Model Predictive Control Strategies for Implementing Rule Curves for the Namakan Reservoir/Rainy Lake Watershed

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Presenter Information

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Biographical Sketch:

Jeffrey C. Kantor is Professor of Chemical and Biomolecular Engineering at the University of Notre Dame. His research interests are in the application of control theory to a range of engineering applications including the integrated finance and control of process operations and network analysis. His teaching interests are in Chemical Engineering, and the ESTEEM program at Notre Dame.

Dr. Kantor has served the University in a variety of senior roles including Director of the Center for Research Computing, concurrent service as Vice President and Dean of the Graduate School from 2001 to 2006, Vice President and Associate Provost with responsibilities for academic budgets, science and engineering concerns from 1996-2001, Chair of the Department of Chemical Engineering, and other administrative and committee assignments.

Dr. Kantor has served in a variety of civic and institutional roles. Dr. Kantor chaired the Board of Directors of the not-for-profit Madison Center, the largest mental health service provider in Indiana with over 1,000 employees. He has served as member of the Board of Directors for Innovation Park at Notre Dame, for Medical Education Foundation of South Bend, and for Cytometry for Life. In December 2001, Dr. Kantor was appointed by the late Indiana Governor Frank O'Bannon to the steering committee of the state's 21st Century Research and Technology Fund Board. He also served on the board of St. Joseph's County Chamber of Commerce, an at-large director for the Indiana Health Industry Forum, and the CACHE Corporation.

A member of the Notre Dame faculty since 1981, Dr. Kantor is a professor of chemical engineering and specializes in the dynamics and control of nonlinear chemical systems, multivariable robust control, and nonlinear state estimation. Most recently, his work has focused on issues in fault detection, the control of discrete manufacturing systems, and the integrated design. Dr. Kantor's research has been supported by the National Science Foundation, the Department of Energy and a number of industrial sponsors. He was the recipient of a National Science Foundation Presidential Young Investigator Award in 1985 and of the Camille and Henry Dreyfus Foundation Teacher-Scholar Award in 1986.

Dr. Kantor was elected a fellow of the American Association for the Advancement of Science in 2005. He is a member of the American Institute of Chemical Engineers, the Institute of Electrical and Electronic Engineers and the American Association for the Advancement of Science and has served in a number of leadership roles in these organizations. Dr. Kantor is co-editor of a volume of an American Institute of Chemical Engineers series on chemical process control. He has published in professional journals and presented numerous seminars, colloquia, and keynote lectures. He has directed 20 master's and doctoral degree candidates.

A 1976 graduate of the University of Minnesota where he served as student representative to the Board of Regents, Dr. Kantor received his master's and doctoral degrees from Princeton University where he was a National Science Foundation fellow from 1976-79 and a George Van Ness Lathrop fellow in 1979-80. Prior to joining the Notre Dame faculty, he spent a year in postdoctoral studies at the University of Tel Aviv in 1980-81. He has held visiting appointments at Imperial College, London, at Lund University, Lund, Sweden, and at Princeton University.

Dr. Kantor is a native of International Falls where he and his wife have a summer residence on Rainy Lake.

<u>Submittal Information</u>

Author: Jeffrey C. Kantor
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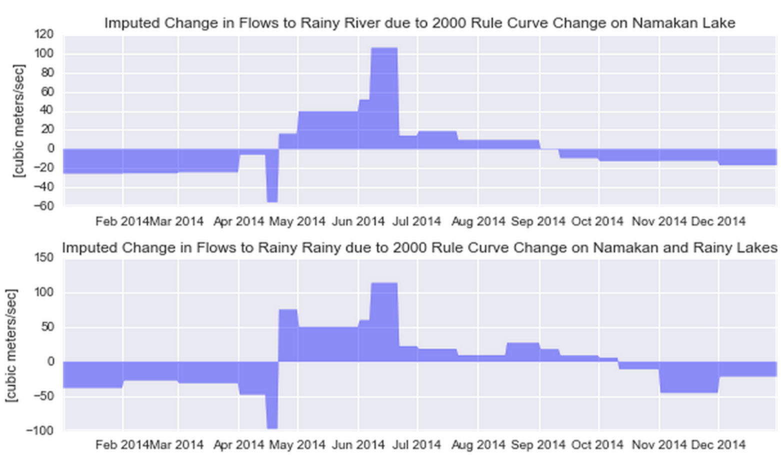
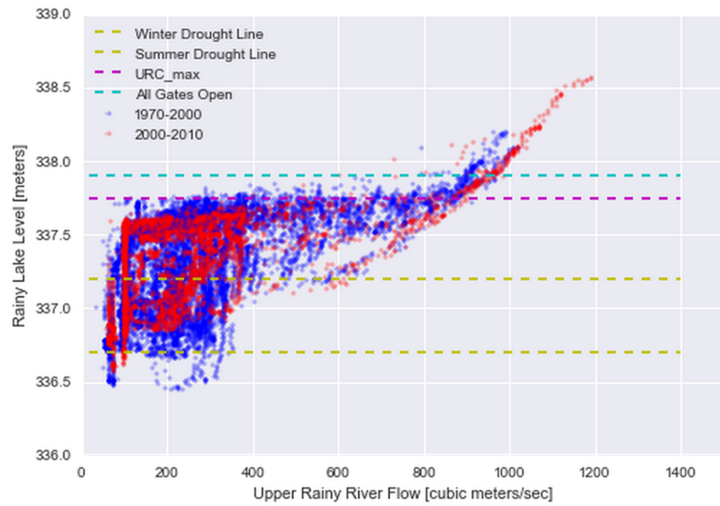
Title: Model Predictive Control Strategies for Implementing Rule Curves for the Namakan Reservoir/Rainy Lake Watershed
Location of Study: Rainy Lake and Namakan Reservoir

Abstract:

This presentation describes preliminary results of modeling and simulation studies exploring improvements in lake level control for the Rainy Lake - Namakan Reservoir system that would be possible with an advanced and integrated control strategy.

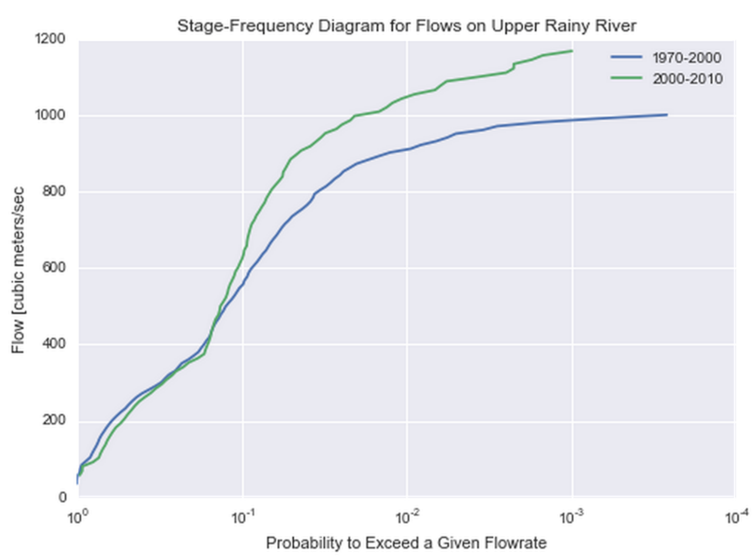
The 2000 change in rule curves for Namakan and Rainy Lakes, if implemented as written, necessarily changes the annual distribution of outflows to Rainy River. As shown on the accompanying figure, the 'imputed' changes in flows on Rainy River are a flow reduction during the winter months of approximately 30 cubic feet per second, and an increase from late April to late June in amounts ranging from 50 cubic feet per second to over 100 cubic feet per second. These changes are primarily a consequence of the reduced surge capacity due to the rule curve changes, and secondarily to the relative timing of the rule curves Rainy and Namakan Lakes.





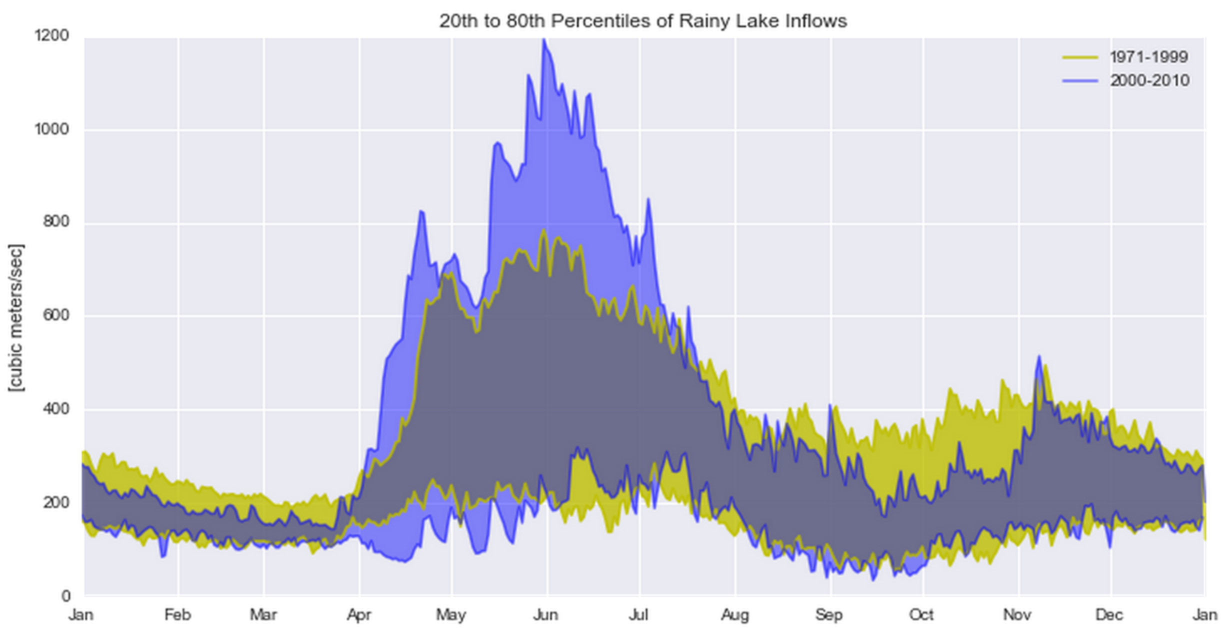
Lake level and river flow data were extracted from the the HYDAT database to test whether the ‘imputed changes’ to the seasonal flow on Rainy River can be observed in the historical data. The correlation of Rainy Lake level to Rainy River flow was compared for the periods from 1970-2000 and 2000-2010. As shown in the accompanying figure, the periods of high water/high flow are more frequent in the 2000-2010 period than 1970-2000. The difference between the two periods is in qualitative agreement with the ‘imputed’ changes in river flow predicted from the 2000 rule curve change. The data demonstrates that an increase of 100 cubic meters/sec in the flow on Rainy River corresponds to an increase of approximately 0.4 meters on Rainy Lake level during periods of high flow.

The statistical significance of this change is verified using an empirical stage-frequency diagram for the flow on upper Rainy River. The K-S Kolmogorov–Smirnov) statistic verifies the statistical significance of this change. Local precipitation data for the same periods are not substantially different by the same statistic. This provides strong empirical evidence for the proposition that the change in seasonal flows caused by the 2000 rule curve change induced high water events on Rainy Lake due to the unique discharge characteristics of upper Rainy River.

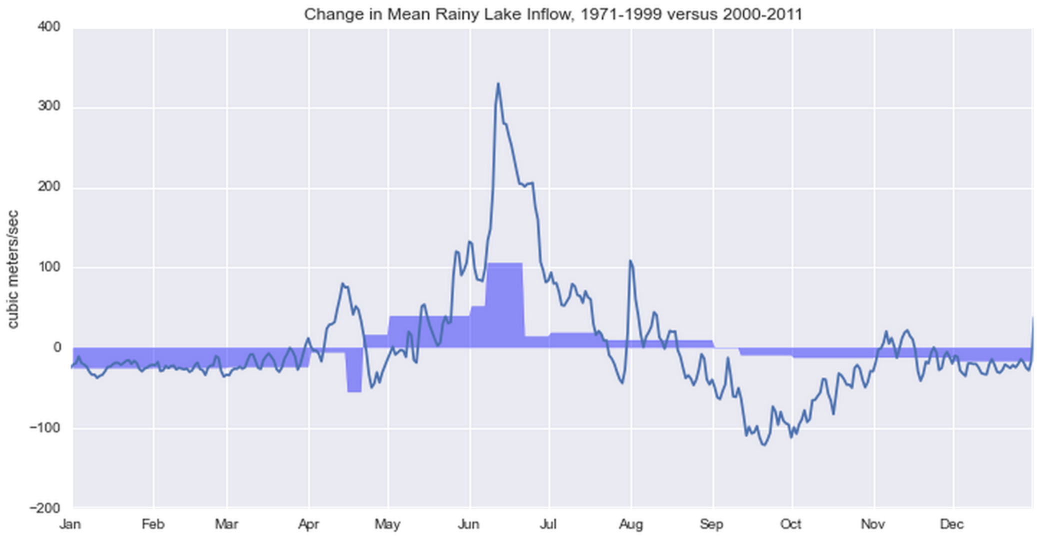


For the purpose of estimating the net inflow to Rainy Lake, a Kalman tracking filter was constructed to estimate inflows using Rainy Lake level measurements and Rainy River flow measurements from the HYDAT database. The serendipitous occurrence of redundant lake measurements in the HYDAT database provided a statistical model for the level measurement errors. The error model was used to tune the tracking filter to produce maximum liklihood estimates of Rainy Lake inflow (details available here: http://nbviewer.ipython.org/github/jckantor/Rainy-Lake-Hydrology/blob/master/Estimating_Rainy_Lake_Inflows_1970-2010.ipynb).

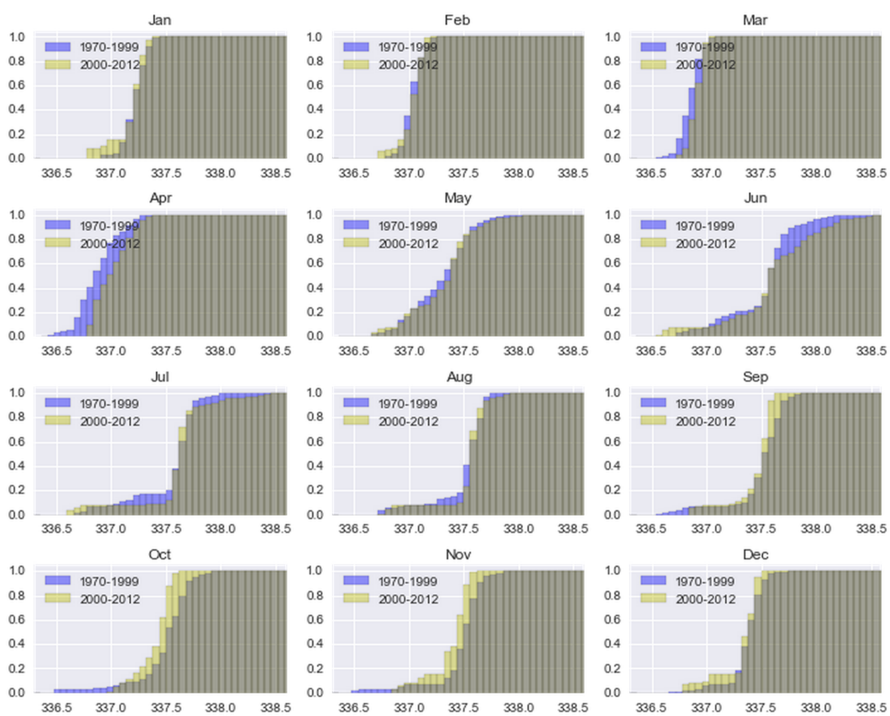
Daily estimated inflows to Rainy Lake were computed for the periods 1971-1999 and 2000-2010 using the tracking filter. The central three quintiles of seasonal flows were then computed and shown in the accompanying figure. As shown, the distribution of Rainy Lake inflows are markedly higher in periods from April through June, and lower in the periods from August through March.



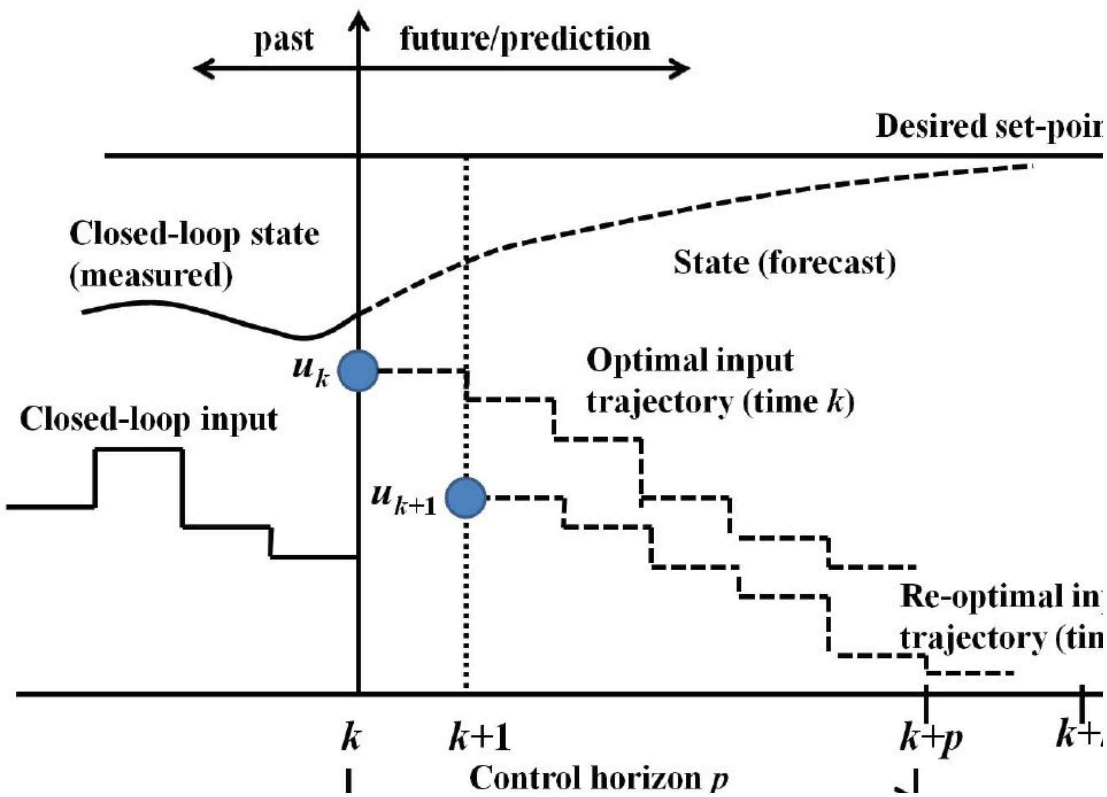
Finally, the median differences in Rainy Lake level between the two periods are shown is compared with 'imputed difference' in Rainy Lake inflows to the 2000 rule curve change. The correlation of observed change in Rainy Lake inflow to the 'imputed' change due to the rule curve change is clearly evident.



Further empirical work compared the empirical distribution of Rainy Lake levels for the 1970-2000 and 2000-2010 periods. As shown by monthly plots of the empirical cumulative distribution of Rainy Lake level, April and June exhibit statistically significant increases in the occurrence of high water levels.



The next stage of this work will develop and simulate the performance of advanced control strategies to control lake levels subject to current rule curves. Model predictive control is a strategy that uses available measurements of Rainy Lake and Namakan Lake levels, a tracking filter to measure ungaged inlet flows, a model of the two reservoir system, and a prediction horizon to estimate an optimal control trajectory. In this instance the control variables are the daily configurations of the dams located at International Falls and at Kettle Falls. Real-time feedback control is achieved by daily updates of the optimal control trajectory in response to new measurements.



Model predictive control is a proven, robust method for multivariable control, and should provide significantly improved control of Rainy Lake levels with minimal changes to current rule curves. The improved performance is a consequence of coordinating the control of the two dams, of the use of reservoir models to anticipate need changes in outflows, and incorporating real-time measurements of lake levels and river flows.

The second stage of this is to extend a linear programming model to determine the minimal rule curve changes for Rainy and Namakan lakes subject to optimal feedback control.

This is ongoing work. Current status of this work is available at this site: http://jckantor.github.io/Rainy-Lake-Hydrology/.