CONTROL FOR RAINY LAKE

Model predictive control strategies for implementing rule curves for the Namakan Reservoir / Rainy Lake Watershed

2015 International Rainy-Lake of the Woods Watershed Forum
March 11-12, 2015

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OVERVIEW

1. Impacts of the Rule Curve Change in 2000
2. Improving Control of Lake Levels
3. Implications for the Rule Curve Review
4. Discussion

IMPACTS OF THE RULE CURVE CHANGE IN 2000

RAINY RIVER DRAINAGE BASIN

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

RAINY LAKE AND NAMAKAN LAKE LEVELS 1911–

Clearly see three rule curve regimes ...

Source: Github Repository for this paper.

RULE CURVE CHANGES IN 2000

Source: Github Repository for this paper.

IMPUTED CHANGE IN FLOWS TO RAINY RIVER

The change in rule curves implies a change in flows to Rainy River. Assuming midpoints of the rule curves ...

Source: Github Repository for this paper.

RULE CURVE PERFORMANCE 1970–1999

Source: Github Repository for this paper.

RULE CURVE PERFORMANCE 2000–2010

Source: Github Repository for this paper.

DISTRIBUTION OF WATER LEVELS ON RAINY LAKE

Source: Github Repository for this paper.

SUMMER HIGH WATER EVENTS (MAY–SEPTEMBER)

		1971–1999 4437 days	2000–2010 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.

FLOW CONSTRICTIONS ON UPPER RAINY RIVER

Constrictions at Ranier limit the discharge rate from Rainy Lake

Source: Github Repository for this paper.

RAINY RIVER FLOWS 1970–1999 VS 2000–2010

Source: Github Repository for this paper.

RAINY RIVER DISCHARGE 1970–2010

Source: Github Repository for this paper.

ESTIMATING RAINY LAKE INFLOWS

$$A_{RL}\frac{dH_{RL}}{dt} = I_{RL} - O_{RL}$$

RAINY LAKE MEASUREMENT MODEL

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

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

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

Measurement model: Given level and outflow measurements

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

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.

IMPROVING CONTROL OF LAKE LEVELS

CURRENT PRACTICE

FEASIBLE RULE CURVES

Rainy Lake Balance

$$\frac{dV_{RL}}{dt} = I_{RL} - O_{RL}$$

assume $O_{RL} \leq O_{RL}^{\max}(H_{RL})$. For a feasible rule curve $H_{RL} = H_{RL}^{RC}$, and

$$I_{RL} \leq A_{RL} \frac{dH_{RL}^{RC}}{dt} + O_{RL}^{\max}(H_{RL}^{RC})$$

where

$$A_{RL} = \frac{\partial V_{RL}}{\partial H_{RL}}$$

MODEL PREDICTIVE CONTROL FOR RAINY LAKE

MODEL PREDICTIVE CONTROL

Source: Martin Behrendt

MATLAB/SIMULINK SIMULATION

A calibrated Matlab/Simulink model of single loop control and full implemention of the 2000 IJC Order for Rainy Lake.

Source: Github Repository for this paper.

SIMULATION RESULTS FOR RAINY LAKE

Simulation results show improved control of high and low water events.

Source: Github Repository for this paper.

INTEGRATED CONTROL OF NAMAKAN AND RAINY LAKE

BASIN MODEL?

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

SEINE RIVER RESERVOIRS

Student Project: Create Matlab/Simulink model for the Seine River system of dams and reservoirs.

Source: Seine River Water Management Plan

IMPLICATIONS FOR THE RULE CURVE REVIEW

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.

CONCLUSIONS

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

1. Contrary to the 1993 Report, 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.
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.

DISCUSSION