# CURRENT PRACTICE

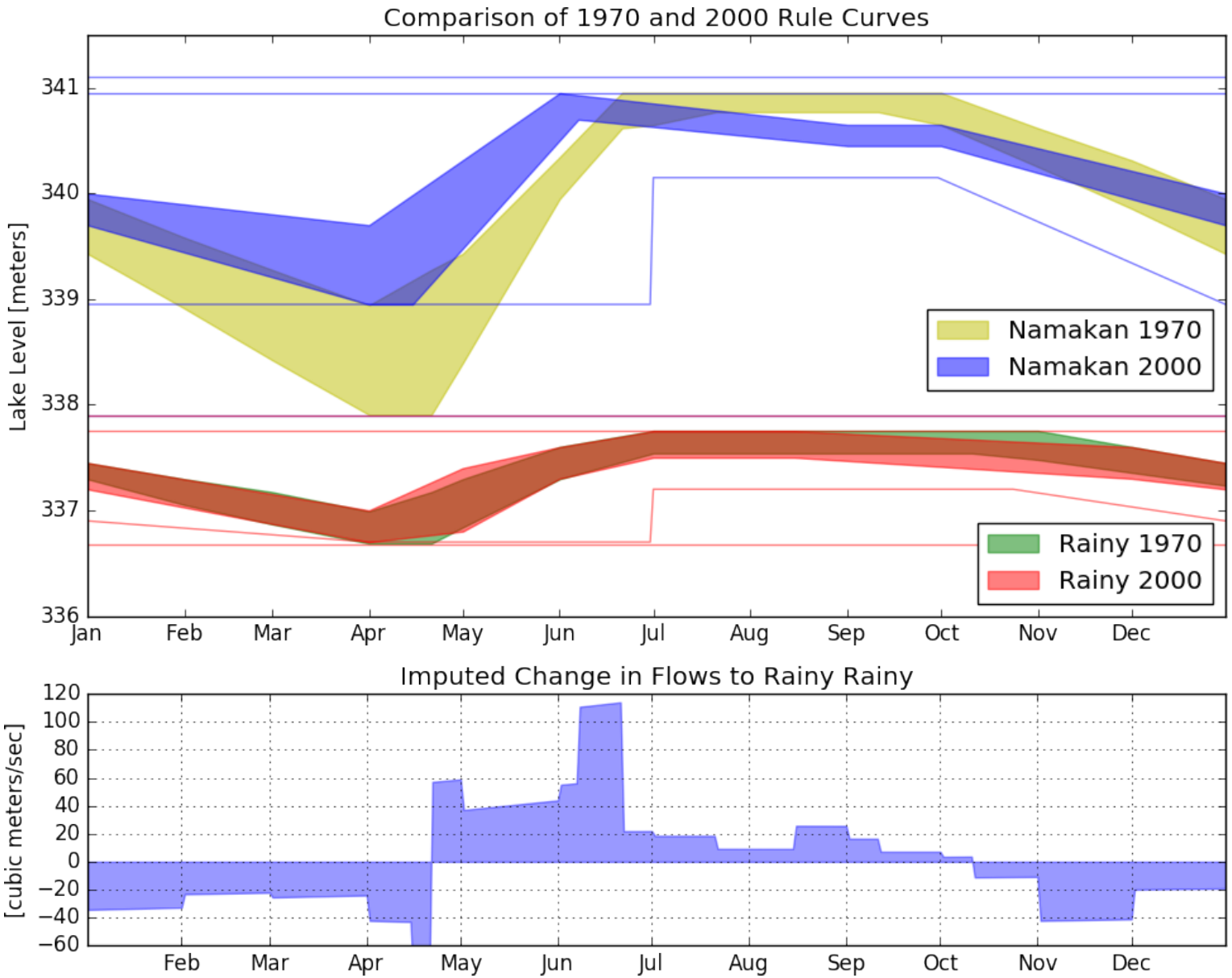


# UPPER RAINY RIVER DISCHARGE CHARACTERISTICS



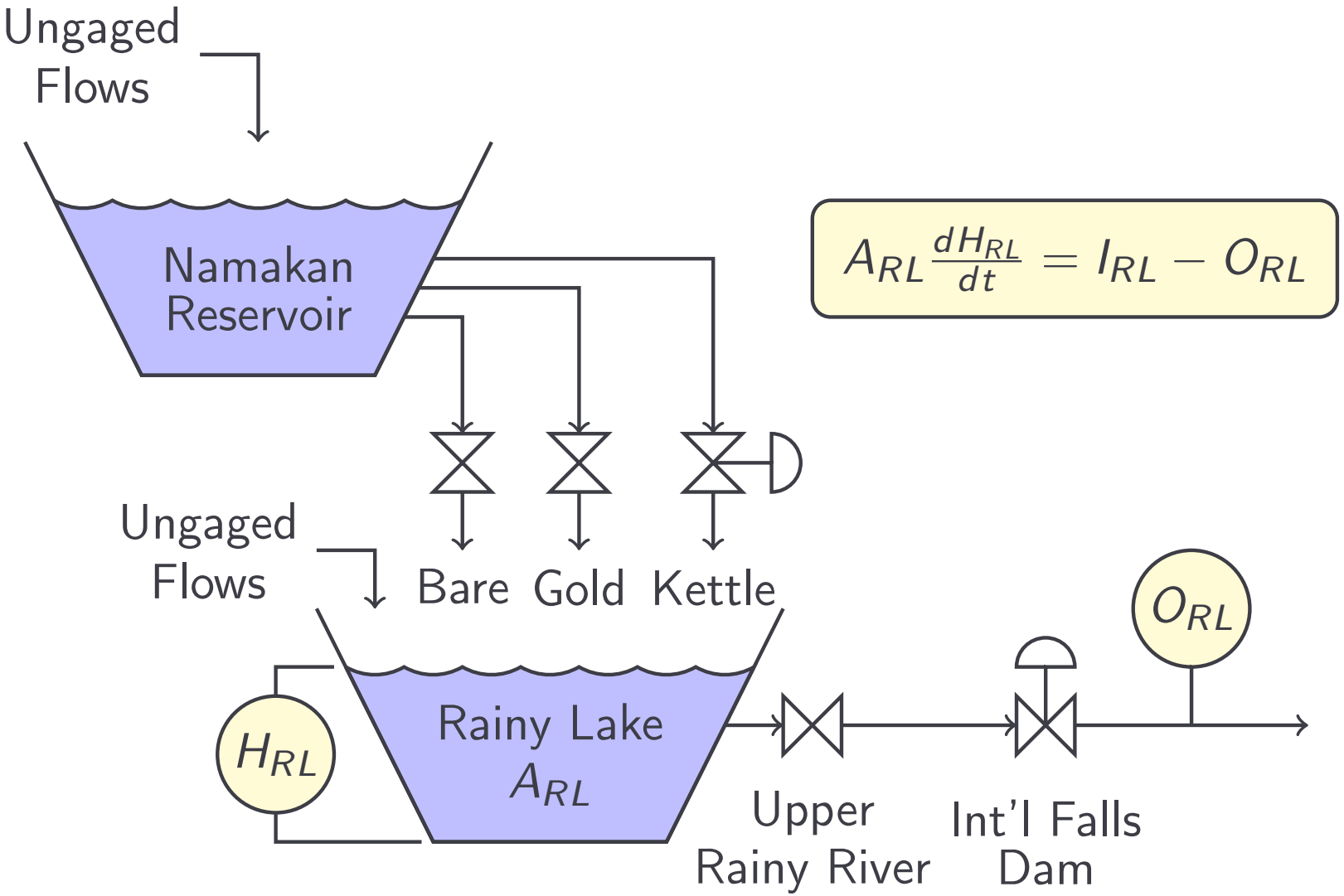

Source: Github Repository for this paper.

# RULE CURVE CHANGES IN 2000




Source: Github Repository for this paper.

# ESTIMATING RAINY LAKE INFLOWS



# RAINY LAKE MEASUREMENT MODEL

**Lake Model:** $H$, $I$, $O$ are lake level, inflow, and outflow

$$\underbrace{\begin{bmatrix} H_{RL}(k+1) \\ I_{RL}(k+1) \\ O_{RL}(k+1) \end{bmatrix}}_{x(k+1)} = \underbrace{\begin{bmatrix} 1 & \frac{\Delta t}{A_{RL}} & -\frac{\Delta t}{A_{RL}} \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{A} \underbrace{\begin{bmatrix} H_{RL}(k) \\ I_{RL}(k) \\ O_{RL}(k) \end{bmatrix}}_{x(k)} + \underbrace{\begin{bmatrix} 0 \\ w_I(k) \\ w_O(k) \end{bmatrix}}_{w(k) \sim \mathcal{N}(\imath, \mathcal{Q})}$$

where $w_I(k)$, $w_O(k)$ are random i.i.d. flow increments.

**Measurement model:** Given level and outflow measurements

$$\underbrace{\begin{bmatrix} y_H(k) \\ y_O(k) \end{bmatrix}}_{y(k)} = \underbrace{\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix}}_{C} \underbrace{\begin{bmatrix} H_{RL}(k) \\ I_{RL}(k) \\ O_{RL}(k) \end{bmatrix}}_{x(k)} + \underbrace{\begin{bmatrix} v_H(k) \\ v_O(k) \end{bmatrix}}_{v(k) \sim \mathcal{N}(\imath, \mathcal{R})}$$

measurement noise $v(k)$ is an i.i.d. random variable.

# EXTENDED KALMAN FILTER

**State Update:** Given state estimate $x'(k-1|k-1)$ and convariance estimate $P(k-1|k-1)$

$$x'(k|k-1) = Ax'(k-1|k-1)$$
$$P(k|k-1) = AP(k-1|k-1)A^T + Q$$

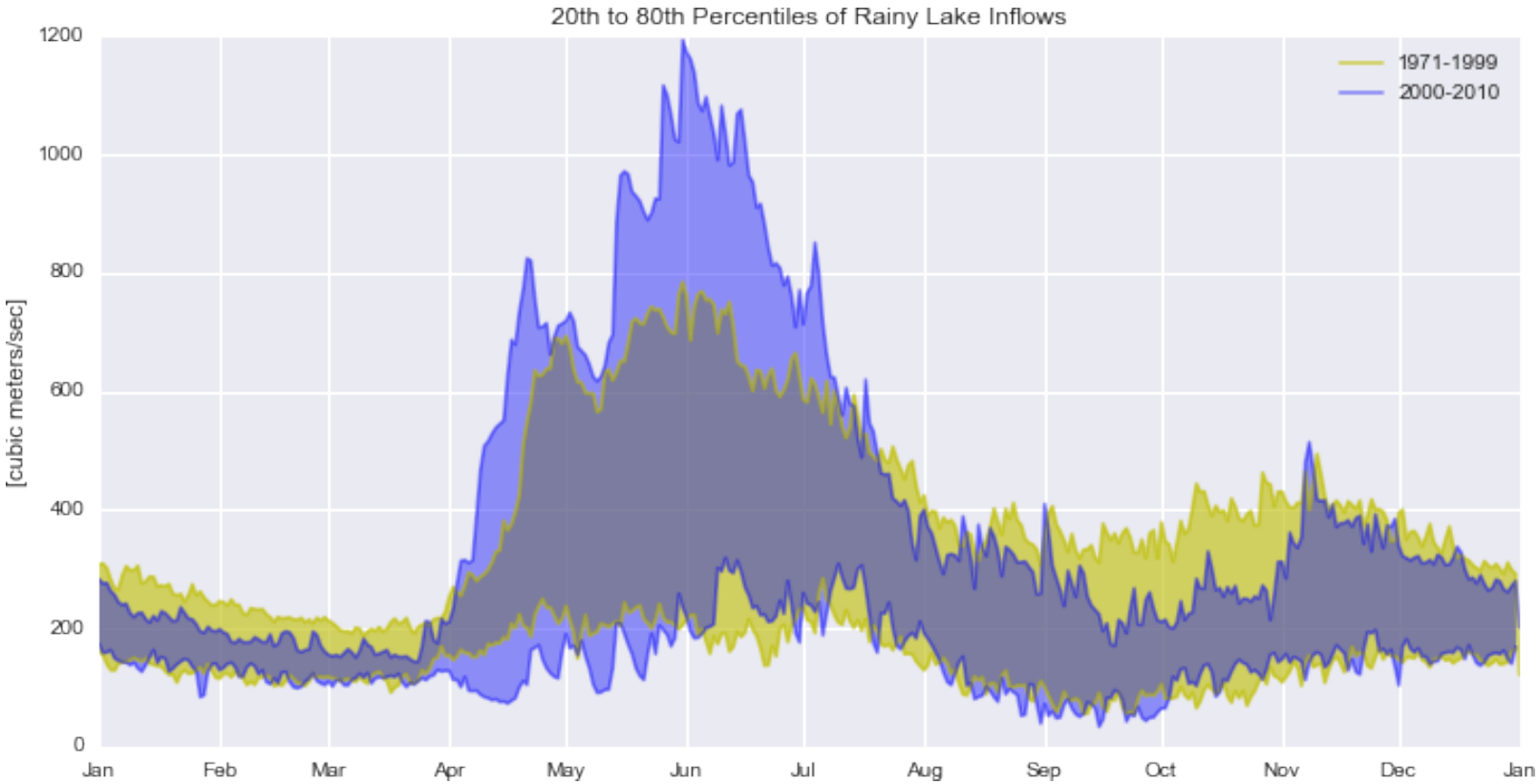
**Measurement Update:** Given estimates $x'(k|k-1)$, $P(k|k-1)$

$$S(k) = CP(k|k-1)C^T + R$$
$$K(k) = P(k|k-1)C^T S^{-1}(k)$$

for state and covariance updates

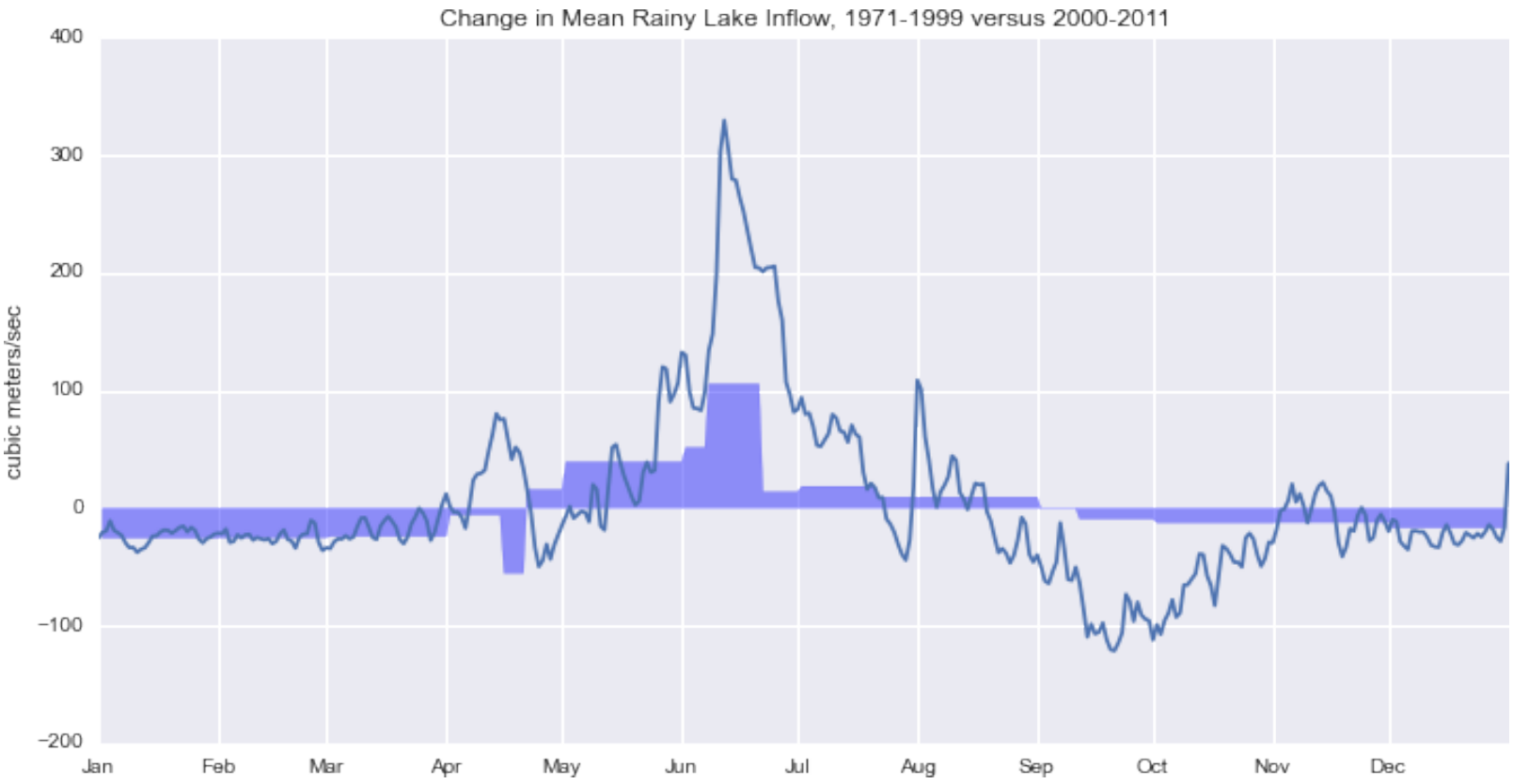
$$x'(k|k) = x'(k|k-1) + K(k)\left[y(k) - Cx'(k|k-1)\right]$$
$$P(k|k) = P(k|k-1) - K(k)S(k)K^T(k)$$

# RAINY LAKE INFLOWS, 1970-1999 VS 2000-2010




Source: Github Repository for this paper.

# CHANGE IN INFLOW TO RAINY LAKE, 1979-99 VS 2000-10

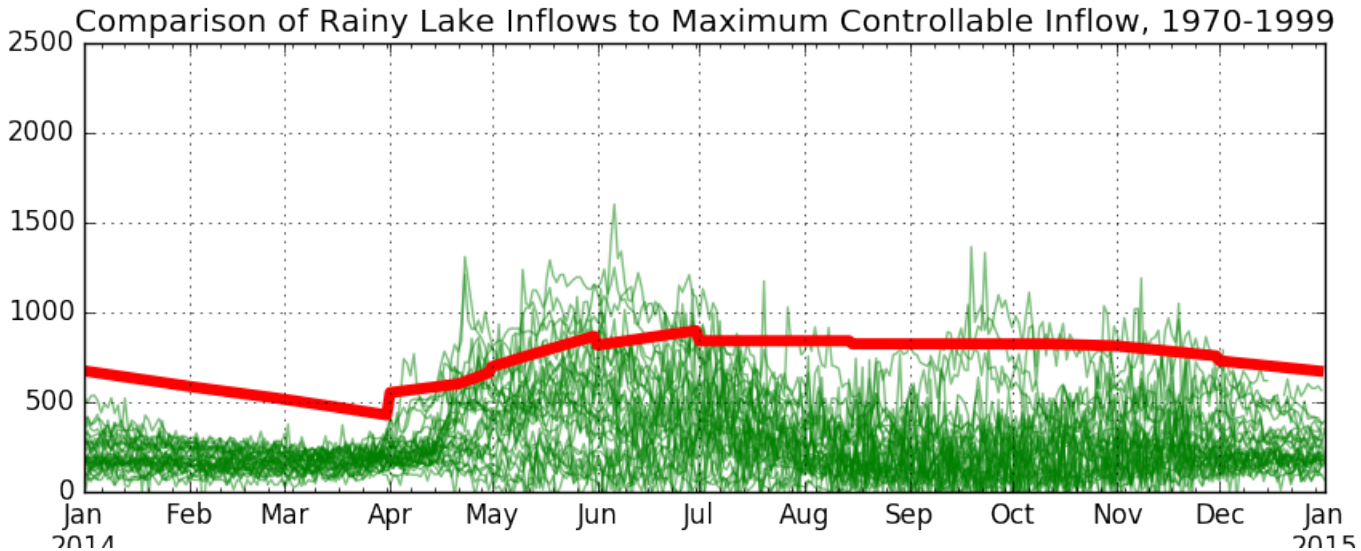


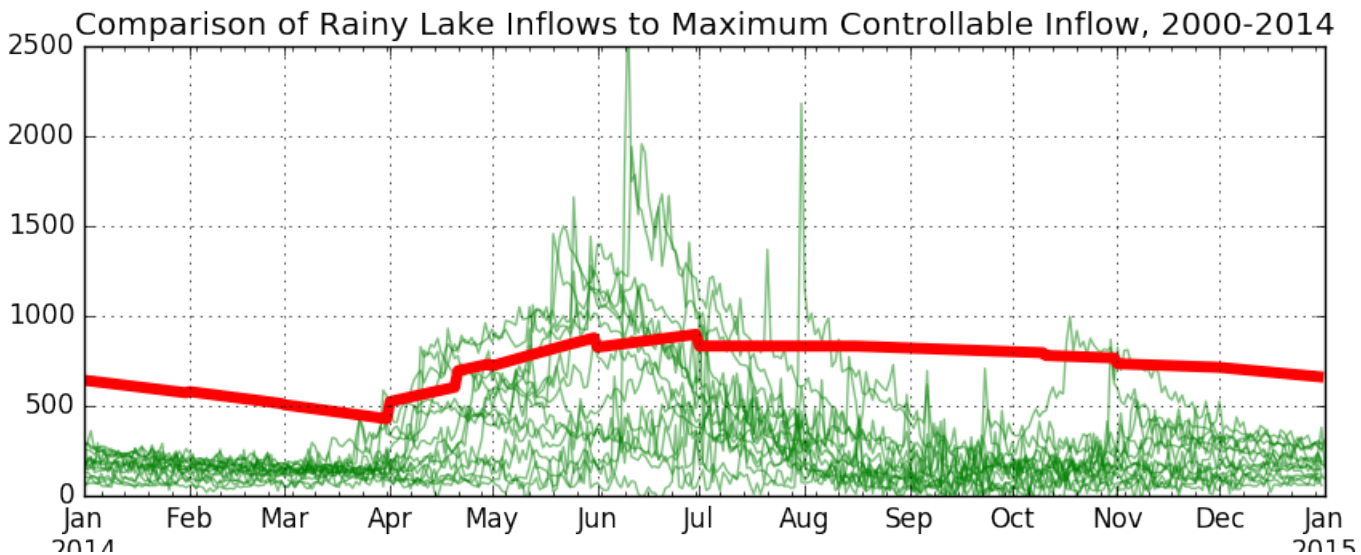

Source: Github Repository for this paper.

# IMPACT OF THE RULE CURVE CHANGE, 1970 - 2000

1. Displaces winter inflow to Rainy Lake from winter to summer months.
2. Flow constrictions in Upper Rainy River lead to water level increases in May/June.

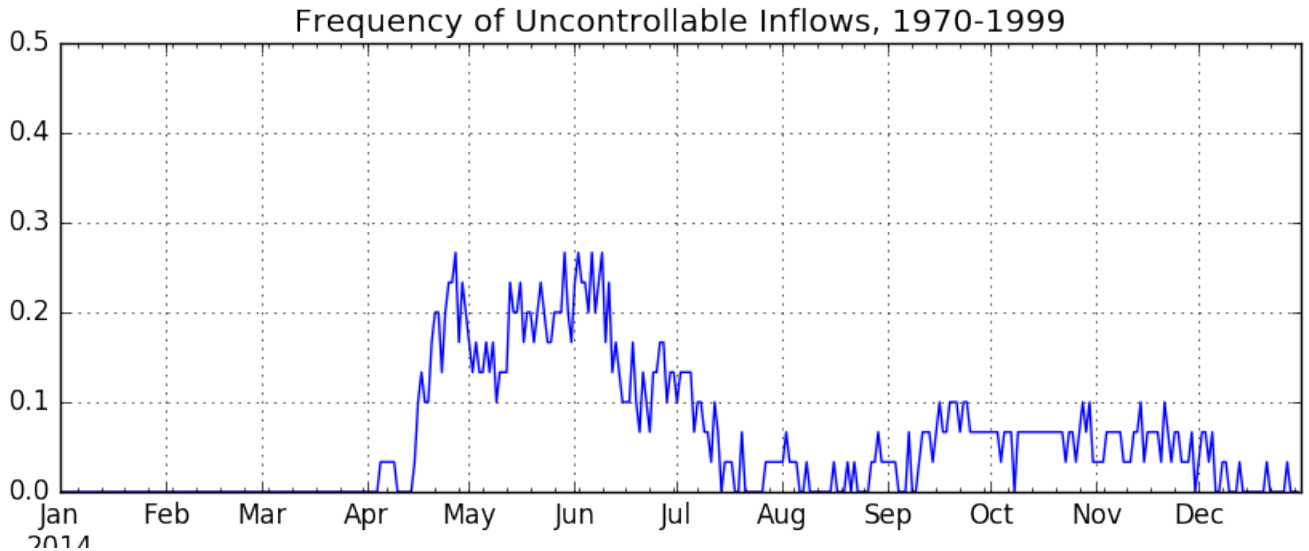
# MAXIMUM CONTROLLABLE INFLOWS

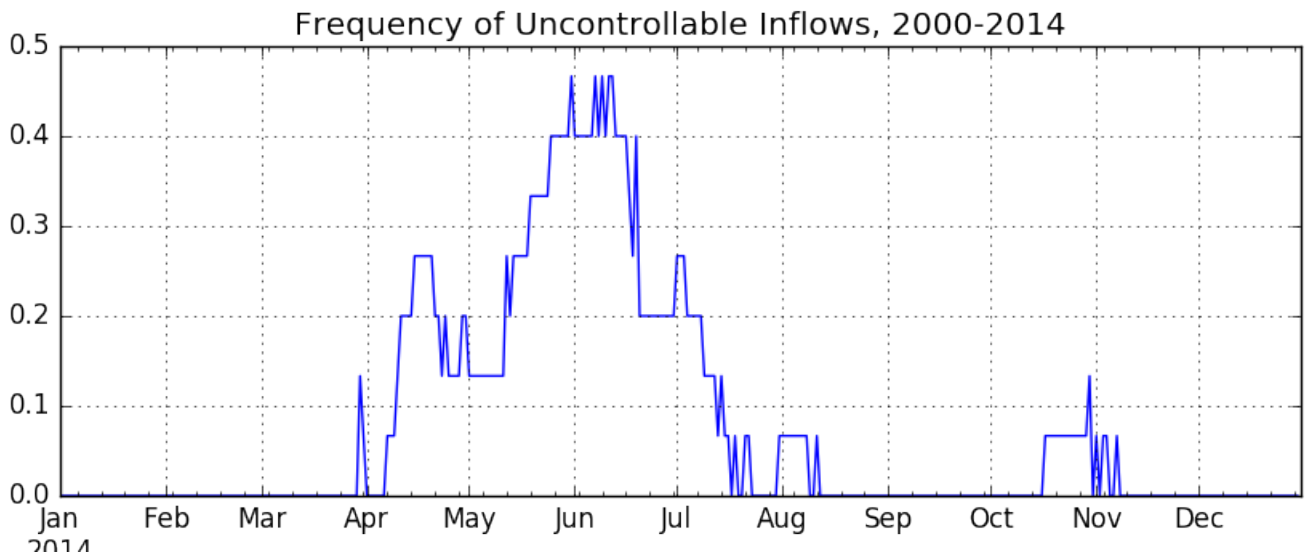



Source: Github Repository for this paper.

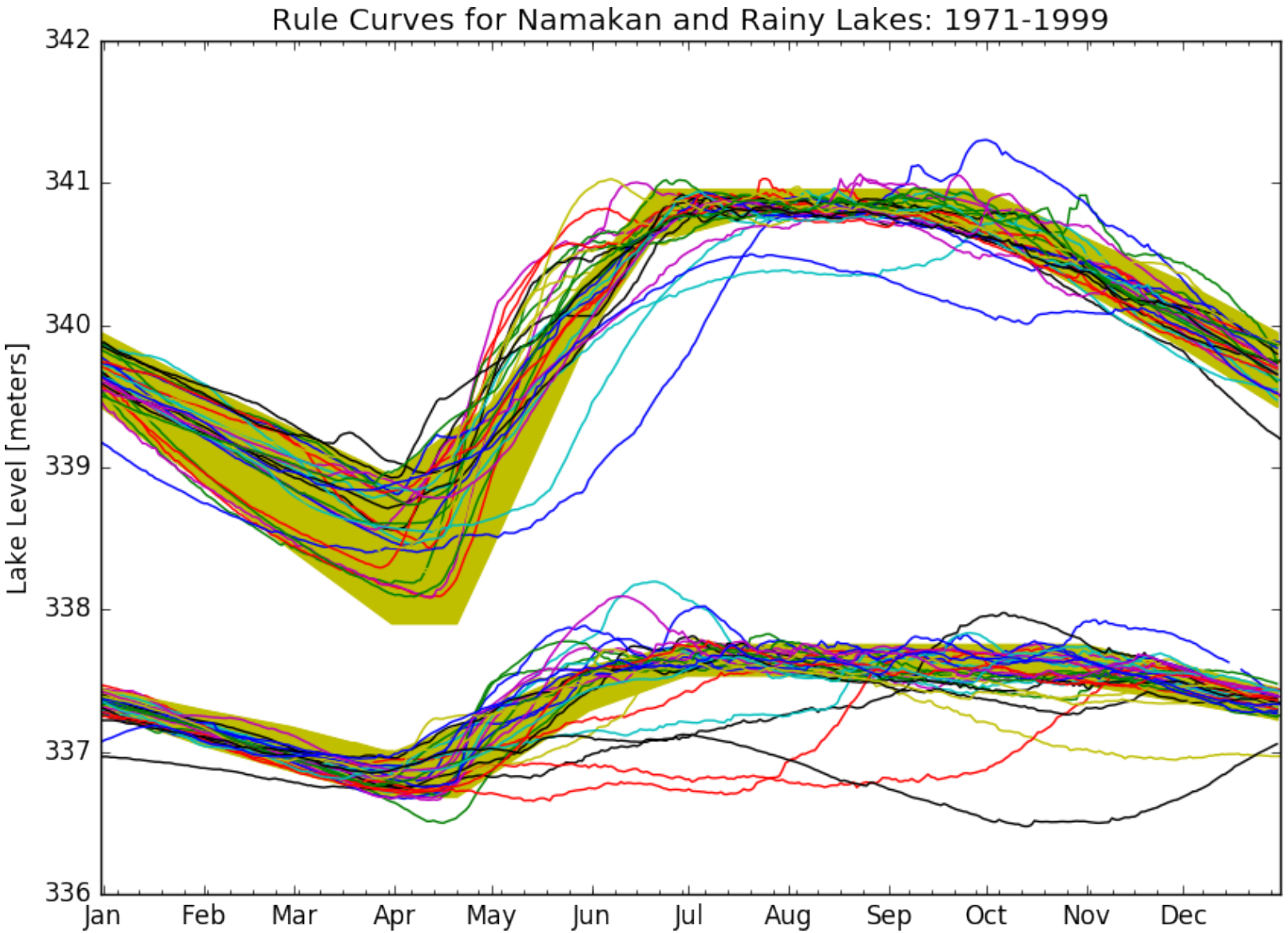
# UNCONTROLLABLE INFLOW FREQUENCY



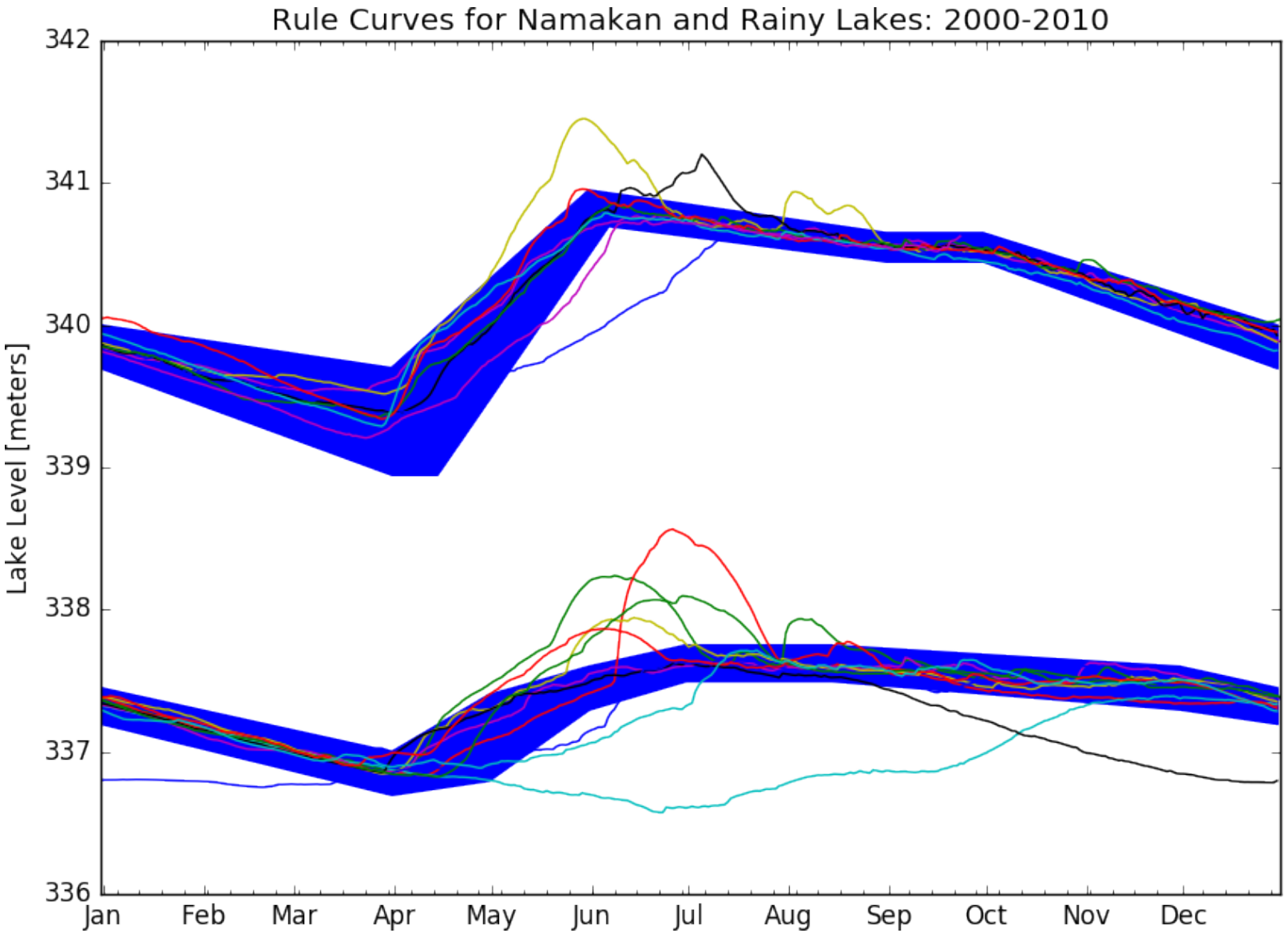

Source: Github Repository for this paper.

# RULE CURVE PERFORMANCE 1970–1999



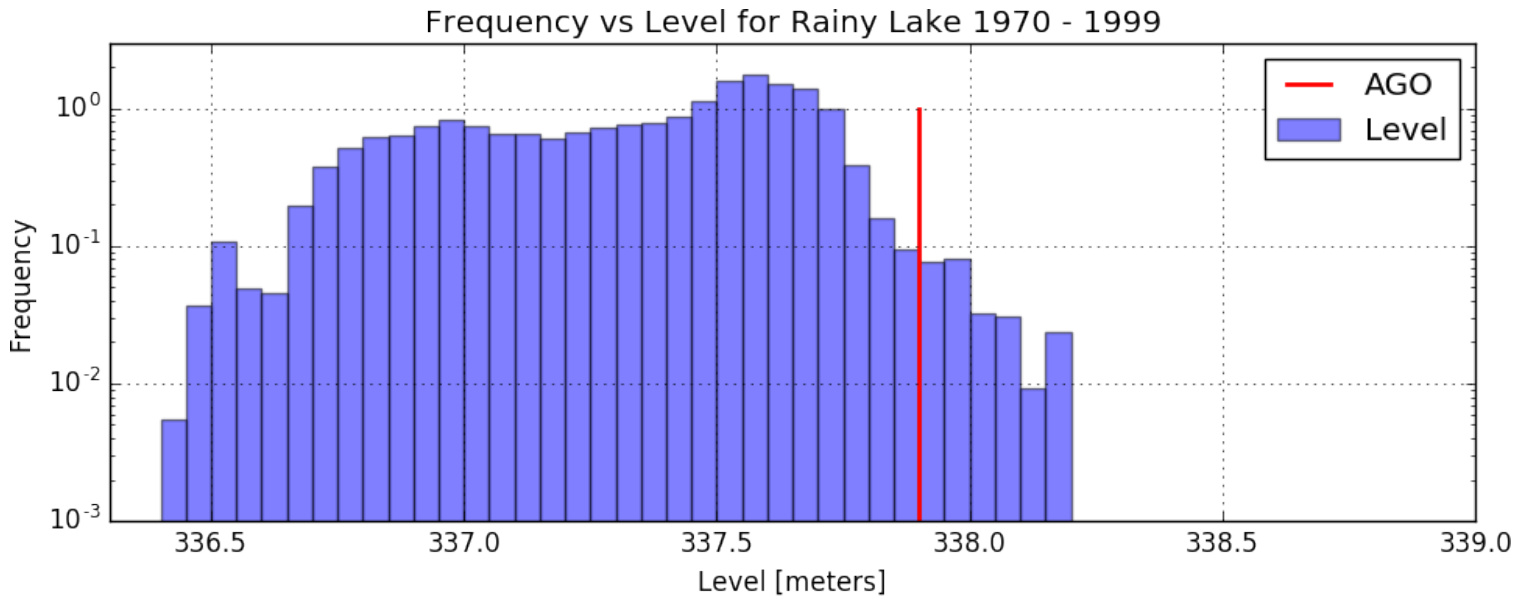

Source: Github Repository for this paper.

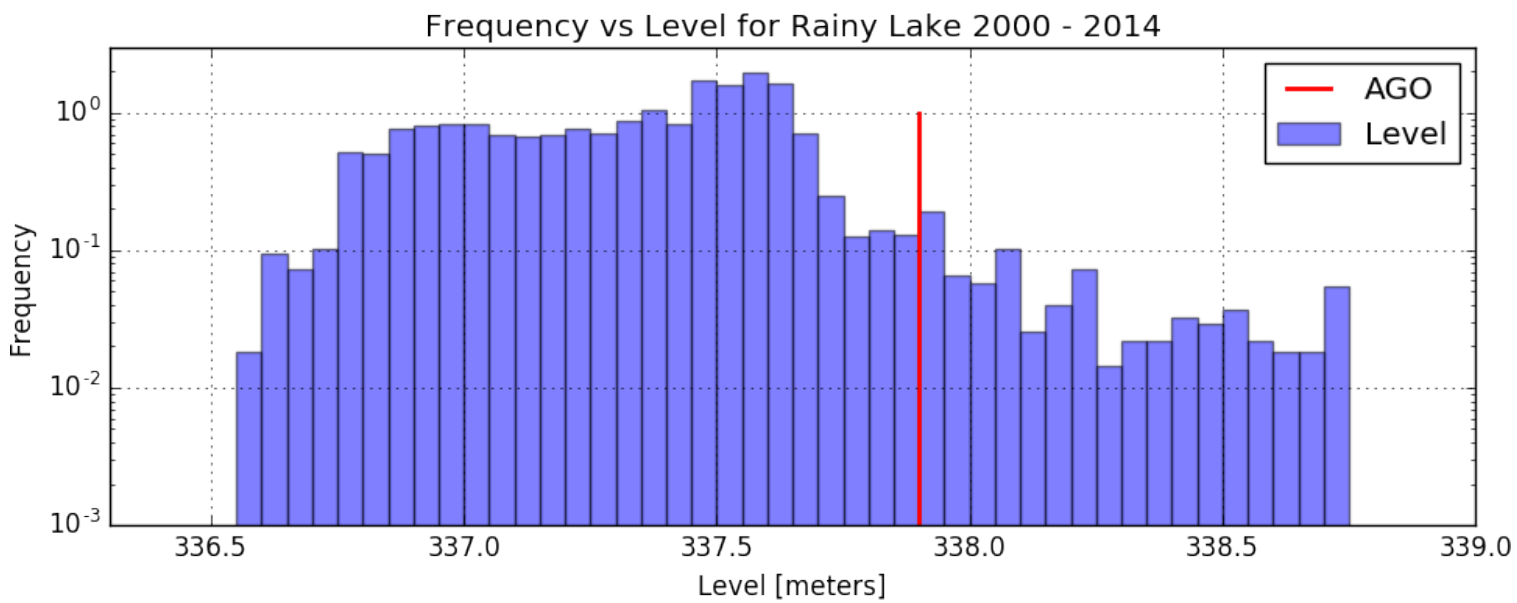
# RULE CURVE PERFORMANCE 2000–2014




Source: Github Repository for this paper.

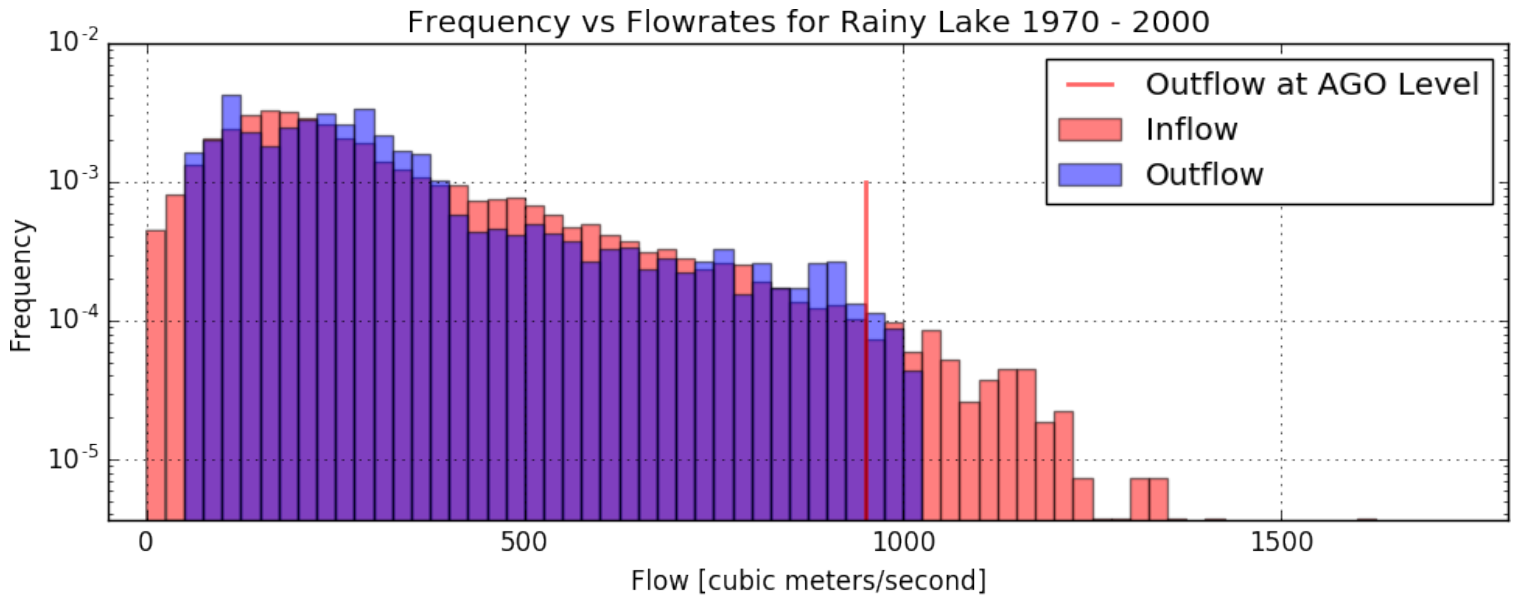
# RULE CURVE PERFORMANCE - RAINY LAKE LEVELS

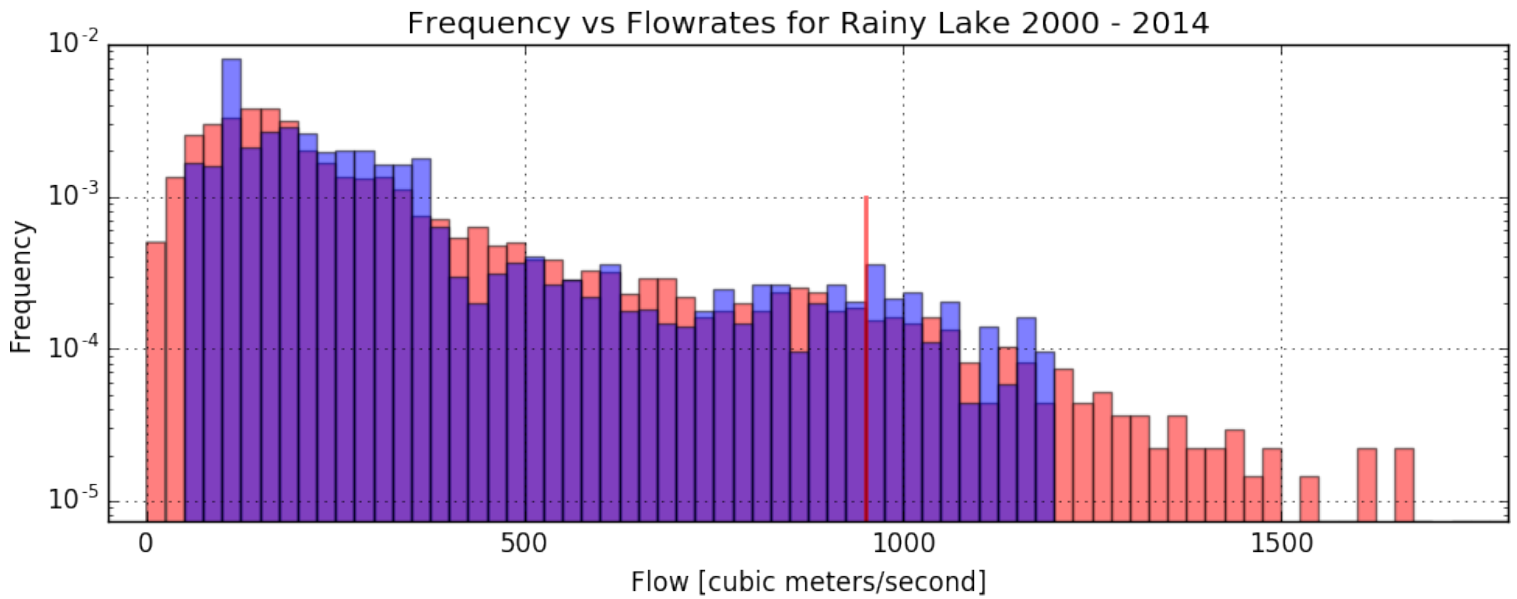



Source: Github Repository for this paper.

# RULE CURVE PERFORMANCE - INFLOWS AND OUTFLOWS

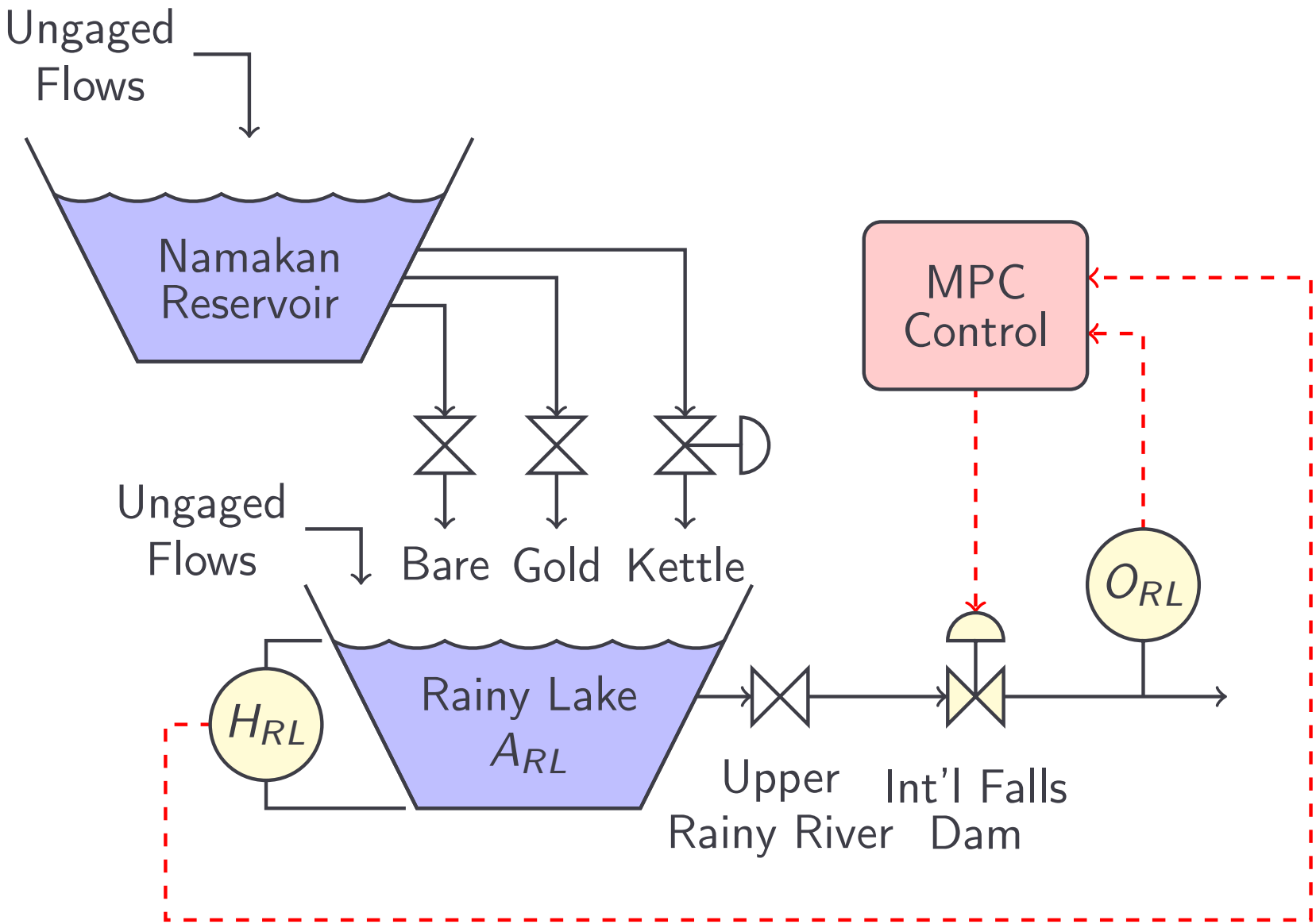


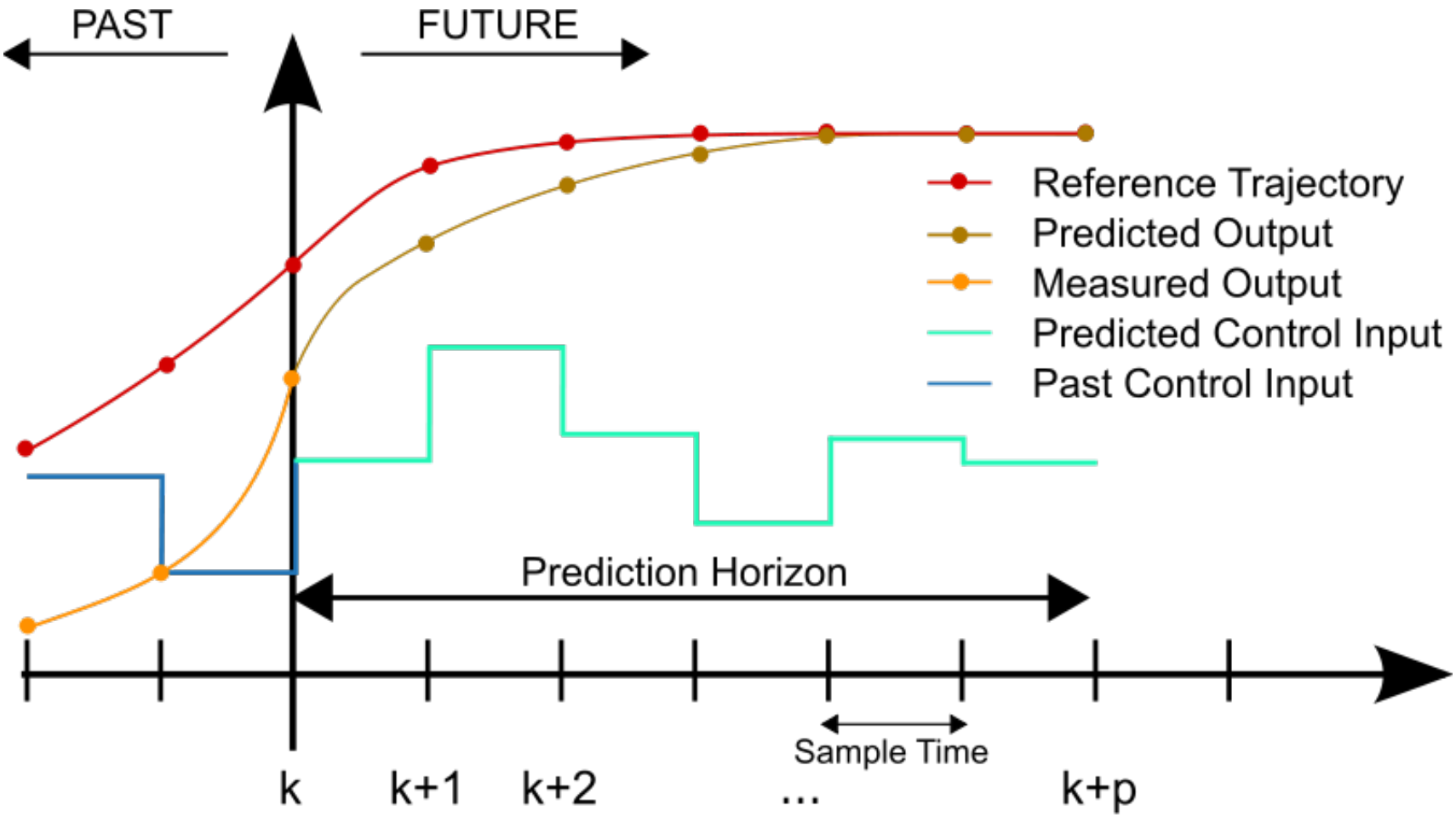

Source: Github Repository for this paper.

# IMPLEMENTING RULE CURVES WITH MODEL PREDICTIVE CONTROL

# MODEL PREDICTIVE CONTROL FOR RAINY LAKE

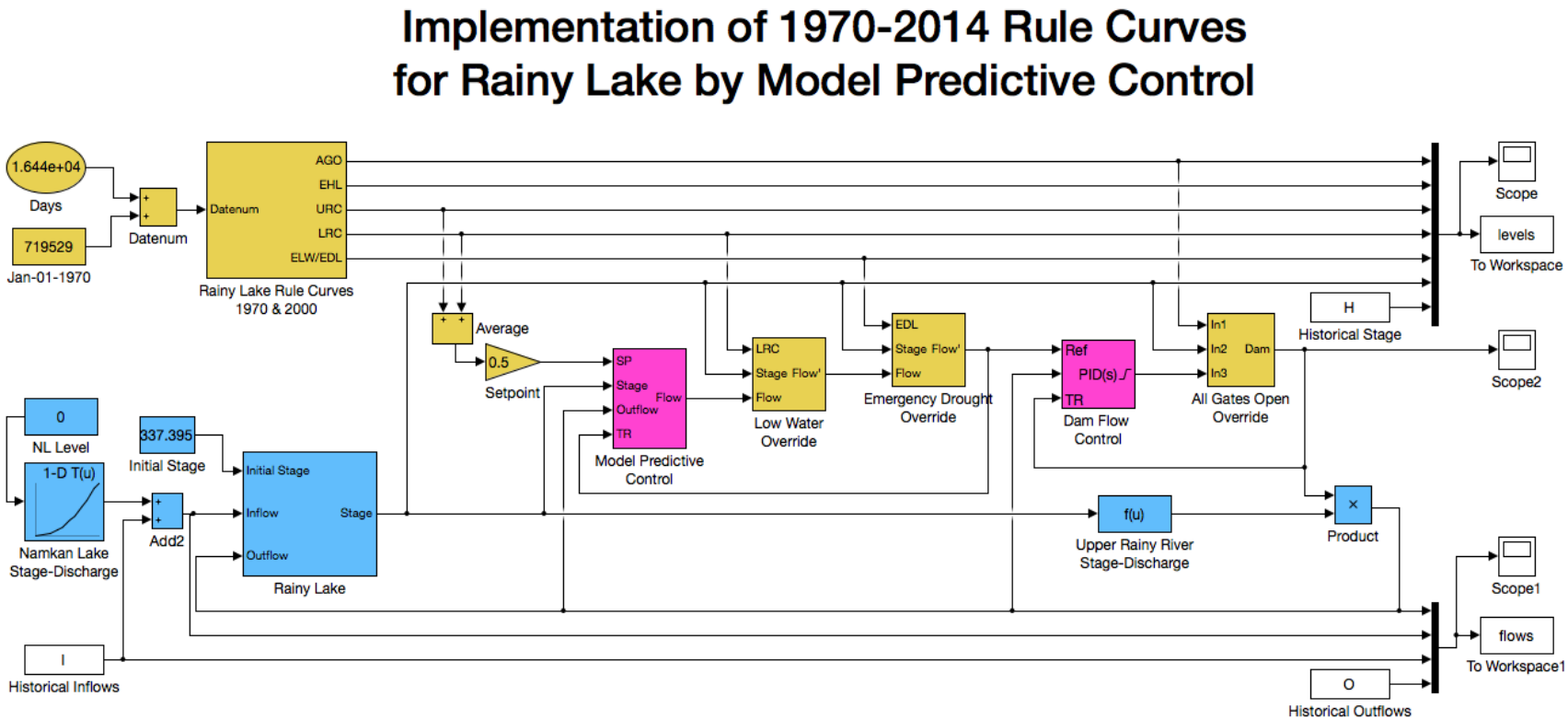


# MODEL PREDICTIVE CONTROL




Source: Martin Behrendt

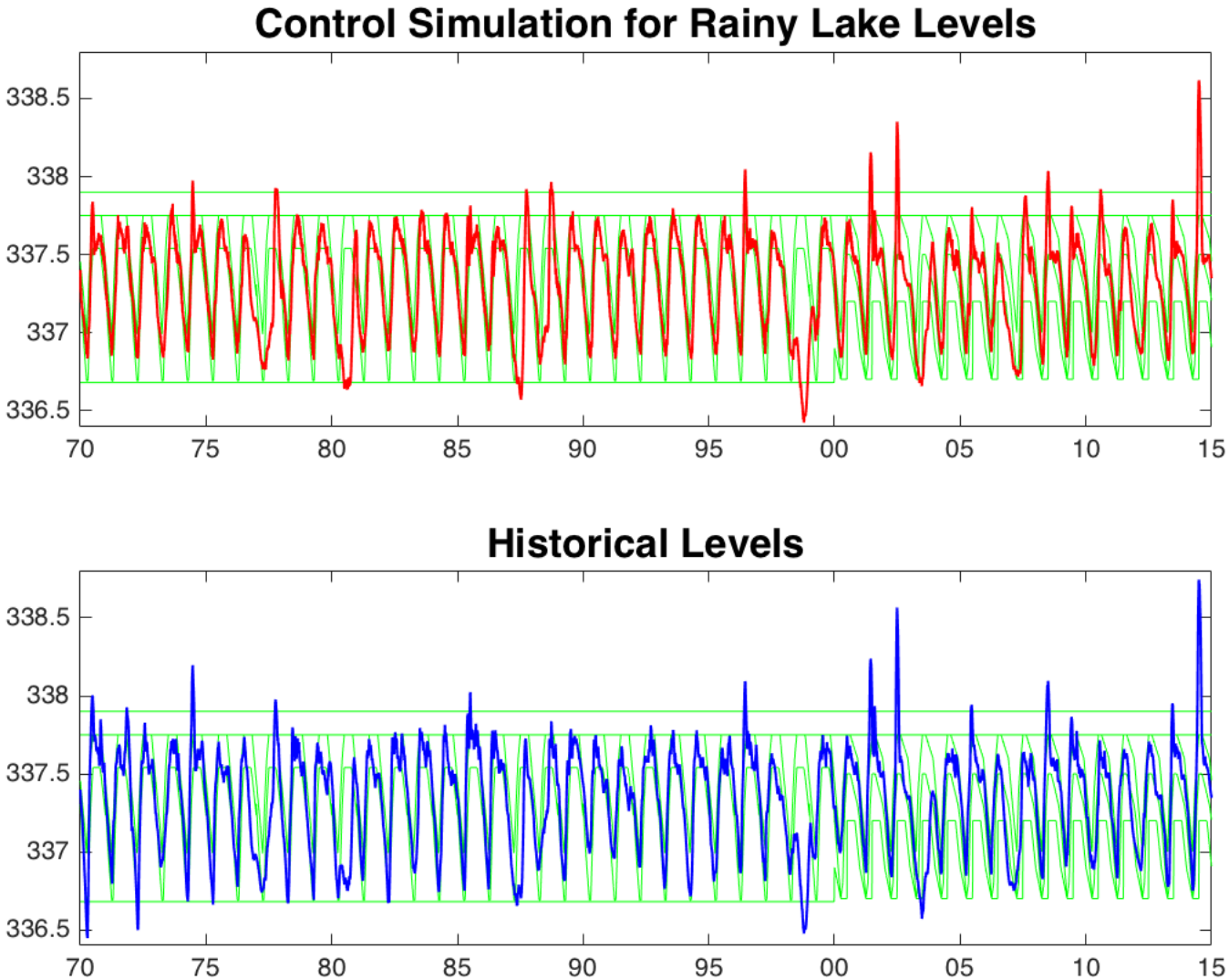
# MATLAB/SIMULINK IMPLEMENTATION




Source: Github Repository for this paper.

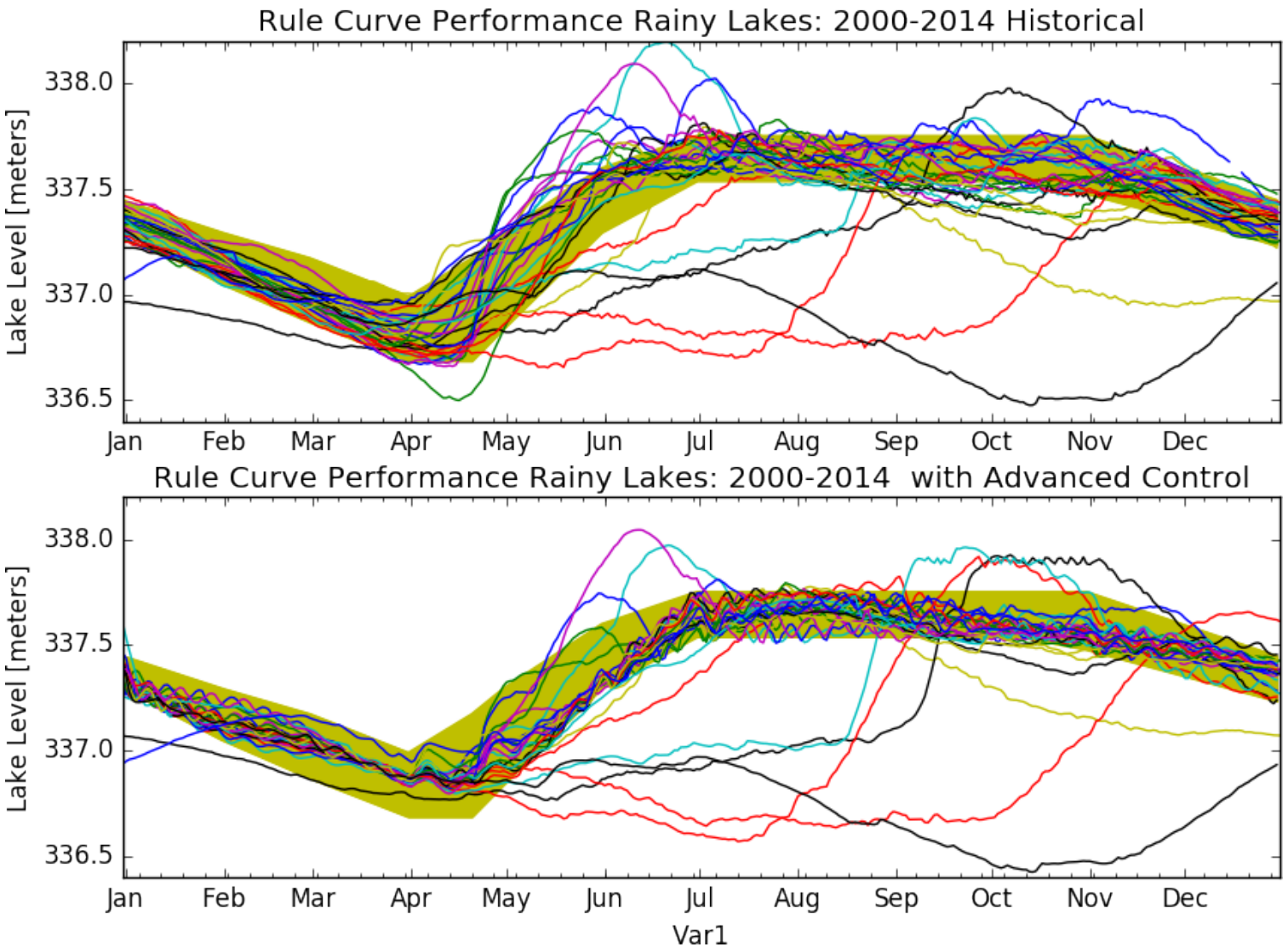
# ASSESSMENT AND IMPLICATIONS FOR RULE CURVE REVIEW

# SIMULATION RESULTS



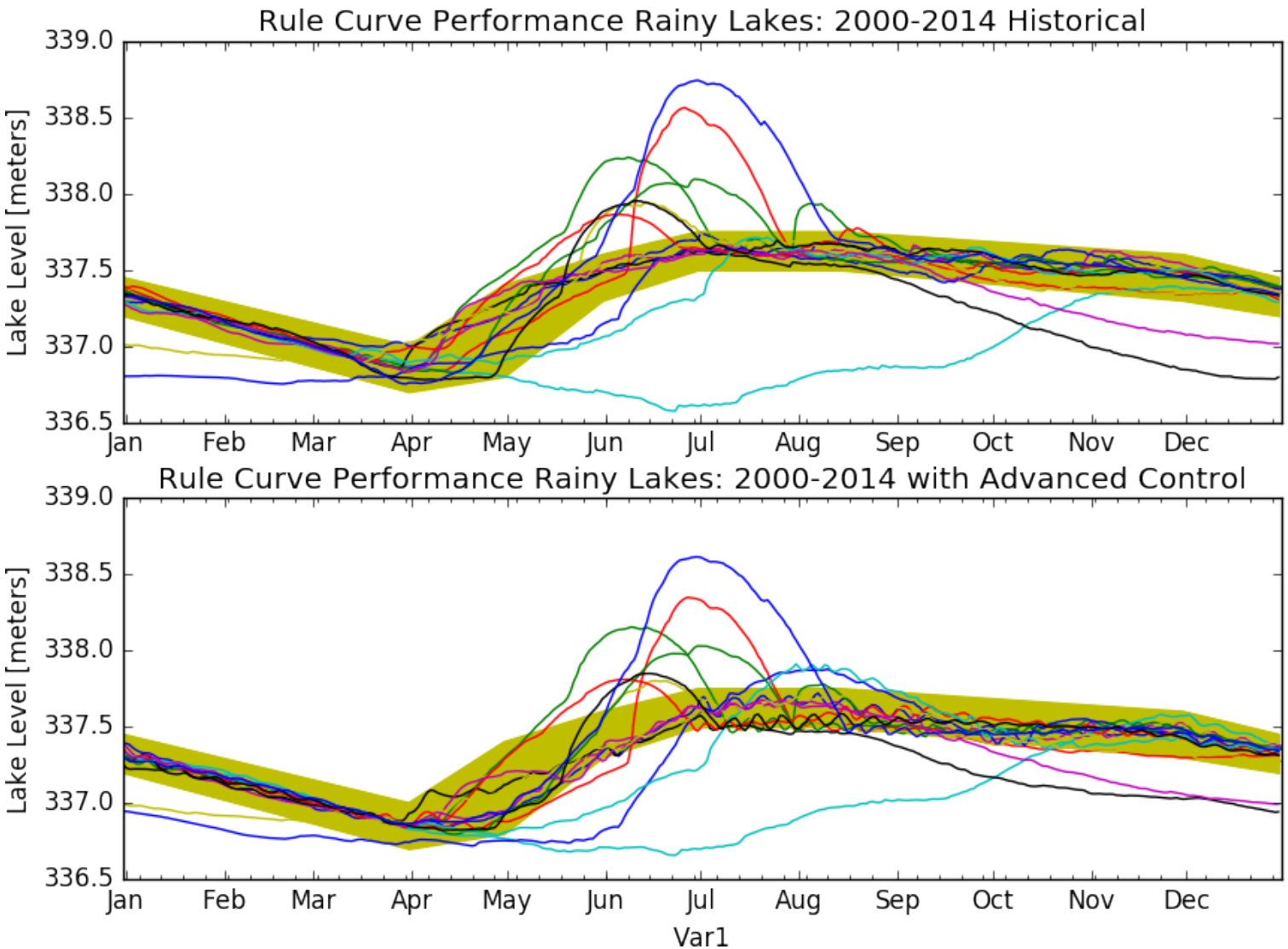

Source: Github Repository for this paper.

# SIMULATION RESULTS



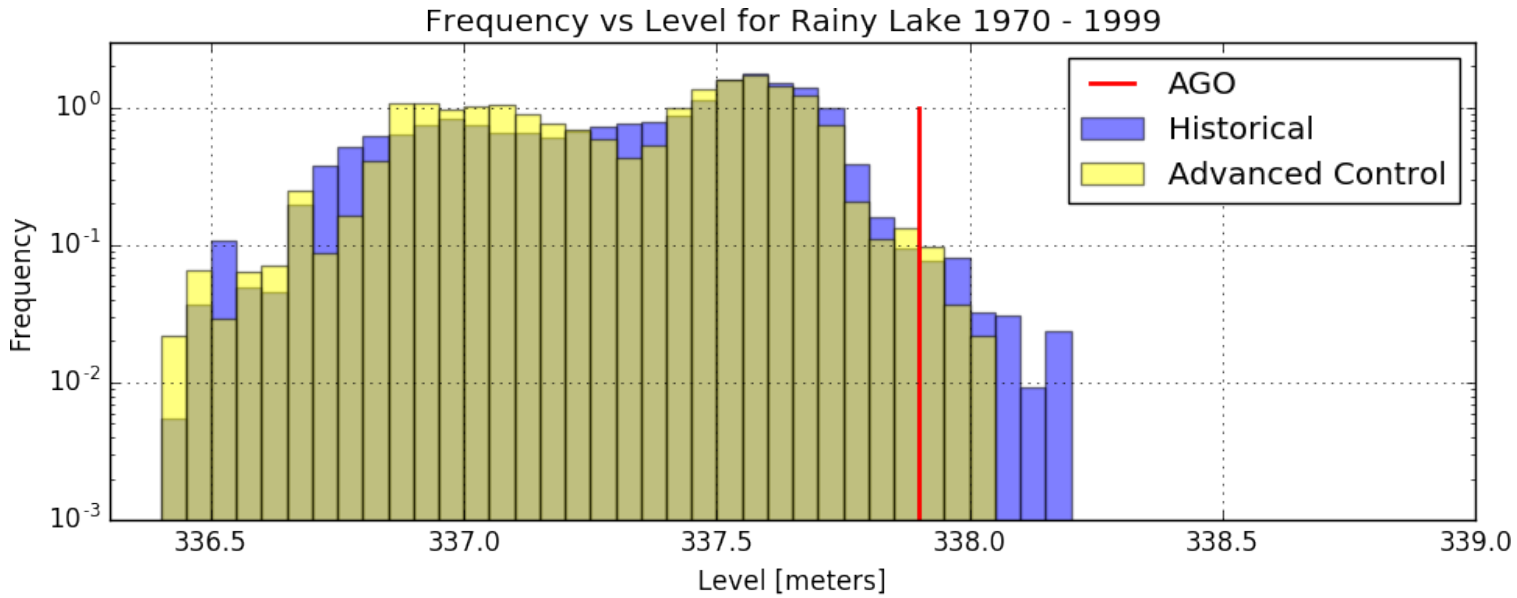

Source: Github Repository for this paper.

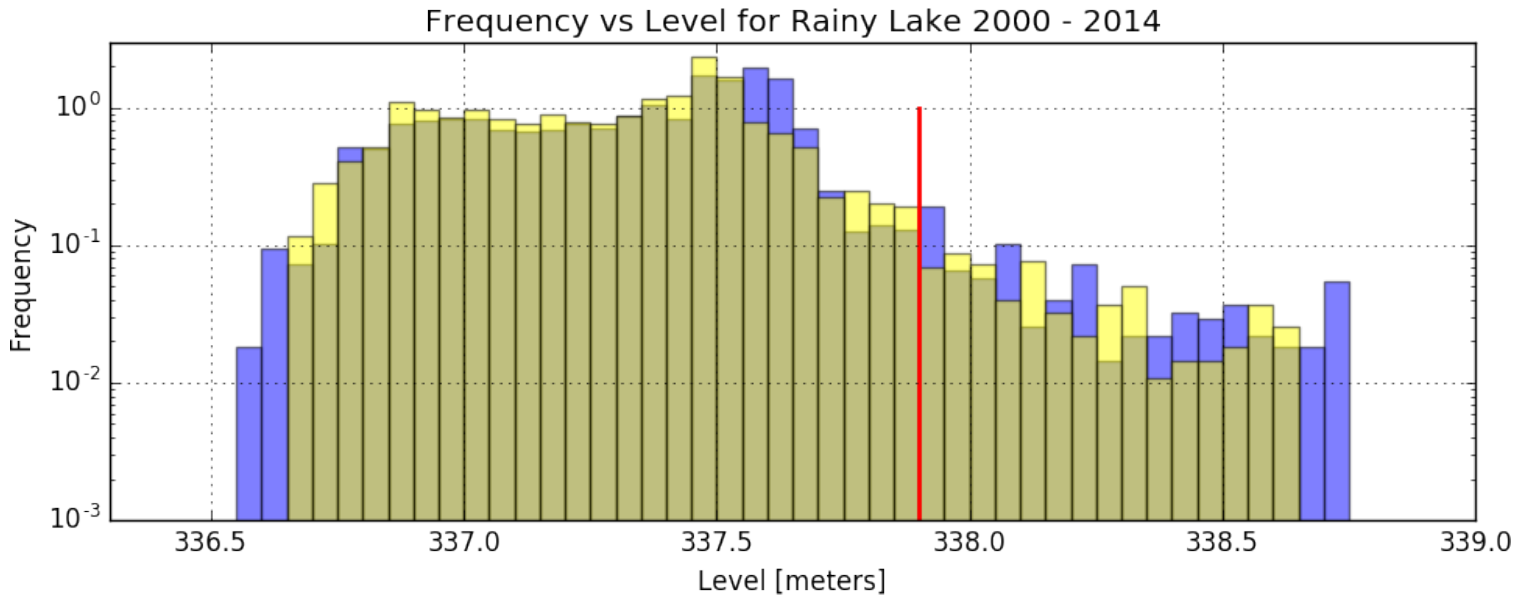
# SIMULATION RESULTS




Source: Github Repository for this paper.

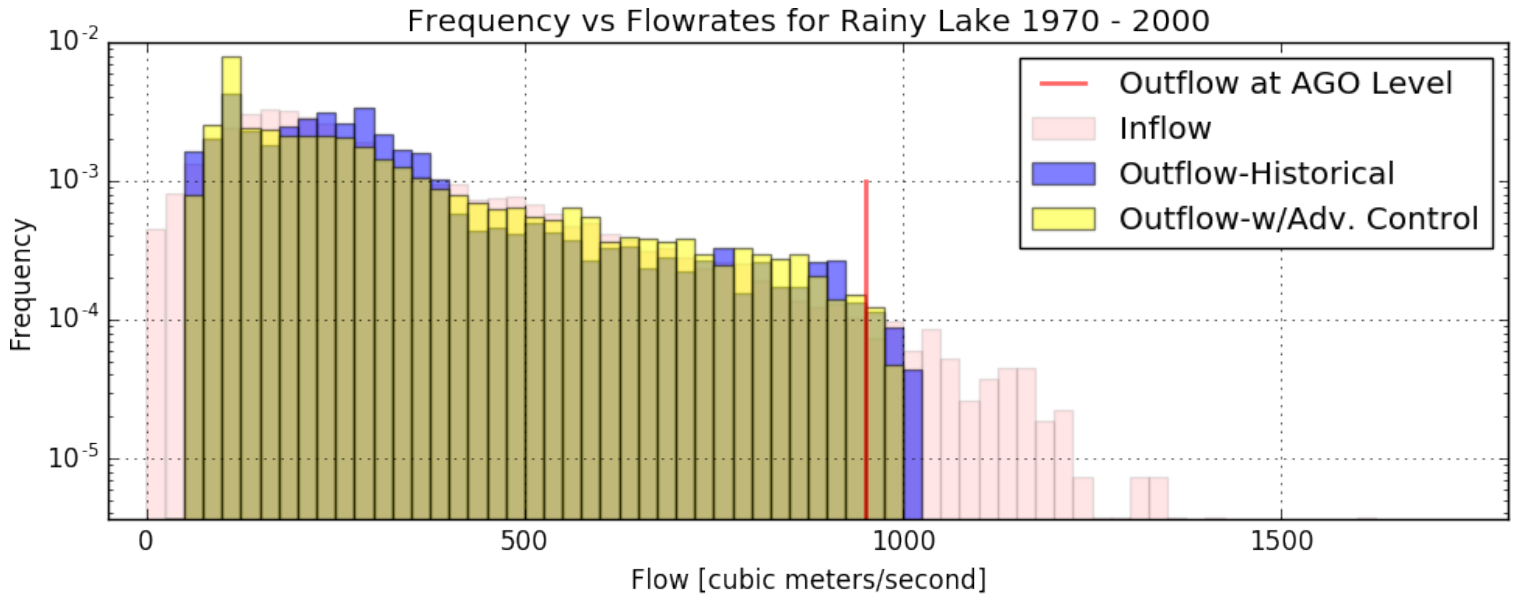
# SIMULATION RESULTS - RAINY LAKE LEVELS

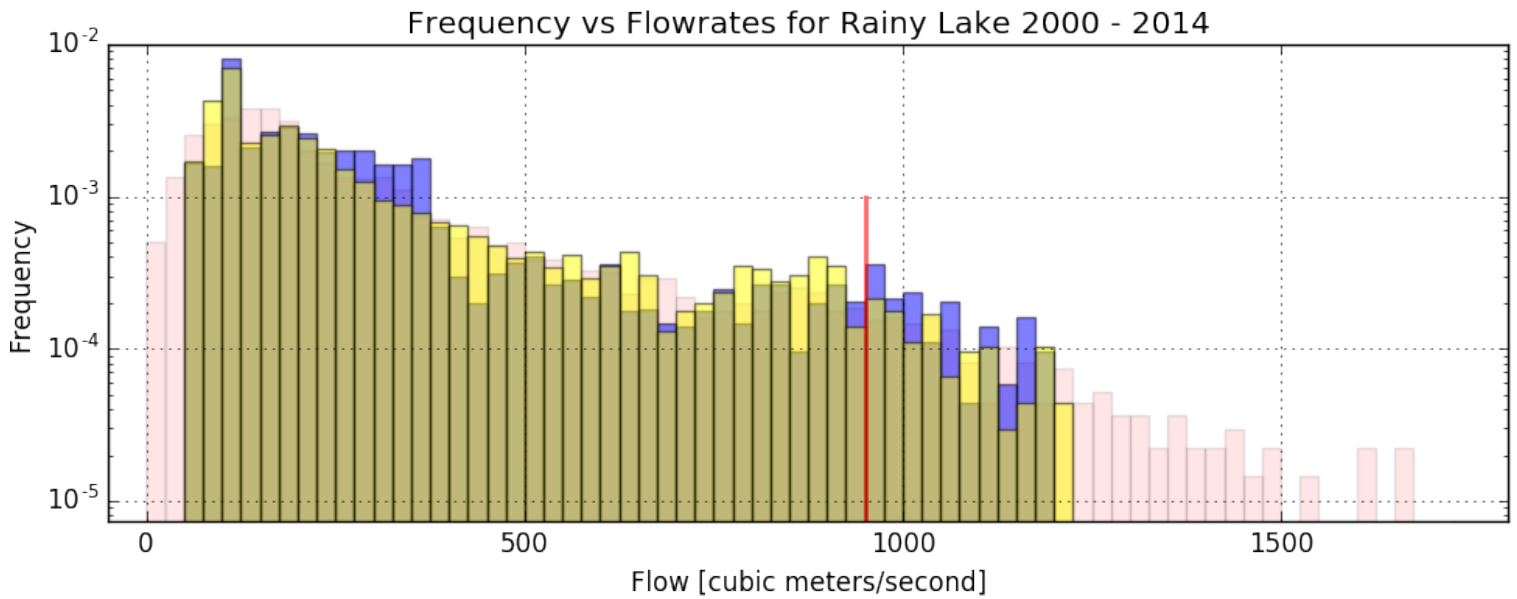



Source: Github Repository for this paper.

# SIMULATION RESULTS - INFLOWS AND OUTFLOWS




Source: Github Repository for this paper.

# SUMMER HIGH WATER EVENTS (MAY–SEPTEMBER), 1970-99

| | | Historical | w/MPC |
|---|---|---|---|
| Rule Curve Exceeded | | | |
| | Frequency | 15.8% | 6.5% |
| | Median | 0.07 m | 0.08 m |
| | 95th Percentile | 0.37 m | 0.32 m |
| Emergency High Water | | | |
| | Frequency | 8.3% | 5.0% |
| | Median | 0.06 m | 0.07 m |
| | 95th Percentile | 0.34 m | 0.25 m |
| All Gates Open | | | |
| | Frequency | 2.4% | 1.3% |
| | Median | 0.10 m | 0.06 m |
| | 95th Percentile | 0.29 m | 0.14 m |

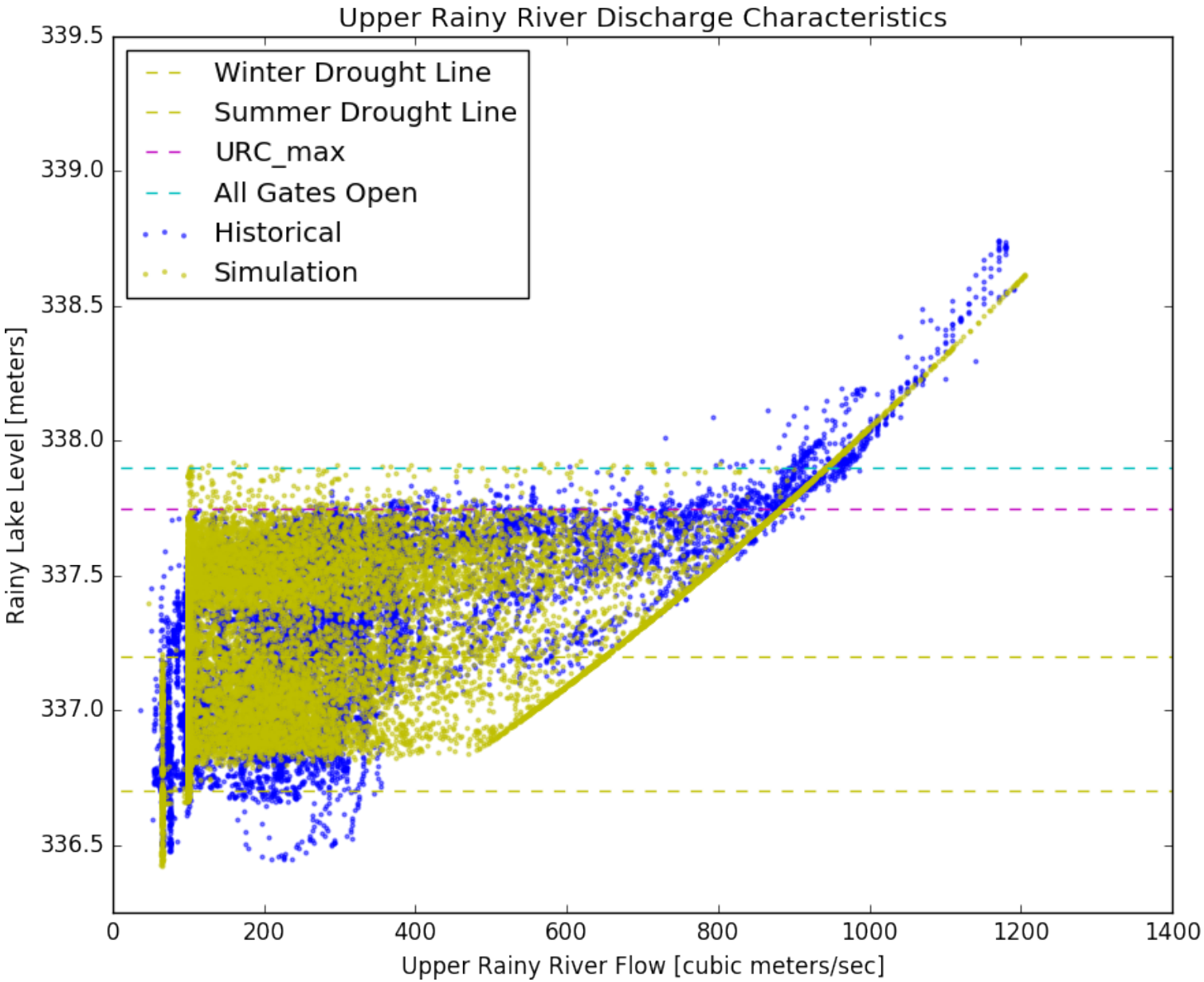
Source: Github Repository for this paper.

# SUMMER HIGH WATER EVENTS (MAY–SEPTEMBER), 2000-14

| | | Historical | w/MPC |
|---|---|---|---|
| Rule Curve Exceeded | | | |
| | Frequency | 18.0% | 18.1% |
| | Median | 0.25 m | 0.15 m |
| | 95th Percentile | 0.91 m | 0.78 m |
| Emergency High Water | | | |
| | Frequency | 14.6% | 15.0% |
| | Median | 0.21 m | 0.14 m |
| | 95th Percentile | 0.94 m | 0.80 m |
| All Gates Open | | | |
| | Frequency | 9.9% | 7.3% |
| | Median | 0.20 m | 0.23 m |
| | 95th Percentile | 0.82 m | 0.69 m |

Source: Github Repository for this paper.

# SIMULATION RESULTS - INFLOWS AND OUTFLOWS




Source: Github Repository for this paper.

# CONCLUSIONS

**The rule curve review needs to include control implementation within the scope of its work.**

1. There is little evidence for "diligent use of existing network of upstream lake level gauges and currently available hydrological models can make this IJC mandate a reality and improve the accuracy and reliability of reservoir level control."
2. The 2000 rule curves are not a feasible mandate for level management on Rainy Lake. Namakan and Rainy Lake rule curves require 'harmonization'.
3. Consideration should be given to an integrated control strategy for flow control points on the Rainy-Lake of the Woods watershed coupled with significant rule curve revisions.

# ACKNOWLEDGEMENTS


- Emmy Popovich, UG research assistant
- Nicole Mejias, UG research assistant
- Alan Hamlet, CEEES, Notre Dame
- Aaron Thompson, Directorate Environment Canada
- RLPOA Research and Technology Committee:
  - Tom Dougherty
  - Jim Yount
  - Bruce Walker
  - Howard Hansen
  - Tom Biondich
  - Kirk Skallman
  - Geo. Simmons
  - Tom Smith
  - Mike Williams
  - Jim Giauque
  - Mark Gagnier
  - Paul Anderson
  - Jason Lindquist
  - Eric Olson
  - Scott Klosner

The content of this presentation is the independent work product of the author conducted in compliance with policies on research and outside activities at the University of Notre Dame. No financial support has been received from any source.