Regulation Plan 2014 for the Lake Ontario and the St. Lawrence River

Compendium Document

December 2016
as amended July 2023

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* The December 2016 version of this compendium was amended in July 2023 to include to previously unpublished references listed in the Technical Description of Plan 2014.

Global Affairs Canada | Affaires mondiales Canada

December 6, 2016

Commissioner Gordon Walker
Canadian Section
International Joint Commission
234 Laurier Ave West, 22nd Floor
Ottawa, ON K1P 6K6

Commissioner Lana Pollack
U.S. Section
International Joint Commission
2000 L St. NW, Suite 615
Washington D.C. 20036

Dear Commissioner Pollack and Commissioner Walker,

Thank you for your letter of June 16, 2014, to which you attached the Commission's "Plan 2014" as the preferred option for regulation of Lake Ontario-St. Lawrence River water levels and flows.

The United States and Canadian Governments concur with the attached Supplementary Order of Approval and the proposed regulation plan, in accordance with the mutual understandings as set forth in this letter. The Governments also concur with the attached table of Lake Ontario water levels that would trigger deviation from the regulation plan, with the low trigger levels set at the levels that will be reached less than 10% of the time, which are to be implemented as set out in Criterion H14.

We understand that the revised Supplementary Order of Approval, which will be issued by the Commission in accordance with the Treaty Between the United States and Great Britain Relating to Boundary Waters, and Questions Arising Between the United States and Canada (the Treaty), will be implemented in a manner that observes the order of precedence set forth in Article VIII of the Treaty and in accordance with applicable domestic law.

The Governments understand that the review specified in Condition O of the Supplementary Order will include a review of the effectiveness of the trigger levels.

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The governments appreciate the work of the Commission and look forward to continued communications with the Commission regarding this matter.

Sincerely,

Martin Benjamin
Director General
North America Strategy Bureau
Global Affairs Canada

Francisco L. Palmieri
Acting Assistant Secretary
Western Hemisphere Affairs Bureau
United States Department of State

CC: Ms. Camille Mageau, Secretary, Canadian Section, International Joint Commission
Mr. Chuck Lawson, Secretary, American Section, International Joint Commission

INTERNATIONAL JOINT COMMISSION
IN THE MATTER OF THE REGULATION
OF LAKE ONTARIO OUTFLOWS
AND LEVELS

SUPPLEMENTARY ORDER OF APPROVAL

December 8 2016

WHEREAS:

On October 29, 1952, the International Joint Commission issued an Order of Approval (1952 Order), pursuant to the Boundary Waters Treaty of 1909 (the "Treaty), to the Government of Canada and the Government of the United States of America for the construction, maintenance and operation of certain structures for the development of power in the International Rapids Section of the St. Lawrence River. This Order was amended by a Supplementary Order dated July 2, 1956 (1956 Order);

The Commission retained jurisdiction in the 1952 Order, as supplemented by the 1956 Order, to make further Order or Orders regarding the subject matter of the governments' applications, after giving notice and an appropriate opportunity to all interested parties to make representations to the Commission;

A 1993 Commission Great Lakes Levels Reference Study recommended that the Orders of Approval for the regulation of Lake Ontario be revised to better reflect the current needs of the users and interests of the system. In letters dated April 15, 1999, the Commission informed the Governments of Canada and the United States that it was becoming increasingly urgent to review the regulation of Lake Ontario levels and outflows. In response the Governments funded a five-year Lake Ontario-St. Lawrence River Study (2001-2006). The study focused on impacts of water level regulation, water supply conditions including potential climate change scenarios, a wide range of alternative regulation plans and the 1956 Order. The Study found that water supplies to Lake Ontario since regulation began under the 1956 Order have been significantly above and below those experienced during the 1860-1954 period of record;

The Commission has now completed a review of the 1956 Order. This review of the regulation of Lake Ontario and the St. Lawrence River culminated in a proposal to modify the existing Orders of Approval and presentation of a new regulation plan. Technical hearings, which were open to the public and featured expert testimony from invited experts, and public hearings on this proposal were held by the Commission in order to provide all interested parties with a convenient opportunity to be heard, in accordance with the Treaty. The following hearings were held: Lockport, New York on July 14, 2013; Toronto and Jordan, Ontario on July 15, 2013; Rochester and Williamson, New York on July 16, 2013; Oswego and Alexandria Bay, New York on July 17, 2013; Montreal, Quebec on July 18, 2013; and Cornwall, Ontario on July 19, 2013; and a public hearing by teleconference on August 27, 2013. The Commission accepted comments on the recommended modifications to the operating conditions and criteria of the Order of Approval through August 30, 2013. Transcripts of the hearings and written submissions are available for public view on the Commission's website and at the Section offices in Washington, D.C., and Ottawa, Ontario;

The Commission has considered the views of the public, as expressed through testimony at the public hearings, and through other submissions, the advice of its International St. Lawrence Board of Control, and the views and comments of the Governments;

In June of 2014 the Commission submitted "Lake Ontario-St. Lawrence River Plan 2014: Protecting against extreme water levels, restoring wetlands, and preparing for climate change" to the Governments of the United States and Canada. In this report the Commission sought the concurrence of the Governments of Canada and the United States on revising the 1956 Order to consider ecosystem health with respect to all other interests and uses of the Lake Ontario-St. Lawrence River system;

The Commission sought the concurrence of the two governments to issue this Supplementary Order and such concurrence was provided with the understanding that changes to the 1952 Order, as supplemented by the 1956 Order, must comply with the terms set out in Article VIII of the Treaty;

The Commission finds that regulation under the 1956 Order is designed for past conditions and interests known at the time the 1956 Order was implemented and that the four-foot target range of elevations in the 1956 Order creates an unrealistic expectation that Lake Ontario water levels can be regulated within a four-foot range (approximately 1.2 meters). Under extreme water supply conditions, such as those experienced on several occasions since regulation began, the Commission finds it is not possible to keep the lake within the four-foot target range. Regulation as practiced under the 1956 Order has harmed the near shore Lake Ontario and upper St. Lawrence River environments by compressing water level fluctuations to much less than they would have been under unregulated conditions. Current regulation does not accurately reflect the full range of experienced conditions or anticipate future changes; and it is now necessary to also consider environmental issues and recreational boating upstream and downstream of the project;

In assessing the benefits provided by regulation under this Supplementary Order, the Commission finds that the terms, conditions and other requirements of this Supplementary Order take into account the high and low water supplies since 1954 and other new information not available when the 1956 Order was developed;

The Commission finds that regulation under this Supplementary Order in combination with improved governance of the system and less frequent deviations from a regulation plan that encompasses a more extensive range of possible conditions will provide long-term benefits, upstream and downstream, including those identified in the 1956 Order with greater security and predictability;

The Commission finds that, in the long term, regulation under this Supplementary Order will help to restore the ecosystem health of Lake Ontario and the Upper St. Lawrence River, continue to provide benefits on the lake and upper river, and maintain the current benefits downstream;

The Commission finds that the terms, conditions and other requirements of this Supplementary Order respond to the requests made by the Governments of Canada and the United States in the joint references dated June 25, 1952, and joint applications dated June 29, 1952, as clarified in the joint letter of December 6, 2016;

The Commission finds that the laws in Canada, and the Constitution and laws in the United States of America, together with the provisions of this Supplementary Order, satisfy the requirements of Article VIII of the Treaty;

The Commission finds that an adaptive management approach would enable the effects of regulation in the Lake Ontario - St. Lawrence River System to be assessed and would provide a valuable source of information for future reviews. Monitoring, data collection, and assessment are necessary to validate the models upon which the regulation plan was built, to evaluate the effectiveness of regulation, to analyze the effects of other changes impacting the system (such as climate change), and to consider possible future improvements in system regulation. Any changes to this Order arising from adaptive management, as well as any changes to the regulation plan or the levels referenced in H14, would be made in accordance with Condition H.

The Commission finds that amendments to Appendix A of the 1952 Order, as supplemented by the 1956 Order, are necessary in order to include definitions and a revision to the description of the power house structures. Changes to the specifications of the works described in the 1952 Order, as supplemented by the 1956 Order, must be submitted for approval by both Governments. Per correspondence from the United States and Canadian Governments received June 17, 2014, and October 15, 2012, both Governments approve or have no objection to the replacement of six ice sluice gates on the Moses-Saunders dam with a concrete structure, as proposed by the power companies. The International St. Lawrence River Board of Control in 2011 recommended that the proposal to replace the ice sluice gates be approved, foreseeing no significant changes to the operation of the project.

NOW THEREFORE THIS COMMISSION ORDERS AND DIRECTS:

The conditions herein provided are to be implemented in accordance with Article VIII and all other relevant provisions of the Treaty.

The conditions of the 1952 Order, as supplemented by the 1956 Order, are revised and supplemented by this Supplementary Order so as to read in their entirety as follows:

CONDITIONS

A. In accordance with the requirements of Article VIII of the Treaty, interests on either side of the International Boundary which are injured by reason of the construction, maintenance and operation of the works shall be given suitable and adequate protection and indemnity as provided by the laws in Canada, or the Constitution and laws in the United States respectively.

B. The works shall be so planned, located, constructed, maintained and operated as not to conflict with or restrain uses of the waters of the St. Lawrence River for purposes given preference over uses of water for power purposes by the Treaty, namely, uses for domestic and sanitary purposes and uses for navigation, including the service of canals for the purpose of navigation, and shall be so planned, located, constructed, maintained and operated as to give effect to the provisions of this Order.

C. The works shall be constructed, maintained and operated in such manner as to safeguard the rights and lawful interests of others engaged or to be engaged in the development of power in the St. Lawrence River below the International Rapids Section.

D. The works shall be so designed, constructed, maintained and operated as to safeguard so far as possible the rights of all interests affected by the levels of the St. Lawrence River upstream from the Iroquois regulatory structure and by the levels of Lake Ontario and the lower Niagara River; and any change in levels resulting from the works which injuriously affects such rights shall be subject to the requirements of paragraph A relating to protection and indemnification.

E. The hydro-electric plants approved by this Order shall not be subjected to operating rules and procedures more rigorous than are necessary to comply with the provisions of the foregoing paragraphs B, C and D.

F. Before Ontario Power Generation or any successor make any changes to any part of the works, which would fall within the scope of Article III of the Treaty, it shall submit to the Government of Canada, and before the New York Power Authority makes any changes to any part of the works, which would fall within the scope of Article III of the Treaty, it shall submit to the Government of the United States, for approval in writing, detailed plans and specifications of that part of the works located in their respective countries and details of the program of construction thereof or such details of such plans and specifications or programs of construction relating thereto as the respective Governments may require. Following the approval of any plan, specification or program, if Ontario Power Generation or the New York Power Authority wishes to make any change therein, it shall first submit the changed plan, specification or program for approval in a like manner.

G. A Board to be known as the International Lake Ontario-St. Lawrence River Board (hereinafter referred to as the "Board") consisting of an equal number of members from Canada and the United States, to include representatives of the Canadian and United States federal governments, shall be established by the Commission. The Board shall include, but is not limited to, at least one member each nominated by the State of New York, the Province of Quebec, and the Province of Ontario. The duties of the Board shall be to give effect to the instructions of the Commission as issued from time to time in accordance with this Order. The duties of the Board shall be to ensure that the provisions of the Order relating to water levels and the regulation of the discharge of water from Lake Ontario as herein set out are complied with, and Ontario Power Generation and the New York Power Authority shall duly observe any direction given them by the Board for the purpose of ensuring such compliance. The Board shall report to the Commission at such times as the Commission may determine. In the event of any disagreement among the members of the Board which they are unable to resolve, the matter shall be referred by them to the Commission. The Board may, at any time, make representations to the Commission in regard to any matter affecting or arising out of the terms of the Order with respect to water levels and the regulation of discharges and flows.

H. The discharge of water from Lake Ontario shall be regulated by the Board (following the Commission's directives) to meet the requirements of conditions B, C, and D hereof and shall be regulated within a range of levels as specified in the below listed criteria, as nearly as may be. The project works shall be operated in such a manner as to provide no less protection for navigation and riparian interests downstream than would have occurred under pre-project conditions and with the 1900 to 2008 adjusted supplies and conditions specified in the basis of comparison. The Commission shall adopt a regulation plan, subject to the concurrence of Canada and the United States, and associated operational guides for the discharge of water from Lake Ontario and its flow through the International Rapids Section of the St. Lawrence River that satisfy the criteria and conditions of this Order, with criterion "H14" governing principles of relief should specified high or low levels be experienced. The flow of water through the International Rapids Section of the St. Lawrence River in any period shall equal the discharge of water from Lake Ontario as determined for that period. The Commission may adopt new regulation plans from time to time provided they are in accordance with this Order, and subject to the concurrence of Canada and the United States.

Criteria

H1. The regulated outflow from Lake Ontario shall be such as not to increase the frequency of low levels or reduce the minimum level of Montreal Harbour below those listed in the table below which would have occurred with the 1900 to 2008 adjusted supplies and conditions (hereinafter called the "supplies of the past as adjusted") that are defined in the document "Basis of Comparison Conditions for Lake Ontario – St. Lawrence River Regulation" .

Note: All elevations use the 1985 International Great Lakes Datum and metric system of measurement.

Montreal Jetty #1 Level IGLD 1985

Meters	Feet	Number of quarter-months in 1900-2008 below level
5.55	18.21	811
5.50	18.21	679
5.40	17.72	366
5.30	17.39	153
5.20	17.06	83
5.10	16.73	45
5.00	16.40	15
4.90	16.08	1
4.80	15.75	1
4.70	15.42	minimum

H2. The regulated outflow from Lake Ontario shall be such as not to increase the frequency of low levels or reduce the minimum level of Lake St. Louis below those listed in the table below which would have occurred with the supplies of the past as adjusted.

Lake St. Louis at Pointe Claire Level IGLD 1985

Meters	Feet	Number of quarter-months in 1900-2008 below level
20.70	67.01	735
20.60	67.58	161
20.50	67.26	87
20.40	66.93	21
20.30	66.6	2
20.20	66.27	1
20.10	65.94	0
20.10	65.94	minimum

H3. The regulated outflow from Lake Ontario shall be such that the frequencies of occurrence of high water levels on Lake St. Louis as measured at the Pointe Claire gauge are not greater than those listed below with supplies of the past as adjusted.

Lake St. Louis at Pointe Claire Level IGLD 1985

Meters	**Feet**	**Number of quarter-months in 1900-2008 above level**
22.50	73.82	0
22.40	73.49	9
22.33	73.26	15
22.20	72.83	51
22.10	72.51	97
22.00	72.18	221
22.48	73.75	maximum

H4. The regulated monthly mean level of Lake Ontario shall not exceed the following elevations (IGLD85) in the corresponding months with the supplies of the past as adjusted.

Lake Ontario Level IGLD 1985

Month	**Meters**	**Feet**
January	75.26	246.92
February	75.37	247.28
March	75.33	247.15
April	75.60	248.03
May	75.73	248.46
June	75.69	248.33
July	75.63	248.13
August	75.49	247.67
September	75.24	246.85
October	75.25	246.88
November	75.18	246.65
December	75.23	246.82

H5. The regulated winter outflows from Lake Ontario shall be maintained so that the difficulties of river ice management for winter power operation are minimized in the International Rapids Section of the St. Lawrence River and the outlet of Lake St. Francis.

H6. Under regulation, the frequency of occurrences of monthly mean elevations of approximately 75.07 meters (m), 246.3 feet (ft) IGLD 1985 and higher on Lake Ontario shall not be greater than would have occurred with supplies of the past as adjusted and with pre-project conditions.

H7. The regulated monthly mean water levels of Lake Ontario, with supplies of the past as adjusted shall not be less than the following elevations (IGLD 1985) in the corresponding months.

Lake Ontario Level IGLD 1985

Month	**Meters**	**Feet**
January	73.56	241.34
February	73.62	241.54
March	73.78	242.06
April	73.97	242.68
May	74.22	243.50
June	74.27	243.67
July	74.26	243.64
August	74.15	243.27
September	74.04	242.91
October	73.83	242.22
November	73.67	241.70
December	73.57	241.37

H8. Consistent with other requirements, the outflow from Lake Ontario shall be regulated so as to maintain levels necessary for navigation in the Montreal to Lake Ontario section of the St. Lawrence River.

H9. Consistent with other requirements, the maximum regulated outflow from Lake Ontario shall provide safe velocities for Seaway navigation and minimize spill at the hydropower facilities in the St. Lawrence River.

H10. Consistent with other requirements, the minimum regulated monthly outflow from Lake Ontario shall be such as to secure the maximum dependable flow for power.

H11. Consistent with other requirements, the levels of Lake Ontario shall be regulated for the benefit of property owners on the shores of Lake Ontario in the United States and Canada so as to reduce extremes of stage which have occurred under pre-project conditions and supplies of the past as adjusted on Lake Ontario.

H12. Consistent with other requirements, the outflow from Lake Ontario shall be regulated to help restore ecosystem health by providing for more natural variations of water levels on Lake Ontario and on the St. Lawrence River.

H13. Consistent with other requirements, the outflow from Lake Ontario shall be regulated so as to benefit recreational boating on Lake Ontario and on the St. Lawrence River.

H14. In the event that Lake Ontario water levels reach or exceed high levels, the works in the International Rapids Section shall be operated to provide all possible relief to the riparian owners upstream and downstream. In the event that Lake Ontario levels reach or fall below low levels the works in the International Rapids Section shall be operated to provide all possible relief to municipal water intakes, navigation and power purposes, upstream and downstream. The high and low water levels at which this criterion applies, and any revisions to these levels, shall be subject to the concurrence of Canada and the United States and shall be set out in a Commission directive to the Board.

I. The Commission's directives to the Board shall make provision for peaking and ponding operations and for deviations from the plan of regulation to address such matters as navigation needs, hydropower plant maintenance, winter operations, emergencies and other special short-term situations, any of such deviations being subject to review by the Commission upon its request.

J. Subject to the requirements of conditions B, C, D and H hereof, the Board, after obtaining the approval of the Commission, may temporarily make minor modifications or changes to the regulated outflows from Lake Ontario for the purpose of determining modifications or changes in the regulation plan that may be advisable. The Board shall report to the Commission the results of such temporary changes or modifications, together with any recommendations arising from such, and the Commission may accept or reject any such recommendations. Any changes or modifications that arise from such recommendations shall be made in accordance with Condition H.

K. The works shall be operated so that the forebay water level at the power houses does not exceed a maximum instantaneous elevation of 74.48 m (244.36 feet).

L. Ontario Power Generation and the New York Power Authority, and any successor entities, shall maintain and supply for the information of the Board accurate records relating to water levels and the discharge of water through the works and the regulation of the flow of water through the International Rapids Section as the Board may determine to be suitable and necessary, and shall install and maintain such gauges, carry out such measurements, and perform such other services as the Board may deem necessary for these purposes.

M. The installation, maintenance, operation and removal of the ice booms in the St. Lawrence River by Ontario Power Generation and the New York Power Authority, and any successor entities, are subject to the following:

1. Any significant modifications in the design or location of the booms shall require the approval of the Commission;
2. The placement and removal of ice booms shall be timed so as not to interfere with the requirements of navigation; and
3. The St. Lawrence Seaway Management Corporation and the St. Lawrence Seaway Development Corporation, and any successor entities, shall be kept informed of all such operations.

N. The Board shall report to the Commission as of 31 December each year on the effect, if any, of the operation of the downstream hydro-electric power plants and related structures on the tail-water elevations at the hydro-electric power plants approved by this Order.

O. No later than 15 years after the effective date of this Order, and periodically thereafter in consultation with the governments, the Commission will conduct a review of the results of regulation under this Order and report to Canada and the United States its findings. This review will include an assessment of the extent to which the results predicted by the research and models used to develop any approved regulation plan occurred as expected, consistent with adaptive management. The review may provide the basis for possible changes to the regulation of water levels and flows to be submitted to the Governments in accordance with condition H.

APPENDIX A to the October 29, 1952, Order is amended by the addition of the below text:

"DEFINITIONS

1. St. Lawrence River – the section of the St. Lawrence River that is affected by flow regulation, which stretches from Lake Ontario to the outlet of Lake St. Pierre.
2. International Rapids Section - the section of the St. Lawrence River that prior to the project was characterized by series of rapids from Ogdensburg, NY- Prescott, ON to Cornwall, ON – Massena, NY.
3. Pre-project conditions – the hydraulic channel characteristics that existed in the Galops Rapids Section of the St. Lawrence River as of March 1955 that formed the control section for Lake Ontario outflows prior to the project. This is defined by a stage-discharge capacity relationship for this condition that also accounts for the effects of glacial isostatic adjustment.

APPENDIX A to the October 29, 1952, Order is amended by the deletion of the text "with provision for ice handling and discharge sluices." under (c) Power House Structures under FEATURES OF THE WORKS APPROVED BY THIS ORDER.

Signed this 8th day of December 2016

Gordon W. Walker

Lana B. Pollack

Benoit Bouchard

Richard M. Moy

Richard A. Morgan

International Joint Commission

International Lake Ontario - St. Lawrence River Board

Directive

This directive updates and replaces the November 16, 1953 directive that created the International St. Lawrence River Board of Control. This directive creates and directs the International Lake Ontario-St. Lawrence River Board as a new Board, with any further direction to the new Board to be issued by the International Joint Commission (the Commission) from this date forward.

Function and Composition of the Board

The International Lake Ontario-St. Lawrence River Board (Board) is responsible for ensuring compliance with the Order of Approval pertaining to the regulation of flows and levels of the St. Lawrence River and Lake Ontario, the regulation plan approved by the Commission and any requirements or duties outlined in directives from the Commission.

The Board shall perform duties specifically assigned to it in the Order of Approval as well as those assigned to it by the Commission directives. Under the Order, the Board has duties related to flow regulation and responsibilities related to adaptive management, communications and public involvement. To carry out these duties, the Board shall meet at least twice a year, hold teleconferences as needed, and provide semi-annual reports to the Commission. It will also follow the Commission's public affairs policy including requirements for regularly meeting with the public.

The Board shall have an equal number of members from each country. The Commission shall determine the number of members (normally a minimum of 10) and shall normally appoint each member for a three-year term. Members may serve for more than one term. Members shall act in their personal and professional capacity, and not as representatives of their countries, agencies or institutions. They are to seek decisions by consensus according to the tradition of the Commission.

Within this binational balance, at least one Board member will be from each of the five jurisdictions – federal, provincial and state. The jurisdictions may nominate members to serve on the Board. The Commission will review nominees, in consultation with the respective nominating federal, state or provincial jurisdiction, to ensure that all Board members are suited to fulfilling the new and continuing responsibilities of the Board. The expertise of potential Board members, their ability to act impartially and effectively with good judgment, their commitment to work towards Board consensus, engage appropriately with the public and reach decisions quickly when necessary will be key considerations for the Commission in the appointment of candidates to the Board. The Commission will appoint the nominees if it finds them suitable. If the Commission determines a nominee is not suitable, it will request the nominating jurisdiction to make an additional nomination (or nominations) until the Commission determines the nominee is suitable. In addition to members nominated by the jurisdictions, the Commission itself may appoint members to obtain an appropriate balance of expertise and geographic representation on the Board. The Commission shall appoint one member from each country to serve as co-chairs of the Board. Each co-chair is to appoint a Secretary, who, under the general supervision of the chair(s), shall carry out such duties as are assigned by the chairs or the Board as a whole. Upon request to the Commission, either co-chair may appoint an alternate member to act as Chair when they are not available to the Board.

The co-chairs of the Board, through the assistance of the Board secretaries, shall be responsible for maintaining proper liaison between the Board and the Commission, among the Board members and between the Board and its sub-groups. Chairs shall ensure that all members of the Board are informed of all instructions, inquiries, and authorizations received from the Commission and also of activities undertaken by or on behalf of the Board, progress made, and any developments affecting such progress.

In order to provide prompt action which may be necessary under winter operations or emergency conditions, each of the co-chairs of the Board shall appoint a Regulation Representative who is authorized by the Board to act on its behalf in such situations. Among other duties, the Regulation Representatives shall maintain a database of hydrological information for the Board, conduct the regulation plan calculations, make needed within-the-week flow adjustments, coordinate and keep account of flow deviations, and advise the Board on regulation operations.

The Board shall appoint an Operations Advisory Group (OAG) composed of representatives from the operating entities and shall keep the Commission informed of OAG membership. The Board and the Regulation Representatives may consult with OAG members individually or collectively as the occasion requires.

Flow Regulation

The Board shall set flows from Lake Ontario into the St. Lawrence River through the Moses-Saunders Dam and Long Sault Dam in accordance with the Order of Approval, normally as specified by the approved weekly flow regulation plan and directives from the Commission. It shall also approve the gate setting at the Iroquois Dam in consideration of Lake St. Lawrence levels and ice management, which may be delegated to the Regulation Representatives for prompt action.

The Board shall oversee the normal flow variations carried out by the hydropower entities according to the directive on peaking and ponding issued by the Commission. The Board shall also supervise the Regulation Representatives in their conduct of within-the-week flow adjustments and shall direct minor and major flow deviations when required, consistent with the Commission's directive and Order of Approval.

Following the regulation plan will be important over the long-term to ensure that the expected objectives for system regulation are achieved.

Adaptive Management

The Board will take part in an adaptive management strategy designed to verify that the effects of the new regulation plan over time are as anticipated, react to the influence of changing conditions such as climate change, and adapt or improve the implementation of the regulation plan as required. The Board may also use the information acquired through the adaptive management strategy to propose to the Commission modifications to the plan should it learn over time that conditions (climatic, socio-economic or environmental) have changed enough such that the plan is no longer meeting its intended objectives or improvements to the plan could realize increased benefits.

Communications and Public Involvement

The Board is directed to have a communications committee. The aim of the communications committee is to ensure that everyone interested in the regulation of the Lake Ontario-St. Lawrence River system is informed and has opportunities to express personal views regarding regulation. The communications committee will ensure that the Board is proactive in acquiring knowledge about stakeholder needs and perspectives on an ongoing basis and in providing them with regular information about Board decisions and the issues before the Board. The Commission encourages the Board to take advantage of multiple means, including modern technology and alternative communications fora, to better inform and receive input from stakeholders and the public within the framework of the Commission's communication strategy. The Board may collaborate with other Commission boards, governmental and quasi-governmental organizations to effectively strengthen information delivery and involve the public.

The Commission (through its public information officers) shall be informed, in advance, of plans for any public meetings or public involvement in the Board deliberations. The Board shall report in a timely manner to the Commission on these meetings, including representations made to the Board.

The Board shall provide the text of media releases and other public information materials to the Secretaries of the Commission for review by the Commission's Public Information Officers, prior to their release in English and French.

Reports, including semi-annual reports, and correspondence of the Board shall normally remain privileged and be available only to the Commission and to members of the Board and its committees (including appropriate individuals who support these entities with respect to Lake Ontario-St. Lawrence River activities) until their release has been authorized by the Commission. Board members and committees shall maintain files in accordance with the Commission policy on segregation of documents. All Board members shall be provided with these policy documents at the time of their appointment to the Board.

The Board shall provide minutes of Board meetings to the Commission within 45 days of the close of the meeting in keeping with the Commission's April 2002 Policy Concerning Public Access to Minutes of Meetings. The minutes will subsequently be put on the Commission's website.

To facilitate communication between the Board and the relevant federal, state and provincial jurisdictions of the Lake Ontario–St. Lawrence River system, the Commission shall request from these jurisdictions the name of an appropriate contact person and provide these names to the Board. The Board should note that its communications with the jurisdictions are only with respect to the carrying out of the functions of the Board, as set out in the Order of Approval and associated directives. It will remain the role of the Commission to engage all the jurisdictions (federal, state, provincial), as appropriate in the consideration of any changes to the regulation plan or directives to the Board. Any issues raised by the jurisdictions with the Board in these respects should be redirected to the Commission.

Other Aspects

According to need and on an ad-hoc basis, the Board may establish any other committees and working groups as may be required to discharge its responsibilities effectively. The Commission shall be kept informed of the duties and composition of any committee or working group. Commissioners and relevant Commission staff are invited to any meetings of the Board and any committees the Board may establish. Unless other arrangements are made, members of the Board, committees, or working groups will make their own arrangements for reimbursement of necessary expenditures. The Commission should also be informed of the Board's plans and progress and of any developments or cost impediments, actual or anticipated, that are likely to affect carrying out the Board's responsibilities.

If, in the opinion of the Board or of any member, any instruction, directive, or authorization received from the Commission lacks clarity or precision, then the matter shall be referred promptly to the Commission for appropriate action. In the event of any unresolved disagreement among the members of the Board, the Board shall refer the matter forthwith to the Commission for decision.

Signed this 8th day of December 2016.

Camille Mageau Secretary Canadian Section	Charles A. Lawson Secretary United States Section

International Joint Commission

Directive to the International Lake Ontario - St. Lawrence River Board on Operational Adjustments, Deviations and Extreme Conditions

This directive was created in conjunction with the proposed revised Order of Approval. It provides specific protocols and guidance to the International Lake Ontario-St. Lawrence River Board for implementing a regulation plan approved by the Commission, particularly as they relate to making operational adjustments, deviating from that plan, and managing extreme conditions. This directive updates and replaces all past directives on these topics to the former International St. Lawrence River Board of Control, including letters from the International Joint Commission (the Commission) dated May 5, 1961 and October 18, 1963 that vested the Board with limited authority to deviate from the approved regulation plan.

Plan 2014 is the combination of the mechanistic release rules labeled “Bv7” (described in Annex B of the June 2014 report on Plan 2014) together with discretionary decisions made by the International Lake Ontario - St. Lawrence River Board to deviate from the flows specified by the rules of Bv7 according to this directive on deviations. In that regard, Bv7 is analogous to Plan 1958-D; each is a set of release rules (algorithms) that produce an unambiguous release amount each week.

Under the 2016 Supplementary Order of Approval, the International Lake Ontario – St. Lawrence River Board is responsible for ensuring compliance with the Order pertaining to the regulation of the St. Lawrence River and Lake Ontario and any requirements outlined in directives from the Commission. This includes setting weekly discharges for the St. Lawrence River through the flow control structures of the Moses-Saunders hydro-electric plant located at Cornwall-Massena according to the regulation plan approved by the Commission. Bv7 release rules are designed to handle a broader range of water supply situations than the previous release rules (Plan 1958-D). In most instances, it will be important to release flows as determined by the release rules in order to realize its expected benefits. Therefore, the Commission anticipates fewer, more limited instances where flow releases would differ from those of the release rules than was the case with 1958-D.

The following sections of this directive describe and differentiate between operational adjustments, minor, major, and emergency deviations. This directive also explains when and how the Board can adjust and deviate from the outflows prescribed by the regulation plan. If the Board cannot establish consensus regarding deviations from plan outflows, then the issue shall be raised immediately to the Commission through the Commission’s Engineering Advisors located in Washington, DC and Ottawa, ON. In such cases, the Board must reach consensus on an interim outflow in consideration of the particular circumstances at the time and that is consistent with the Treaty, while the Commission makes a decision.

Operational Adjustments due to Inaccurate Forecasts

The rules and logic of the regulation plan determine the flow to be released for the coming week based on observed and forecasted hydrologic and ice conditions. As forecasts of conditions have some uncertainty, there will be occasions when the actual within-the-week conditions experienced differ significantly from the forecasted conditions used to calculate the regulation plan flow. Due to inaccurate forecasts, in some cases adjustments to the flows determined by the regulation plan at the beginning of the regulation week will be required later in the week in order to maintain the intent of the plan. The Board will consider these flow adjustments as within-plan operations and not as deviations from the plan.

The rules and logic of the plan provide protection against extreme high and low levels downstream in balance with Lake Ontario levels. The Board shall oversee operational adjustments to successfully manage rapidly varying flood and low flows coming from the Ottawa River in accordance with the rules set out in the regulation plan, unless conditions require minor or major deviations as defined below. The plan also includes rules, based on decades of operational experience, to form and manage the ice cover in the river reaches of importance upstream of the Moses-Saunders and Beauharnois hydro-electric plants. The Board shall also continue flow changes as needed for ice management in these river reaches consistent with the intent of the plan. Ottawa River discharges and St. Lawrence River ice conditions can change significantly from day-to-day, and the week-ahead forecasts of Ottawa River flows and St. Lawrence River ice conditions used for regulation calculations are subject to rapid variations due to changing weather conditions. Therefore, short-term within-the-week flow adjustments will be made when needed to avoid flooding near Montreal consistent with the intent of the plan when the Ottawa River flow is very high and changing rapidly. Such adjustments will also be made when required to maintain St. Lawrence River levels above the minimums specified in the plan when inflows to the river are varying. As ice conditions can vary quickly due to changing weather conditions, it is anticipated that adjustments will also be necessary for the formation of a smooth ice cover to prevent ice jams in the International Rapids Section of the St. Lawrence River and the Beauharnois Canal. Within-the-week flow adjustments may also be required to address other unexpected within-the-week changes in river conditions. These flow adjustments are consistent with and accounted for in the design of the regulation plan, which was developed with the assumption that the flows during the Ottawa River freshet, droughts and the ice formation would be adjusted in practice within the week as they have been with Plan 1958DD. Therefore, no future offsetting adjustments are needed to compensate for within-the-week flow adjustments due to uncertainties in forecasts of Ottawa River flows, St. Lawrence River ice conditions, or other weather-related circumstances that are made to maintain the intent of the Plan.

The Board may direct its Regulation Representatives to be responsible for monitoring conditions, making operational flow adjustments and tracking their use. Tracking records will be used to replicate plan results, as needed for subsequent plan reviews.

Minor Deviations for the St. Lawrence River

To respond to short-term needs on the St. Lawrence River, the Commission will allow the Board to make minor discretionary deviations from the approved regulation plan that have no appreciable effect on Lake Ontario levels. Minor deviations are made to provide beneficial effects or relief from adverse effects to an interest, when this can be done without appreciable adverse effects to other interests and is consistent with the requirements of the Order of Approval. Unlike flow adjustments made to maintain the intent of the plan, minor deviations from the plan require accounting and flow restoration.

Minor deviations, while not necessarily limited to only these situations, could include those to address contingencies such as:

- short-term flow capacity limitations due to hydropower unit maintenance;
- assistance to commercial vessels on the river due to unanticipated low water levels;
- assistance, when appropriate, with recreational boat haul-out on Lake St. Lawrence or Lake St. Louis at the beginning or at the end of the boating season; and,
- unexpected ice problems on the St. Lawrence River downstream of Montreal.

These deviations will affect levels on Lake St. Lawrence and the St. Lawrence River downstream to Montreal, but due to the relatively small volume of water involved, such deviations would have a very minor effect on Lake Ontario levels and the river upstream of Cardinal, ON. The intention is for minor flow deviations to be restored by equivalent offsetting deviations from the plan flow as soon as conditions permit to avoid or minimize cumulative impacts on the Lake Ontario level and avoid changing the balance of benefits under the approved regulation plan. Some discretion will be left to the Board as to whether conditions permit the restoration of the volume of water released or held back by these deviations. However, the Board shall not allow the cumulative effect of these minor deviations to cause the Lake Ontario level to vary by more than +/- 2 cm from that which would have occurred had the releases prescribed by the approved plan been strictly followed. The intent is to accommodate, where possible, those needs of the river interests that are difficult to foresee and build into the plan, while being consistent with the intent of the regulation plan and Order of Approval.

The Board will provide post-action reports to the Commission of these minor deviations from plan flows as part of normal semi-annual reporting requirements. However, if circumstances are such that minor deviations cause the Lake Ontario level to vary more than +/- 2 cm from the level resulting from the approved plan (*i.e.,* potentially having a significant impact on Lake Ontario levels), then the Board shall advise the Commission in advance as soon as the potential need for the longer-term deviation is known. If there is a need for a longer-term deviation, the Board must provide a flow restoration plan and obtain approval from the Commission, or obtain a waiver from the Commission not requiring flow restoration. It is intended that such a waiver be rarely used so as to avoid changing the balance of benefits associated with the approved regulation plan.

The Board may direct its Regulation Representatives to approve minor deviations from plan flow, within parameters set by the Board.

Major Deviations

Major deviations are significant departures from the approved regulation plan that are made in response to extreme high or low levels of Lake Ontario in accordance with criterion H14 of the revised Order of Approval:

> *In the event that Lake Ontario water levels reach or exceed extremely high levels, the works in the International Rapids Section shall be operated to provide all possible relief to the riparian owners upstream and downstream. In the event that Lake Ontario levels reach or fall below extremely low levels, the works in the International Rapids Section shall be operated to provide all possible relief to municipal water intakes, navigation and power purposes, upstream and downstream. The high and low water levels at which this provision applies, and any revisions to these levels, shall be subject to the concurrence of Canada and the United States and shall be set out in a Commission directive to the Board.*

Major deviations are expected to significantly alter the level of Lake Ontario compared to the level that would occur by following the approved regulation plan. Although the approved regulation plan was developed to perform under a wide range of hydrological conditions and with the experience gained in four decades of regulation operations, extreme high or low Lake Ontario water levels could require major deviations from the plan. Extreme high and low Lake Ontario levels to trigger major deviations are set out in Table 1 of this directive based on quarter-month levels through the year. If the Board expects that lake levels will be outside the range defined by the trigger levels, then based on analysis using the technical expertise at its disposal, the Board will inform the Commission that it expects to make a major deviation from the plan once the trigger level is reached to moderate the extreme levels. The Board is authorized to use its discretion to set flows in such conditions and deviate from the approved plan to provide balanced relief to the degree possible, upstream and downstream, in accordance with criterion H14 and the Treaty. For example, if the lake level is above the high trigger, then the Board could decide to increase the flow to the maximum specified by the limits used in the approved regulation plan if the plan flow is not already at this maximum, or it could apply the maximum flow limits used in Plan 1958DD, or it could release another flow consistent with criterion H14. While major deviations take downstream interests into account, they are not triggered by downstream levels, as the Bv7 release rules are designed to prevent extreme levels downstream, provided that Lake Ontario levels are not at extremes.

The Commission emphasizes that for the objectives of the approved regulation plan to be met, the regulation plan needs to be followed until water levels reach any of the defined triggers. The Board shall keep the Commission informed of the difference between the Lake Ontario level and the defined trigger levels. The Board will provide regular reports on implementation of the major deviation to the Commission. As the extreme event ends, the Board shall develop for Commission approval a strategy to return to plan flows and recommendations as to whether or not equivalent offsetting deviations from the plan flow should be made, as appropriate on a case-by-case basis.

The effectiveness of major deviations initiated with the trigger levels defined in Table 1 will be assessed as part of the adaptive management process through follow-up monitoring and modeling. The trigger levels or implementation of major deviations could be modified by the Commission through future directives if warranted.

Emergency Deviations

Emergency situations are considered to be those that threaten the physical integrity of the water management system and that may lead to a loss of the ability to control the flows in the system, or unusual life-threatening situations. Examples could include the failure of a lock gate, flooding of the hydropower control works, failure of a spillway gate, dike failure, a regional power outage, or other such active or imminent incidents. Such incidents arise only on extremely rare occasions. In such cases, immediate action is required and the Board is directed to authorize the Regulation Representatives to direct and approve, on the Board's behalf, emergency flow changes as required. The Regulation Representatives will report any such emergency actions as soon as possible to the Board and immediately thereafter the Board will report such actions to the Commission.

The Board will determine the need to make subsequent equivalent offsetting deviations from the plan flow, as appropriate, on a case-by-case basis.

Signed this 8th day of December 2016.

Camille Mageau
Secretary
Canadian Section

Charles A. Lawson
Secretary
United States Section

TABLE 1 Lake Ontario quarter-monthly high and low water levels to trigger operations according to criterion H14.

Quarter-month of the year		Lake Ontario level (metres IGLD85)		Lake Ontario level (feet IGLD85)*	
		High Trigger	Low Trigger	High Trigger	Low Trigger
1	1-Jan	75.03	74.28	246.16	243.70
2		75.07	74.28	246.29	243.70
3		75.10	74.28	246.39	243.70
4		75.13	74.27	246.49	243.67
5	1-Feb	75.14	74.27	246.52	243.67
6		75.14	74.26	246.52	243.64
7		75.13	74.26	246.49	243.64
8		75.14	74.26	246.52	243.64
9	1-Mar	75.16	74.28	246.59	243.70
10		75.18	74.31	246.65	243.80
11		75.22	74.34	246.78	243.90
12		75.27	74.40	246.95	244.09
13	1-Apr	75.33	74.48	247.15	244.36
14		75.40	74.54	247.38	244.55
15		75.45	74.59	247.54	244.72
16		75.50	74.64	247.70	244.88
17	1-May	75.53	74.67	247.80	244.98
18		75.56	74.69	247.90	245.05
19		75.60	74.72	248.03	245.14
20		75.62	74.74	248.10	245.21
21	1-Jun	75.63	74.75	248.13	245.24
22		75.62	74.75	248.10	245.24
23		75.60	74.76	248.03	245.28
24		75.59	74.76	248.00	245.28
25	1-Jul	75.57	74.75	247.93	245.24
26		75.54	74.75	247.83	245.24
27		75.50	74.74	247.70	245.21
28		75.47	74.72	247.60	245.14
29	1-Aug	75.43	74.70	247.47	245.08
30		75.39	74.68	247.34	245.01
31		75.34	74.65	247.18	244.91
32		75.30	74.62	247.05	244.82
33	1-Sep	75.26	74.59	246.92	244.72
34		75.20	74.56	246.72	244.62
35		75.15	74.53	246.56	244.52
36		75.10	74.50	246.39	244.42
37	1-Oct	75.06	74.47	246.26	244.32
38		75.01	74.44	246.10	244.23
39		74.97	74.41	245.96	244.13
40		74.95	74.39	245.90	244.06
41	1-Nov	74.94	74.36	245.87	243.96
42		74.92	74.35	245.80	243.93
43		74.91	74.33	245.77	243.86
44		74.92	74.32	245.80	243.83
45	1-Dec	74.93	74.31	245.83	243.80
46		74.93	74.31	245.83	243.80
47		74.95	74.29	245.90	243.73
48		75.00	74.28	246.06	243.70

* As regulation operations are conducted in metres, approximate conversions to feet are listed for convenience.

Annex B

Lake Ontario – St. Lawrence Plan 2014

Lake Ontario - St. Lawrence Plan 2014 is the combination of the mechanistic release rules labeled "Bv7" together with discretionary decisions made by the International Lake Ontario - St. Lawrence River Board to deviate from the flows specified by the release rules Bv7 according to the Directive on Operational Adjustments, Deviations and Extreme Conditions. In that regard, Bv7 is analogous to Plan 1958-D. Each is a set of functions that can be programmed to produce a release based on established categories of input conditions such as current water levels. The following is a technical description of the Bv7 algorithm or release rules.

B1. Technical Description of Plan Bv7 Release Rules

B1.1 Objectives

The objective of the Bv7 release rules is to return the Lake Ontario-St. Lawrence River System to a more natural hydrological regime, while limiting impacts to other interests. Bv7 rules build on the B+ rules developed during the International Lake Ontario - St. Lawrence River Study. Bv7 differs from B+ in that it includes additional rules to maintain navigation and flood reduction benefits on the lower St. Lawrence River (Lake St. Louis to Lake St. Pierre) and adjustments to the B+ rules to balance Lake Ontario and lower river levels. Bv7 maintains most of the benefits of the current regulation regime because the range of levels and flows that Bv7 produces are closer to the current regulation regime than to unregulated conditions.

B1.2 Goals

The goals of the rules are to:

- Maintain more natural seasonal level and flow hydrographs on the lake and river;
- Provide stable lak e releases;
- Maintain benefits to coastal interests as much as possible while enhancing environmental conditions;
- Maintain benefits to recreational boating as much as possible while enhancing environmental conditions;
- Obtain inter-annual highs and lows required for healthy vegetation habitats;
- Enhance diversity, productivity, and sustainability of species sensitive to water level fluctuations;
- Provide flood and low water protection to the lower St. Lawrence River comparable to Plan 1958-D with Deviations; and,
- Maintain benefits as much as possible for municipal water intakes, commercial navigation and hydropower interests while taking other interests into account.

Bv7 uses short-term forecasts and a longer-term index of water supplies in conjunction with the pre-project stage-discharge relationship to determine lake releases. Rules are included to reduce the risk of flooding on the lake and river. Flow limits are applied to prevent river flows from falling too low, facilitate stable river ice formation, provide acceptable navigation conditions, provide safe operating conditions for control structures, and ensure controlled week-to-week changes in flows.

B2. Approach

B2.1 Rule Curves

Lake releases are primarily a function of a sliding rule curve based on the pre-project stage-discharge relationship adjusted to recent long-term supply conditions. The open-water pre-project stage-discharge relationship, in units of cubic meters per second (m^3/s) is:

$$\text{Pre-project release} = 555.823(\text{Lake Ontario level} - 0.035 - 69.474)^{1.5}$$

In the equation above, the 0.035 meter term adjusts the Lake Ontario level (referenced to IGLD 1985) for differential crustal movement fixed to the year 2010[26]. The pre-project relationship is that from Caldwell and Fay (2002), but here the ice retardation effect is not considered.

The flow computed with this equation is then adjusted depending on the recent supply conditions. As water supplies trend above normal, lake releases are increased. As supplies trend below normal, lake releases are decreased.

For supplies above normal (the index is greater than or equal to 7,011 m³/s), the lake release is determined by:

Table B1.
Bv7 Rule Curve Parameter Values based on Historical Supplies

Climate	A_NTS_{max}	A_NTS_{avg}	A_NTS_{min}
Historical (1900-2000)	8552 m^3/s	7011 m^3/s	5717 m^3/s

The rule curve parameters should be updated periodically to account for climate change.

$$outflow_t = preproject\ release + \left[\frac{F\_NTS - A\_NTS_{avg}}{A\_NTS_{max} - A\_NTS_{avg}}\right]^{P_1} x(C_1)$$

For supplies below normal (the index is less than 7,011 m^3/s), the lake release is determined by:

$$outflow_t = preproject\ release - \left[\frac{A\_NTS_{avg} - F\_NTS}{A\_NTS_{avg} - A\_NTS_{min}}\right]^{P_2} x(C_2)$$

In the equation above, ***F_NTS*** is a supply index based on the net total supply for the past 52 weeks (48 quarter-months), and ***A_NTS*** represents the maximum, minimum and average statistics of the annual net total supply series. The constants C_1 and C_2 determine the rate of flow adjustment to the pre-project release. C_1 is further dependent on the long-term trend in supplies. If the categorical long-term trend indicator is 1 (demonstrating above normal supplies; that is, when the current supply value exceeds 7,237 m^3/s) and the confidence indicator is 3 (indicating high confidence in extreme supplies; that is, when the current supply value exceeds 7,426 m3/s), then C_1 is set to 2,600 m^3/s, otherwise it is equal to 2,200 m^3/s. The value of C_2 is 600 m^3/s. The exponents P1 and P2 serve to accelerate or decelerate the rate of flow adjustment. The values of P_1 and P_2 are 0.9 and 1.0, respectively.

The flow is further reduced by 200 m3/s if the 52 week (48 quarter-month) running lake level mean is less than or equal to 74.6 m IGLD 1985.

Variability of releases from one week (or quarter-month) to the next is smoothed by taking the average of short-term forecasts[27] of releases four weeks (or quarter-months) into the future:

$$outflow = \frac{\sum_{t=1}^{t=4} outflow_t}{4}$$

This averaging also has the impact of accelerating releases during periods of rising lake levels (typically spring), and decelerating releases during periods of falling lake levels (typically fall). Sensitivity analysis indicated that forecasts four quarter-months into the future were optimal.

Bv7 also has a rule to reduce the risk of Lake Ontario and St. Lawrence River flooding in the following spring and summer. If the level of Lake Ontario is relatively high, then it adds to the rule curve flow to reduce the level of Lake Ontario in the fall. It lowers otherwise high Lake Ontario by the onset of winter, thus preparing for spring and making temporary lake storage available for reduced flows during the Ottawa River freshet. It also provides

[26] The year 2010 was selected by the ILOSLRS Plan Formulation and Evaluation Group to compare what pre-project conditions would be near the completion of the Study. The year should be fixed as otherwise there would be a gradual increase in the lake level due to the continual adjustment for glacial isostatic uplift of the lake's outlet.

[27] See Lee (2004) for the derivation of the forecast algorithms

some benefit (relative to the Natural Plan) to the lower river muskrats by reducing winter den flooding. The rule strives to lower Lake Ontario to 74.8 m by January 1 whenever Lake Ontario level is above 74.8 m at the beginning of September. The rule curve flow is linearly increased by the amount needed to eliminate the storage on the lake above 74.8 m over the remaining time before January 1. A check is made to ensure that the adjusted flow for the first week of September does not exceed that of the last week in August to prevent falling levels affecting Lake St. Lawrence recreational boaters through the Labor Day weekend. The adjusted flow is constrained by the L Limits.

B2.2 Flow Limits

Several flow limits, adapted from previous plan development, are used in Bv7. If the rule curve flow (described above) falls outside of these limits, then the lowest of the maxima, or the minimum limit, as applicable, constrains the rule curve flow.

- J Limit – maximum change in flow from one week (or quarter-month) to the next unless another limit takes precedence. Flows are permitted to increase or decrease by up to 700 m^3/s. If the lake is above 75.2 m, and ice is not forming, then the flow may increase by up to 1,420 m^3/s from one week (or quarter-month) to the next.
- M Limit – minimum limit flows t o balance low levels of Lake Ontario and Lake St. Louis primarily for Seaway navigation interests. This limit uses a one week (or quarter-month) forecast of Ottawa River and local tributary flows to estimate the inflows to Lake St. Louis, other than those from Lake Ontario. In actual operation, the flow will be adjusted from day-to-day to maintain the level of Lake St. Louis above the applicable level determined by the Lake Ontario stage.
- I Limit – maximum flows for ice formation and stability.[28] During ice cover formation, either downstream on the Beauharnois Canal or on the critical portions of the International Section, the maximum flow is 6,230 m^3/s. Once a complete ice cover has formed on the key sections of the river, the winter flow constraint prevents the river level at Long Sault from falling lower than 71.8 m. (Note the J limit also applies.) This limit may apply in the non-Seaway season whether ice is present or not. This flow limit is calculated using the stage-fall discharge equation for Kingston-Long Sault, which includes an ice roughness parameter that must be forecast for the coming period. This limit prevents low levels that might impact municipal water intakes on Lake St. Lawrence, and also acts to limit the shear stress on the ice cover and maintain stability of the ice cover. The I limit also limits the maximum flow with an ice cover present in the Beauharnois and/or international channels to no more than 9,430 m^3/s.
- L Limit – maximum flows to maintain adequate levels and safe velocities for navigation in the International Section of the river (navigation season) and the overall maximum flow limit (non-navigation season). Maximum releases are limited to 10,700 m^3/s if the Lake Ontario level should rise above 76.0 m during the navigation season and 11,500 m^3/s during the non-navigation season.

[28] Managing flows during ice formation on the Beauharnois Canal and upstream is paramount, since a restriction caused by a build-up of rough ice in the Beauharnois Canal or upper river can constrain outflows the remainder of the winter which may, in some cases, exacerbate high Lake Ontario levels. During ice formation, operation of the Iroquois Dam must be done in consideration of ice conditions on Lake St. Lawrence.

Table B2.
M Limits as used in Plan Bv7.

Lake Ontario level (m, IGLD 1985)	Total Flow from Lake St. Louis (m^3/s)	Approximate Corresponding Lake St. Louis level at Pointe Claire (m IGLD 1985)
> 74.2	6,800	20.64
> 74.1 and ≤ 74.2	6,500	20.54
> 74.0 and ≤ 74.1	6,200	20.43
> 73.6 and ≤ 74.0	6,100	20.39
≤ 73.6	Minimum of 5,770 or pre-project flow	20.27 or less

Table B3.
L Limits as used in Plan Bv7.

Lake Ontario level (m, IGLD 1985)	L Limit Flow (m^3/s)
For Seaway navigation season (i.e. quarter-months 13-47):	
≤ 74.22	5,950
> 74.22 and ≤ 74.34	5,950+1,333 (Lake Ontario level – 74.22)
> 74.34 and ≤ 74.54	6,111+9,100 (Lake Ontario level – 74.34)
> 74.54 and ≤ 74.70	7,930+2,625 (Lake Ontario level – 74.54)
> 74.70 and ≤ 75.13	8,350+1,000 (Lake Ontario level – 74.70)
> 75.13 and ≤ 75.44	8,780+3,645 (Lake Ontario level – 75.13)
> 75.44 and ≤ 75.70	9,910
> 75.70 and ≤ 76.00	10,200
> 76.00	10,700
For outside Seaway season (i.e. quarter-months 48-12) all levels	
Any	11,500

Table B4.
Lake St. Louis (Pointe Claire) levels corresponding to Lake Ontario levels for limiting lower St. Lawrence River flooding damages (F limits).

Lake Ontario level (m, IGLD 1985)	Pte. Claire level (m, IGLD 1985)
< 75.3	22.10
≥ 75.3 and < 75.37	22.20
≥ 75.37 and < 75.5	22.33
≥ 75.5 and < 75.6	22.40
≥ 75.6	22.48

An additional rule limits the maximum flow in the Seaway season to prevent the weekly mean level of Lake St. Lawrence at Long Sault Dam from falling below 72.60 m. To deal with very low levels, if the Lake Ontario level is below chart datum (74.20 m) then the level of Lake St. Lawrence at Long Sault Dam in this rule is allowed to be equally below the 72.60 m level.

A final check ensures that the L Limit does not exceed the actual channel hydraulic capacity (in m^3/s) defined as (Lee *et al.*, 1994):

$$\text{channel capacity} = 747.2(\text{Lake Ontario level} - 69.10)^{1.47}$$

- F limit – the maximum flow to limit flooding on Lake St. Louis and near Montreal in consideration of Lake Ontario level. It is a multi-tier rule that attempts to balance upstream and downstream flooding damages by keeping the level of Lake St. Louis below a given stage for a corresponding Lake Ontario level as follows:

This limit uses a one week (or quarter-month) forecast of the Ottawa River and local tributary inflows and the following relationship between Lake St. Louis outflows and levels at Pointe Claire:

$$Pte.\,Claire\ level = 16.57 + \left[\left(R_{Pt.Claire} \times Q_{L.St.Louis} / 604.0\right)^{0.58}\right]$$

In this equation, ***R*** is the roughness factor and ***Q*** (in m^3/s) is the total flow from Lake St. Louis. In operation the flow will be adjusted from day to day to maintain the level of Lake St. Louis below the applicable level determined by the Lake Ontario stage.

B3. Application

Bv7 uses imperfect forecasts of Lake Ontario total supplies, Ottawa River and local tributary flows, ice formation and ice roughness. The water supply forecasts are based on time-series analysis of the historical data as described in Lee (2004). Overall, the statistical forecasts were found to have similar error to those in use operationally. Because the operational methods generally rely upon hydrometeorological data not available for either the historical time series or the stochastic time series, actual forecasts could not be used. However, it was envisioned that operationally, the best available real-time forecasts would be used. In addition, because week-ahead forecasts will generally be imperfect, it is expected that in actual operations the flows will be adjusted within the week[29] taking into account the actual ice and downstream inflow conditions to achieve the intent of the Bv7 rules and limits.

B3.1 Procedure

1. For each of the next four weeks (quarter-months), calculate the Lake Ontario annual net total supply index, forecast the weekly (quarter-monthly) Lake Erie inflow and Lake Ontario net basin supply, Ottawa River and local tributary flows to Lake St. Louis, and ice roughness.
2. For each of the next four weeks (quarter-months), sequentially route the supplies and determine forecasts of lake outflows using the sliding rule curve.
3. Average the next four weeks (quarter-months) forecast releases to determine the next period's release.
4. If the current time period is within September through December inclusive, and Lake Ontario was at or above 74.8 m on September 1 (end of quarter-month 32), then increase the basic rule curve by the amount needed to achieve 74.8 m by January 1, not exceeding the flow in the week before Labor Day (quarter-month 32) in the flow in the Labor Day week (quarter-month 33).
5. Apply the M, L, I, J and F limits. If the plan flow is outside of the maximum of the minimum limits and the minimum of the maximum limits, the appropriate limit becomes the plan flow.

B4. Simulation of Bv7 with 1900-2008 Hydrology and Ice Conditions

The tables on the following pages are based only on the Bv7 release rules, not the deviations in Plan 2014. The tables show how often under Bv7 water levels will be above a range of levels for Lake Ontario, Lake St. Lawrence, Lake Louis and Montreal Harbour, and how often releases from the Moses-Saunders dam will be above certain flows. The tables are based on a simulation of Bv7 on a quarter-monthly time step and with the 1900-2008 dataset of supplies and inflows, ice conditions, channel roughness factors,

[29] See **Annex C** for more on operational adjustments

and related conditions. This 109-year simulation includes 436 quarter-months for each calendar month, 5,232 quarter-months in all. For example, in Table B-5, Lake Ontario never rises above 75.80 meters, but rises above 75.70 meters six times in May and three times in June.

The tables are:

- Table B 5 Bv7 Historical Lake Ontario Levels
- Table B 6 Bv7 Historical Lake Ontario Outflows
- Table B 7 Bv7 Historical Lake St Lawrence at Long Sault Dam Levels
- Table B 8 Bv7 Historical Lake St. Louis Levels
- Table B 9 Bv7 Historical Montreal Harbour at Jetty 1 Levels

Table B5.
Bv7 Historical Lake Ontario Levels

Lake Ontario Quarter-monthly mean levels Number of Occurences Above Level Shown ... 1900-2008 supplies simulation													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All Months
Level (m IGLD 1985)													
75.8	0	0	0	0	0	0	0	0	0	0	0	0	0
75.7	0	0	0	0	6	3	0	0	0	0	0	0	9
75.6	0	0	0	6	10	12	6	0	0	0	0	0	34
75.5	0	0	0	12	23	27	13	2	0	0	0	0	77
75.4	0	0	1	24	43	52	30	9	0	0	0	0	159
75.3	2	6	3	39	90	91	61	18	1	0	0	0	311
75.2	12	15	19	70	143	146	107	46	6	4	1	4	573
75.1	17	28	33	115	183	204	176	99	26	4	4	5	894
75.0	32	50	68	166	241	269	245	179	69	11	4	7	1341
74.9	63	79	115	216	296	322	312	251	136	34	17	23	1864
74.8	121	138	166	274	340	357	357	312	230	116	66	76	2553
74.7	163	185	226	339	381	397	389	368	306	230	143	135	3262
74.6	209	223	266	371	410	420	412	402	361	310	257	215	3856
74.5	306	295	335	397	418	420	419	410	394	351	321	312	4378
74.4	360	366	379	410	426	428	426	417	410	392	363	364	4741
74.3	390	390	396	418	428	429	432	421	413	408	391	388	4904
74.2	407	405	401	425	434	436	435	427	418	412	411	408	5019
74.1	415	409	411	428	436	436	436	436	423	418	420	414	5082
74.0	420	419	420	434	436	436	436	436	434	424	421	422	5138
73.9	424	424	427	435	436	436	436	436	436	429	424	424	5167
73.8	424	425	432	436	436	436	436	436	436	434	428	424	5183
73.7	431	432	436	436	436	436	436	436	436	436	433	430	5214
73.6	432	435	436	436	436	436	436	436	436	436	436	432	5223
73.5	436	436	436	436	436	436	436	436	436	436	436	436	5232
Maximum Level	75.31	75.39	75.46	75.7	75.75	75.72	75.65	75.59	75.36	75.26	75.22	75.25	75.75
Minimum Level	73.55	73.56	73.72	73.84	74.16	74.24	74.2	74.12	73.96	73.76	73.61	73.55	73.55

Table B6.

Bv7 Historical Lake Ontario Outflows

Lake Ontario Quarter-monthly mean Outflows Number of Occurences Above Flow Shown ... 1900-2008 supplies simulation													
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**All Months**
Flow (m^3/s)													
10400	0	0	0	0	0	0	0	0	0	0	0	0	0
10200	0	0	0	0	0	0	0	0	0	0	0	0	0
10000	0	0	0	0	4	1	0	0	0	0	0	0	5
9800	2	0	2	5	14	15	5	1	0	0	0	0	44
9600	2	0	2	8	18	21	10	1	0	0	0	0	62
9400	2	0	6	9	22	24	16	3	0	0	0	0	82
9200	2	1	10	9	27	26	21	6	0	2	0	0	104
9000	2	5	15	12	37	37	25	10	1	4	1	3	152
8800	2	5	19	18	40	53	33	15	8	4	2	4	203
8600	2	7	24	31	61	70	61	32	24	8	4	7	331
8400	2	10	34	42	75	93	80	52	45	20	20	27	500
8200	5	24	48	66	104	115	95	65	59	30	29	29	669
8000	11	36	61	92	123	137	114	86	79	49	46	42	876
7800	13	48	76	114	147	165	135	108	110	69	59	52	1096
7600	26	63	97	130	175	192	172	132	139	86	73	67	1352
7400	33	76	121	168	201	220	207	165	164	114	91	84	1644
7200	38	97	149	212	244	259	250	216	199	136	115	100	2015
7000	50	128	178	246	292	299	290	260	238	178	147	114	2420
6800	99	174	211	284	326	340	322	297	262	212	179	146	2852
6600	123	224	256	325	356	365	360	333	286	251	225	177	3281
6400	151	265	305	358	390	387	376	374	347	312	279	216	3760
6200	322	338	349	386	401	407	414	415	403	376	348	331	4490
6000	373	375	394	399	408	419	428	432	420	405	382	381	4816
5800	398	401	409	404	421	429	434	434	427	412	400	403	4972
5600	416	416	415	412	425	432	436	436	434	427	414	413	5076
5400	424	422	421	421	431	435	436	436	435	431	423	425	5140
5200	429	429	427	429	433	436	436	436	436	432	430	434	5187
5000	434	435	431	431	435	436	436	436	436	432	435	435	5212
4800	435	436	433	434	436	436	436	436	436	435	436	435	5224
4600	436	436	436	436	436	436	436	436	436	436	436	436	5232
Maximum Flow	9910	9290	9910	9910	10200	10200	9910	9880	9150	9220	9060	9180	10200
Minimum Flow	4620	4910	4650	4780	4870	5250	5640	5760	5290	4800	4980	4780	4620

Table B7.

Bv7 Historical Lake St. Lawrence at Long Sault Dam Levels

Lake St. Lawrence at Long Sault Dam Quarter-monthly mean levels Number of Occurences Above Level Shown ... 1900-2008 supplies simulation													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All Months
Level (m IGLD 1985)													
74.4	0	0	0	0	0	0	0	0	0	0	0	0	0
74.3	4	0	0	0	0	0	0	0	0	0	0	0	4
74.2	6	0	0	0	0	0	0	0	0	0	0	1	7
74.1	8	0	0	0	0	0	0	0	0	0	0	2	10
74.0	13	1	0	0	0	0	0	0	0	0	0	5	19
73.9	21	2	0	3	1	4	6	1	0	0	0	10	48
73.8	30	6	6	67	139	130	95	52	7	0	2	19	553
73.7	44	10	18	138	208	209	190	141	28	13	15	33	1047
73.6	60	11	46	212	277	280	255	210	94	82	57	63	1647
73.5	90	14	76	278	336	314	287	259	177	155	138	134	2258
73.4	114	20	110	323	373	353	318	300	223	211	203	195	2743
73.3	136	29	132	369	397	386	346	331	270	267	257	242	3162
73.2	156	41	156	392	418	409	382	351	314	301	292	285	3497
73.1	186	65	188	414	428	422	409	374	341	336	328	323	3814
73.0	208	88	216	431	431	432	423	399	368	362	359	350	4067
72.9	221	114	242	433	432	434	429	412	393	388	381	374	4253
72.8	241	152	264	434	433	436	433	427	415	404	400	391	4430
72.7	261	180	292	434	435	436	435	433	426	416	417	410	4575
72.6	275	212	312	436	436	436	436	436	436	435	428	425	4703
72.5	299	228	331	436	436	436	436	436	436	436	433	432	4775
72.4	320	257	349	436	436	436	436	436	436	436	435	434	4847
72.3	339	276	359	436	436	436	436	436	436	436	436	434	4896
72.2	351	291	373	436	436	436	436	436	436	436	436	436	4939
72.1	359	307	382	436	436	436	436	436	436	436	436	436	4972
72.0	370	323	392	436	436	436	436	436	436	436	436	436	5009
71.9	376	336	402	436	436	436	436	436	436	436	436	436	5038
71.8	401	380	424	436	436	436	436	436	436	436	436	436	5129
71.7	436	436	436	436	436	436	436	436	436	436	436	436	5232
Maximum Level	74.35	74.09	73.88	73.92	73.92	73.93	73.93	73.91	73.86	73.74	73.81	74.29	74.35
Minimum Level	71.74	71.71	71.72	72.66	72.66	72.84	72.69	72.66	72.63	72.6	72.39	72.22	71.71

Table B8.
Bv7 Historical Lake St. Louis Levels

Lake St. Louis at Pointe Claire Quarter-monthly mean levels Number of Occurences Above Level Shown ... 1900-2008 simulation													
	Jan	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**All Months**
Level (m IGLD 1985)													
22.5	0	0	0	0	0	0	0	0	0	0	0	0	0
22.4	0	0	0	3	4	2	0	0	0	0	0	0	9
22.3	0	0	0	10	17	6	0	0	0	0	0	0	33
22.2	0	0	0	14	26	11	0	0	0	0	0	0	51
22.1	1	4	5	27	45	15	0	0	0	0	0	0	97
22.0	3	8	15	80	85	26	2	0	0	0	0	2	221
21.9	7	14	25	107	101	45	7	0	0	1	4	5	316
21.8	13	20	39	131	123	58	19	4	0	1	6	10	424
21.7	23	35	57	162	155	77	30	8	1	3	10	18	579
21.6	43	63	72	200	196	101	44	17	8	7	22	28	801
21.5	68	96	96	237	240	145	79	30	22	23	34	40	1110
21.4	93	128	134	276	279	188	114	63	51	41	52	63	1482
21.3	133	157	156	311	318	229	152	91	77	73	91	86	1874
21.2	175	193	179	337	347	268	187	128	110	90	124	106	2244
21.1	234	240	222	366	375	308	241	167	148	125	157	144	2727
21.0	279	280	262	394	397	344	288	226	190	165	183	183	3191
20.9	347	337	298	405	409	380	326	271	241	203	211	223	3651
20.8	385	369	335	413	419	404	366	318	277	245	249	263	4043
20.7	405	406	384	421	426	415	393	369	329	301	295	321	4465
20.6	423	419	412	428	436	436	436	430	418	412	408	402	5060
20.5	431	427	423	432	436	436	436	436	426	421	419	417	5140
20.4	435	433	436	436	436	436	436	436	436	430	421	427	5198
20.3	436	434	436	436	436	436	436	436	436	436	436	435	5229
20.2	436	436	436	436	436	436	436	436	436	436	436	435	5231
20.1	436	436	436	436	436	436	436	436	436	436	436	435	5231
20.0	436	436	436	436	436	436	436	436	436	436	436	436	5232
Maximum Level	22.16	22.17	22.2	22.48	22.48	22.48	22.04	21.86	21.74	21.94	21.98	22.08	22.48
Minimum Level	20.35	20.21	20.41	20.41	20.63	20.61	20.62	20.55	20.42	20.38	20.38	20.1	20.1

Table B9.

Bv7 Historical Montreal Harbour at Jetty 1 Levels

Montreal Harbour at Jetty #1 Quarter-monthly mean levels Number of Occurences Above Level Shown ... 1900-2008 supplies simulation													
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	All Months
Level (m IGLD 1985)													
9.2	0	0	0	0	0	0	0	0	0	0	0	0	0
9.0	1	1	0	0	0	0	0	0	0	0	0	0	2
8.8	1	1	0	2	1	1	0	0	0	0	0	0	6
8.6	1	3	0	3	9	2	0	0	0	0	0	0	18
8.4	1	5	0	7	22	5	0	0	0	0	0	0	40
8.2	1	5	3	18	40	7	0	0	0	0	0	0	74
8.0	2	5	5	53	66	12	0	0	0	0	0	0	143
7.8	2	7	11	84	85	21	0	0	0	0	0	0	210
7.6	3	15	23	115	103	27	3	0	0	0	0	2	291
7.4	5	22	32	157	132	38	6	0	0	0	6	5	403
7.2	14	32	63	199	181	60	11	3	0	1	7	8	579
7.0	32	51	88	240	224	85	34	13	3	6	15	23	814
6.8	60	86	119	286	273	124	58	23	8	21	27	37	1122
6.6	96	144	152	321	328	185	106	43	37	43	67	65	1587
6.4	139	182	189	350	356	239	155	88	70	75	112	94	2049
6.2	183	224	239	382	375	291	201	144	114	107	144	130	2534
6.0	262	295	287	399	402	343	271	198	174	148	179	185	3143
5.9	300	327	306	410	411	362	296	237	205	176	195	206	3431
5.8	336	352	333	415	419	381	322	272	234	196	214	225	3699
5.7	368	373	361	420	423	396	352	305	267	235	236	252	3988
5.6	384	397	381	427	431	410	380	336	289	267	272	286	4260
5.5	404	414	402	428	434	422	393	373	321	309	316	316	4532
5.4	413	420	417	430	436	426	420	411	392	365	355	359	4844
5.3	427	430	428	432	436	433	434	430	416	406	396	397	5065
5.2	432	433	434	435	436	436	436	435	426	421	412	410	5146
5.1	436	434	435	435	436	436	436	436	431	423	420	426	5184
5.0	436	436	436	436	436	436	436	436	436	430	431	431	5216
4.9	436	436	436	436	436	436	436	436	436	436	436	434	5230
4.8	436	436	436	436	436	436	436	436	436	436	436	435	5231
4.7	436	436	436	436	436	436	436	436	436	436	436	435	5231
4.6	436	436	436	436	436	436	436	436	436	436	436	436	5232
Maximum Level	9.08	9.17	8.34	8.96	8.94	8.9	7.73	7.26	7.19	7.4	7.5	7.69	9.17
Minimum Level	5.11	5.03	5.03	5.06	5.43	5.27	5.21	5.2	5.01	4.94	4.91	4.7	4.7

B5. References

Caldwell, R. and Fay, D.(2002). Lake Ontario Pre-project Outlet Hydraulic Relationship Final Report. Hydrology and Hydraulics Technical Work Group, International Joint Commission Lake Ontario-St. Lawrence River Study.

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Appendix

Unpublished References listed in the Technical Description of Regulation Plan 2014

LAKE ONTARIO PREPROJECT
OUTLET HYDRAULIC RELATIONSHIP

Final Report

Hydrology & Hydraulics TWG, Task 2
IJC Lake Ontario - St. Lawrence River Study

March 28, 2002

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TABLE OF CONTENTS

1 OBJECTIVE

The purpose of the current study was to review and document the hydraulic relationship for the Lake Ontario preproject outlet control section that existed at the head of the Galop Rapids near Cardinal, Ontario. Where possible, any deficiencies in the method used to simulate the outflows under preproject outlet conditions were to be corrected. An updated preproject outflow relationship taking into account ice retardation and crustal movement effects was developed.

2 BACKGROUND

Prior to regulation, Lake Ontario outflows were limited by the hydraulic capacity of the river channel. Rock sills at the head of the Galop Rapids (in the vicinity of Galop and Adam Islands) formed the natural constraint. Originally, these two islands divided the rapids into three channels: the Canadian Galop Rapids, the Gut, and the American Galop Rapids. This section was modified to facilitate navigation in the late 19th and early 20th centuries by dredging (of the Canadian Galop Rapids) and construction of a submerged weir (Gut Dam) (ILOBOE, 1958). This weir was removed by January of 1953. In its Orders of Approval for the Regulation of Lake Ontario, the International Joint Commission (IJC) defined the preproject outlet conditions as those existing between 1953 and 1955, after the removal of the Gut Dam, but prior to the beginning of the St. Lawrence hydropower project. This state is hydraulically similar to the natural state of the channel prior to 1900 (ILOBOE, 1958).

The Lake Ontario outflow and level regime that would exist under unregulated conditions is one of the scenarios to be used for comparison in the evaluation of Lake Ontario regulation in the present IJC study (SLR-LOPOST, 1999). The preproject outlet condition represents the unregulated condition for flows from Lake Ontario.

It its natural state, the river fell approximately 1.5 m in 1.6 km within the Galop Rapids (CCGLBHHD, 1958). From Lake Ontario to the head of the Galop Rapids, the fall was 0.6 m over a distance of 112 km. Below the rapids, the river fell 4 m over the next 16 km to the head of Rapide Plat (rapids that formerly existed adjacent to Ogden Island). The channel constriction at the Galop Rapids was sufficient to create a backwater effect, and flow at these rapids reached speeds in excess of what is defined (hydraulically) as “critical velocity”. In other words, water levels upstream of the rapids were independent of levels and flows below the rapids. As such, a stage-discharge relationship could be defined that was dependent only upon upstream level conditions.

Such a stage-discharge relationship to estimate preproject outflows was developed in the 1950s for the International St. Lawrence River Board of Control (ISLRBC). The relationship includes terms to account for ice retardation and the relative crustal movement between Lake Ontario and the Galop Rapids over time. The accuracy of this relationship and the method of calculation of preproject outflows is uncertain since the development of the relationship is not well documented.

The Committee on Levels and Flows (COL&F) of the ISLRBC submitted a proposed “Procedure for Determining Lake Ontario Preproject Levels" as Appendix I of its 24 September 1956 report to the Board (COL&F, 1956). This routing procedure's basic premise is that, during any time after altering the outlet control of Lake Ontario (i.e., by channel dredging and dam construction), the difference between the water storage on Lake Ontario accumulated under such conditions and that under preproject conditions is the difference between the outflow observed and the outflow which would have occurred under preproject conditions. This storage difference equates to a difference in water surface elevation of Lake Ontario due to the difference in flow caused by the project on the St. Lawrence River. Since preproject flows may be estimated using a stage-discharge relationship, the effects on lake levels are obtainable, and thereby preproject levels may be determined.

However, determination of preproject flows in the winter must take into consideration flow retardation due to ice conditions. Ice retards (i.e., reduces) the outflow in the St. Lawrence River and generally results in a temporary increase in water levels upstream of the ice formation.

3 PROCEDURE

3.1 Review of the General Form of the Relationship

As stated above, a preproject stage-discharge relationship could be developed which depended solely on level and ice conditions upstream of the natural constraint at Galop Rapids. The general form of this relation is normally expressed as:

$$Q_{pp} = a(H-b)^c + d \qquad (1)$$

where: Q_{pp} = flow (m^3/s),
H = river stage (upstream of Galop Rapids) (m),
a, b, and c are constants, and
d represents the decrease in flow due to ice retardation.

3.1.1 Consideration for Retardation due to Ice

In general, the term ($a(H-b)^c$) is sufficient to describe the unique relationship which exists during the open-water season. However, as noted above, ice retardation must be considered in determination of flows in the winter. Note that if the stage can be measured directly at the control section (e.g., at Galop Rapids in this case), then the ice term, d, is unnecessary.

Direct estimates of ice retardation were made for the period prior to the commencement of the St. Lawrence River project in 1955 (IGLLB, 1964). Values were determined as the difference between the outflows resulting from the open-water relationship (using the level at Oswego in this case), and the recorded outflows. Monthly mean estimates for "d", the ice retardation (expressed in m^3/s), were determined for the period from 1900-1955 inclusive (IGLLB, 1964). This data constitutes the historical ice retardation record.

However, after the construction of the St. Lawrence River project, the Galop Rapids were drowned out and the outflow control shifted to the downstream dams. Thus, the existing stage-discharge relationships could no longer be used to calculate the actual flow. To estimate the preproject ice retardations after 1955, other empirical methods are required. The currently adopted method is described later.

3.1.2 Consideration of Crustal Movement

The preproject control section at the Galop Rapids is known to be rising with respect to the land surrounding Lake Ontario due to the effects of crustal movement. It is a geological fact that, for thousands of years, there has been a near-continuous differential uplifting of the earth's crust in and around Lake Ontario (Price, 1954; CCGLBHHD, 1999). This movement is due to forces attempting to restore the isostatic equilibrium greatly disturbed by the growth and retreat of Ice Age glaciers across the region.

After the retreat of the last ice sheet from the Lake Ontario region, Lake Iroquois was formed (Price, 1954). Since the St. Lawrence River valley was blocked by the ice sheet, this ancient lake was forced to discharge to the Atlantic Ocean via the Mohawk valley to the Hudson River. When the ice sheet retreated from the St. Lawrence River valley, the lake could then empty through this lower outlet. Thus, Lake Iroquois shoreline beaches can now be found at elevations much higher than the current Lake Ontario shoreline. When formed, these ancient beaches must have been on a level plane. These beaches are now differentially uplifted by as much as 100 m. The general slope of this uplift is N20°E (Price, 1954).

Since the natural control section of Lake Ontario at the Galop Rapids was drowned out after construction of the project in the late 1950s, to be able to estimate preproject outflows and levels using current information, it was necessary to develop an operational preproject stage-discharge relationship using water levels on Lake Ontario in lieu of at the control section. Therefore, it proved necessary to transpose the stage at the Galop Rapids to Lake Ontario. Price (1954) estimated that the land at Lock 27 (near the Galop Rapids) was rising with respect to the land at Oswego at a rate of 0.55 feet (0.17 m) per century. This value was adopted for use in the relationship currently used by the ISLRBC.

3.2 Review of Current Preproject Outflow Relationship

The preproject stage-discharge equation currently used by the ISLRBC for open-water periods is:

$$Q_{pp} = 577.19\,(\text{Oswego Level} - 0.0017\,(\text{Year}-1903) - 69.485)^{1.5} \quad (2)$$

where:

Q_{pp} = flow (m^3/s), and
Oswego Level is given in metres on IGLD 1985.

This relation was developed in the mid-1950s using an earlier datum and English units, but no known reference is available describing its development. Several recent attempts to try to determine the source of Equation 2 have been unsuccessful. It's existence was mentioned in a report by the Committees on Levels & Flows (COL&F, 1956) in describing procedures for calculating preproject levels for use by the ISLRBC, but no reference was given. Development may have been based on fitting Oswego adjusted level data to the computed flows in the 1953-1955 period directly.

An ice retardation factor, K, is employed during the months of January to March, inclusive, as prescribed by the currently adopted method (COL&F, 1956). The factor expresses the retarded Lake Ontario outflow as a percentage of the expected open-water outflow. The authors realized that December and April outflows are also occasionally affected by ice, but it was noted that the effect follows no consistent trend, such as was found for the other three winter months (COL&F, 1956). In general, results were obtained by regression of a direct relationship between antecedent air temperature observations at Ogdensburg, NY, and observed ice retardation effect, expressed in percent. Mention was made in the report that it is very difficult to predict preproject Lake Ontario flows (particularly in the winter), and that a revised procedure should be adopted whenever improvements to this "satisfactory" method could be developed. To date, the original procedure remains in use.

The term 0.0017(Year-1903) (m) is to account for crustal movement between Oswego and the preproject control section at the Galop Rapids. This assumes that the outlet is rising with respect to the land at Oswego at a rate of 17 cm/century (0.55 ft./century). It is believed that this value was taken from a 1954 report by Charles Price of the Canadian Hydrographic Service (CHS). A 1958 report by the International Lake Ontario Board of Engineers (ILOBOE) also made use of this rate in the adjustment of Oswego levels to those at the outlet (i.e., Lock 25). This adjustment meant that the differences between the adjusted Lake Ontario levels and those in the Prescott-Lock 23 reach now would describe only physical effects due to channel changes (ILOBOE, 1958). Since the benchmarks had been brought to a common datum in 1903, corrections are made progressively forward (or backward) in time, and it is assumed that upstream (e.g., Oswego) gauges move with respect to the area around the Galop Rapids. Note, then, that adjusted Oswego estimates are relative to the Galop Rapids section (in order to describe a stage-discharge relationship immediately upstream of this former control section) and are not actual water levels.

3.2.1 Recent Attempt to Determine the Source of Equation 2

Since details of the development of Equation 2 are not known, an attempt was made recently to determine the source of the equation and to verify its validity based on available data.

Recorded outflows were originally computed using a stage-discharge equation developed for Lock 25 (at Iroquois, downstream of the Galop Rapids) (supplemented by those at Locks 23, 24, and 27) (CCGLBHHD, 1958). This relationship is:

$$Q = 23.79\ (\text{Lock }25 - 188.51)^{2.5} \qquad (3)$$

Where:

Q = flow (ft^3/s), and
Lock 25 = water level at Lock 25 (ft on U.S.L.S. 1903 datum).

Equation 3 was considered to be unaffected by upstream channel changes (i.e., at Galop Rapids) and was deemed valid from 1860-1954 (CCGLBHHD, 1958).

During the late 1950s, to determine the effect that Gut Dam and other channel changes had, relationships between Lock 25 levels and Oswego levels (adjusted for crustal movement) were developed (ILOBOE, 1958). A graphical relationship developed using 15 pairs of Oswego and Lock 25 monthly mean levels for the open-water months in 1953 to June 1955 (after Gut Dam was removed but before project dredging commenced) was presented in this reference (using the U.S.L.S. 1903 datum). To confirm the validity of Equation 3 under these same conditions, reported monthly mean outflows as published by CCGLBHHD (1958) were "matched up" with the Lock 25 monthly mean levels reported by ILOBOE (1958). A simple linear regression analysis, forcing the exponent to 2.5 and the stage adjustment to 188.51 feet, resulted in a multiplicative constant of 23.79 and an almost exact linear fit. In other words, Equation 3 would yield excellent flow estimates during the preproject period as well.

From the graphical relationship between Oswego and Lock 25 for the open-water months in 1953 to June 1955 reported by ILOBOE (1958), the following simple linear equation relating adjusted preproject Oswego levels to Lock 25 levels was determined (Equation 4; in feet on U.S.L.S. 1903 datum). Note that this was done by visual "line of best fit" in an attempt to replicate the method which would have most likely been used in the late 1950s.

$$\text{Lock 25} = -107.08 + 1.366\ \text{Oswego}_{\text{adjusted}} \qquad (4)$$

The constants, -107.08 and 1.366, would have been determined to be -100.49 and 1.339 using modern regression software. The effect on this loss of accuracy is less than half an inch (1 cm) except during periods of extreme water levels.

Substituting into Equation 4 into Equation 3 yields (in Imperial units):

$$Q_{pp} = 51.88\ (\text{Oswego Level} - 0.0055(\text{Year} - 1903) - 216.39)^{2.5} \qquad (5)$$

To convert Oswego levels to IGLD 1985, 0.71 feet is added. Converting Equation 5 to metric yields:

$$Q_{pp} = 28.64\ (\text{Oswego Level} - 0.0017(\text{Year} - 1903) - 65.739)^{2.5} \qquad (5b)$$

Where:

Q_{pp} = flow (m^3/s), and
Oswego Level is given in metres on IGLD 1985.

Note that, although this equation yields similar results as Equation 2, they are different. The authors of Equation 2 may have fit the Oswego adjusted levels data directly to the computed flows in the 1953-1955 period.

Attempts were then made to develop stage-discharge equations directly from this same data by least squares regression. There was observed to be very little difference in the fit between the forms of the equations (all had R^2 values of 0.997; the coefficient of multiple determination [p. 90, Draper & Smith, 1981], a measure of how well each data series fit one another). The newly fit equations having the same exponents as Equations 2 and 5, respectively, were:

$$Q_{pp} = 561.14\ (\text{Oswego Level} - 0.0017(\text{Year} - 1903) - 69.378)^{1.5} \qquad (6)$$

and

$$Q_{pp} = 27.79\ (\text{Oswego Level} - 0.0017(\text{Year} - 1903) - 65.625)^{2.5} \qquad (7)$$

Both Equations 6 and 7 are expressed in cubic metres per second and metres on IGLD 1985. As can be seen, the constants of regression in both very closely match their counterparts developed previously (see Equations 2 and 5b). To indicate the magnitude of the difference in the results from the equations, computed flows for Oswego levels of 74.10 m (low level) and 75.37 m (Criterion (h) level) were made. The year was assumed to be 1996. See Table 1.

Table 1: Outflows (m^3/s) Estimated from Derived Preproject Relationships

EQUATION	WITH OSWEGO LEVEL @ 74.10 m IN 1996	WITH OSWEGO LEVEL @ 75.37 m IN 1996
Equation 2	5430	7910
Equation 5b	5520	7910
Equation 6	5470	7910
Equation 7	5540	7910

All the relationships yield the same result for the higher level, but differ by up to 110 m^3/s at the lower level. Considering that flows and levels in the 1953-1955 data set used to develop the equations ranged from 6710 to 8330 m^3/s and 74.70 to 75.50 m, respectively, and that 74.10 m is below this range, these equations all give reasonable results. Based on this investigation, Equation 2, the preproject equation currently in use, was deemed to be reasonable.

3.3 Review of the Existing Crustal Movement Term

As stated previously, the general slope of the differential crustal uplift in the Lake Ontario-St. Lawrence River region is N20°E. Price (1954) used this information as the basis of his investigation. Comparing relative gauge elevation differences between each of the ten gauge location pairs for five gauges on Lake Ontario, he found progressive departures during the full period of records dating back as far as 1860 (with the exception of the Kingston/Cape Vincent relation, which showed no such departure). Using five-year moving mean water levels for the period from June to September each year, he found that the overall direction of changing gauge relations was N40°E. Though he observed that this only defines the current direction and rate of change in slope and does not establish a zero line or "hinge", he assumed this direction to establish a base line drawn at N50°W through Port Dalhousie (the most westerly of the gauges considered). Price (1954) used a constant rate of ±0.53 ft. per 100 miles per 100 years (±10.0 cm per 100 km per 100 years) to define differences from location-to-location from this base line. A relative uplift of +0.55 ft. (+17 cm) per century was found for Lock 27 (adjacent to the Galop Weir) relative to Oswego. This is the value used in the currently adopted crustal movement term given in Equation 2.

Although Price concluded that one can linearly interpolate values from the base line (within the Lake Ontario basin), the Lock 27 estimate was determined by linear extrapolation.

Even though Price's 1954 approach appears reasonable, new state-of-the-art techniques continue to immerge and may yield more accurate estimates of relative uplift.

3.3.1 Other Available Estimates

A recent investigation was undertaken to determine the validity of Price's (1954) estimate.

The crustal movement term in Equation 2 could not be reasonably calculated using regression methods due to the short period of valid record after the removal of Gut Dam (1953-1955). However, since there were no channel changes from 1908 to 1952 that affected the stage-discharge relationship between Oswego and the outlet (ILOBOE, 1958), the parameters of a stage-discharge relationship for this period with Gut Dam in place and with a crustal movement term could be estimated.

The effect of Gut Dam on Lake Ontario levels was reported to be from +4.00 to +4.75 inches (10.2 to 12.1 cm), depending on the outflow (ILOBOE, 1958). 10 cm was subtracted from the Oswego levels from November 1903 to November 1952 to provide a coarse adjustment for Gut Dam's effect on the preproject relationship. Now, by least squares, the parameters were estimated as:

$$Q_{pp} = 550.2\ (\text{Oswego Level} - 0.0016(\text{Year} - 1903) - 69.426)^{1.5} \qquad (8)$$

The 95% confidence interval for the crustal movement rate estimate in this regression was 0.00141 to 0.00179 m/yr. Price's (1954) 0.0017 m/yr. estimate falls within this range.

The Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (CCGLBHHD) revisited the phenomenon of crustal movement in the Great Lakes basin in May 1999 using the state-of-the-art at the time (CCGLBHHD, 1999). The averages of the monthly means for the months June-September were used for gauges throughout the Great Lakes System. Linear regressions were made of the differences between gauge pairs with time on each lake. Rates for each lake were combined using least-squares adjustment, and weighted according to the number of years used in each regression. The outlet of Lake Ontario (i.e., at Cape Vincent) was found to be rising at a rate of 6 cm/century (with a standard error of estimate of 0.4 cm/century) relative to the land at Oswego. Relative vertical movements outside of the Lake Ontario basin were obtained using the ICE-4G postglacial rebound model. From graphical estimates drawn from these results, it was recently estimated that the relative uplift from the preproject outlet at Galop Rapids to Oswego is approximately 12 cm/century.

André Mainville, Natural Resources Canada, Ottawa, very recently led a similar investigation using current state-of-the-art techniques (CGLBHHD, 2001). This time, year-round monthly mean levels for gauges throughout the Great Lakes System were used (along with an extended period of record). Cape Vincent was found to be rising at a rate of 4.5 cm/century (with a standard error of estimate of 0.2 cm/century) relative to Oswego. A relative uplift rate of 14.1 cm/century was found to exist between the Galop Rapids and Oswego (Mainville, 2001). This rate was determined by extrapolation from a plane fit by least-squares adjustment through the five Lake Ontario gauges closest to the outlet. Dr. Mainville noted that the precision of this estimate was likely only on the order of a few centimetres per century since it was obtained by extrapolation at more than 100 km outside the lake (Mainville, 2001). The global post-glacial rebound models ICE3G and ICE4G (developed by Prof. R. Peltier and associates, University of Toronto), as well as repeated gravimetric measurement models (by Prof. S. Pagiatakis, York University) all appear less precise than the above gauge-derived result. Dr. Mainville suggested that the above estimate would provide the best possible approximation for use in an update of the preproject relation (Mainville, 2001).

3.4 Review of Ice Retardation Estimates

3.4.1 The Currently Adopted Method

Under ice conditions, the Oswego stage-discharge relationship was invalid due to the retardation effect of ice on river outflows, and actual preproject outflows were originally determined using stage-discharge relationships for locations in the International Reach Section of the St. Lawrence River. Attempts were made to develop relationships for the Upper St. Lawrence River to permit estimation of preproject levels and outflows given postproject conditions. Studies were undertaken by the Committee on Levels and Flows in 1956 that related ice retardation with air temperature. Favourable results were obtained from January to March in a direct correlation between antecedent air temperatures observed at Ogdensburg, NY (the closest weather station at the time to Galop Rapids), and observed ice retardation effect (expressed in percent). Monthly values of ice retardation were determined for the period 1912-1955. The CoL&F (1956) reported that best results were obtained by correlating the cumulative observed ice retardation and the cumulative observed air temperatures at Ogdensburg, NY (expressed in terms of the sum of the monthly mean temperatures from December to the current month). An ice retardation factor, K, was determined as follows:

$$K = 1 - \frac{Q_{pp} - Q_{recorded}}{Q_{pp}} \qquad (9)$$

where: Q_{pp} = outflow from open-water Oswego preproject stage-flow relation, and
$Q_{recorded}$ = outflow from preproject stage-flow relationships in International Rapids Section.

Here, ice retardation is defined as:

$$d = -Q_{pp}\left(\frac{1}{K} - 1\right) \qquad (10)$$

where: d = ice retardation (m^3/s),
Q_{pp} = open-water preproject outflow (estimated using Equation 2) (m^3/s), and
K = ice retardation factor.

The computed preproject open-water flow is corrected for ice retardation in practice by reducing flows determined with Equation 2 by the amount given by Equation 10.

The accuracy of this estimation was shown using a continuous computation of Lake Ontario levels and flows from May 1933 through December 1952. Table 2 shows the average difference of computed to observed Lake Ontario level, and the greatest positive and negative difference for each of the winter months in question through the test period. Recall that ice retardation is assumed to be negligible in December and April.

In practice, it is no longer possible to obtain a continuous record of daily air temperatures at Ogdensburg, NY, since National Climatic Data Center observers no longer take weekend readings (since December 1995). Therefore, daily maximum and minimum air temperatures from Cornwall's weather station located at the Water Purification Plant are now used for this computation (since December 1999). A preliminary study demonstrated that the average daily air temperatures at Ogdensburg appeared to be approximately 1.0 °C warmer than those at Cornwall (Young, 2001). Hence, from January 2000 through March 2001, 1.0 °C was added to the mean air temperatures at Cornwall to arrive at estimated mean temperatures at Ogdensburg.

Table 2: Estimated Limits of Accuracy for the COL&F (1956) Method

MONTH	AVERAGE DIFFERENCE (cm)	MAXIMUM POSITIVE DIFFERENCE (cm)	MAXIMUM NEGATIVE DIFFERENCE (cm)
December	0.55	2.44	-2.23
January	0.73	2.23	-3.02
February	0.37	2.77	-4.18
March	0.03	4.24	-4.45
April	0.43	5.00	-3.26

3.4.2 Effect of Using Cornwall Air Temperatures

In order to estimate the effect of using corrected Cornwall air temperatures to perform the ice retardation estimates with the COL&F (1956) tables developed for Ogdensburg, a sensitivity analysis was undertaken. Historic monthly mean air temperatures were tabulated for both stations from December 1954 to March 1995 due to the near-complete records at both locations during this time. The average difference between Ogdensburg and Cornwall monthly mean air temperatures for each of the four winter months was found to be 0.6 °C. However, note that the standard deviation was at least 0.7 °C, and a maximum difference of 4.6 °C was observed. Therefore, it was not possible to decisively conclude whether or not the Cornwall temperatures should be corrected by as much as 1.0 °C.

Consequently, preproject levels and outflows were estimated each month from January to March 2001 for air temperature corrections of 0, 0.5, 0.6, 0.7, and 1.0 °C (see Table 3). As can be seen, a change in the correction factor of 1 °C results in a change in the estimated outflows on the order of 1%. Though this difference is minor, the effect should be minimized. Therefore, it was proposed that Cornwall air temperatures be corrected by +0.6 °C henceforth to estimate Ogdensburg air temperatures. Since December 2001, 0.6 °C has been added to the mean air temperatures at Cornwall to arrive at estimated mean temperatures at Ogdensburg. Further, it is recommended that additional review of this correction factor (i.e., using all available years of records) be undertaken if the Cornwall record continues to be used in the future.

Table 3: Estimates of Preproject Conditions for Various Air Temperature Correction Factors

MONTH	CORRECTION FACTOR (°C)	K	PREPROJECT LEVEL (m)	PREPROJECT FLOW (m^3/s)
January 2001	0.0	0.977	74.58	6163
	0.5	0.984		6208
	0.6	0.985		6214
	0.7	0.986		6220
	1.0	0.989		6239
February 2001	0.0	0.943	74.61	6003
	0.5	0.945		6016
	0.6	0.946		6022
	0.7	0.947		6029
	1.0	0.949		6042
March 2001	0.0	0.969	74.71	6357
	0.5	0.975		6396
	0.6	0.976		6403
	0.7	0.977		6409
	1.0	0.980		6429

3.4.3 Search for Other Methods

It is well accepted that ice formation, growth, and breakup are all strongly related to two interrelated factors: air temperature and surface water temperature. The other technique originally put forth to estimate ice retardation under preproject conditions was that of the U.S. Lake Survey (1957). This method is based on the use of (air temperature) freezing degree-days since the date of preproject freezeup (see later for a full description). The existing method does not require estimates of freezeup dates.

Many estimation techniques for freezeup dates are based solely on water temperature determinations, however. Anticipated climate change investigations, nonetheless, would likely revert back to air temperature simulations in order to model water temperature. More sophisticated models are considered impractical due to the need for detailed weather data, and parameters needed for estimating energy fluxes due to shortwave radiation, evaporation, and convection cannot be accurately determined (Shen & Yapa, 1985). Officials at the St. Lawrence Seaway Management Corporation looked at using freezing degree days to estimate the freezeup date along various reaches of the St. Lawrence River, with limited success (McKercher, 2001). To help evaluate the U.S.L.S. method, attempts were made to estimate freezeup dates using several techniques.

Due to the availability of various related data in recent years (and the corresponding sparsity in the early half of the 20th century), an investigation of ice roughness in relation to freezing degree days (FDDs) was undertaken for the period from 1961-2000. It is recognized that ice conditions have changed since project construction (due to changes in the flow regime and, subsequently, changes to the hydraulic thermodynamics within the river), but insufficient data are available for an initial analysis using preproject conditions. The apparent roughness factor, N, was used since it can be readily computed from known parameters (i.e., actual water levels at Kingston and Long Sault, and Lake Ontario outflow), plus it provides a good estimation of ice retardation potential, and offers insight into freezeup and breakup. N is the ratio of the head losses from Kingston to Long Sault under ice conditions to those computed for the same Kingston level and flow with open water. Attempts made to find a relationship between N and FDDs using both daily and quarter-monthly data were unsuccessful. However, some observations are noteworthy. It appears that significant roughness is noticed only after 200 cumulative Celsius FDDs (from December 1). However, this does not demonstrate that 200 CCFDDs is the threshold limit for freezeup. Smooth ice covers may be formed at either higher or lower values, and, during severe conditions, freezeup may result in large increases in roughness values at other CCFDDs. Other comparisons included roughness versus air temperature, year, day, and quarter-month, as well as determinations of the maximum annual FDD to corresponding roughness, and the maximum annual roughness to corresponding FDD. It appears that none of these parameters are significantly inter-related.

Barrie Bonsal and Terry Prowse of Environment Canada's National Hydrology Research Institute in Saskatoon recently presented a paper on using "isotherms" to estimate freezeup dates on small northern rivers (Bonsal & Prowse, 2001). Isotherms are the date on which the moving average air temperature passes a certain value. For example, the -5.9 °C isotherm in this study was defined as the Julian Day on which the 31-day terminal (i.e., the average from the past 31 days) moving mean air temperature fell below -5.9 °C. A terminal moving average was used as it proves most useful for future forecasting purposes. One of the goals of this investigation is to be able to estimate the date of first ice effect given a different air temperature distribution, for any year (for use in future climate change sequence studies, or to predict freezeup dates during postproject years assuming preproject hydraulic thermodynamics). The latter example is illustrated later in this report.

3.4.4 Investigation of Isotherms

It was decided that a similar investigation may yield useful information with regard to freezeup and breakup dates along the St. Lawrence River. To this end, freezeup and breakup dates at the Beauharnois Canal and the International Reach of the St. Lawrence River (defined as the forebay of the Moses/Saunders hydropower plant upstream to Long Sault Dam) as provided by Hydro Quebec and Ontario Power Generation, respectively, plus the date of first ice effect (as determined by in-house roughness monitoring for the Long Sault to Morrisburg reach) were plotted. Since such data were not collected prior to the hydropower projects' completion dates, only the period from December 1960 to present was considered in the initial analysis. Note that both freezeup and breakup dates are subjective observations, based on visual assessment of ice conditions. Discussion here will be limited to isotherms in relation to date of first ice effect between Long Sault and Morrisburg. Although air temperature data at Ogdensburg, NY, has traditionally been used for such assessments, due to the sparsity of data from this location since 1995, it was decided to use Cornwall daily mean air temperatures for this analysis. Keep in mind that Cornwall's mean daily air temperatures are approximately 0.6 °C lower than Ogdensburg on average.

As shown on Figure 1, there appears to be a convincing relationship between the -5.5 °C 31-day isotherm and the date of first ice effect. Note, too, that, on average, this isotherm occurred on or about the day of first effect (i.e., often on the same Julian date). All years of record had a -5.5 °C isotherm. Other similar isotherms did not appear to have as strong a relationship with the date of first ice effect. Also, note that there has been a gradual upward trend in both series (as demonstrated by the regression estimates shown), which may suggest warmer fall temperatures and later freezeup dates brought about by climate change.

A linear regression using the -5.5 °C isotherm to predict the date of first ice effect was undertaken using the general equation:

$$JD_{1fx} = A(-5.5 \text{ iso.}) + B \qquad (11)$$

Where:

JD_{1fx} = Julian date of first ice effect,
-5.5 Iso. = Julian date of the -5.5 °C isotherm, and
A and B = regression constants.

This analysis resulted in an R^2 (the coefficient of multiple determination [Draper & Smith, 1981], a measure of how well each data series fit one another) of 0.69 and a t-statistic of 9.3. A regression rule of thumb (known as the "sequential F-test", made on the t-statistic [Draper & Smith, 1981]) suggests that, if an independent variable is significant to a regression, the absolute value of its x-coefficient to standard error of the x-coefficient (i.e., the t-statistic) will be greater than four.

Next, in an effort to explore other potential relationships and help explain the remaining difference in the two series, cumulative Celsius freezing degree days (from December 1) were plotted against dates of first effect (see Figure 2) and outflows (means from the first quarter-month of December as well as the first two quarter-months of December) were plotted against the residual error of the date of first effect based on the -5.5 °C isotherm (see Figure 3). One might expect that the date of first effect could be related to the number of FDDs, and that freezeup might occur later during periods of high flow. However, no strong relationship was found in either case.

It was decided to plot the distributions of both 31-day terminal moving average air temperature and freezing degree days for each season against Julian date. A typical plot is shown for the Winter of 1964-65 as Figure 4. The dates of freezeup and first effect were superimposed on these curves. Again, no obvious links were found.

At this point, it should be reiterated that one of the goals of this investigation is to be able to estimate the date of first ice effect given a different air temperature distribution, for any year (for use in, among other things, future climate change sequence studies). To this end, three models were put forth to estimate the dates of first effect (denoted JD_{1fx}) (see Figure 5):

1) estimated based on the apparent trend in the data since 1960 due perhaps to climatic change (i.e., JD_{1fx} = 0.2676(Year-1968)),

2) the average Julian date of first effect (i.e., JD_{1fx} = 3.7), and

3) transformed from the -5.5 °C isotherm by the mean difference (i.e., JD_{1fx} = (-5.5 Iso.) - 0.5).

Clearly, the best fit is afforded by transformation of the -5.5 °C isotherm by the mean difference of -0.5 days in this case. Again, this relation yields an R^2 of 0.69 and a t-statistic of 9.3.

It is important to note that this relation is only valid for conditions experienced since the construction of the St. Lawrence Hydropower and Seaway Project and is for ice formation within only the Moses/Saunders Dam forebay. Preproject conditions can be expected to alter this relation somewhat. Since the control section in question in this case was at the Galop Rapids (much further upstream), later freezeup dates and shorter periods of ice cover would have been experienced (since ice forms in the lower reaches first).

3.4.5 Preproject Isotherm Study

Unfortunately (as noted earlier) ice observations were not routinely made along the River prior to

1953, at which time the U.S.L.S. and the Hydroelectric Power Commission of Ontario began keeping records (U.S.L.S., 1957). The most complete records found were those from the Aluminum Corporation of America (ALCOA), wherein measurements of forebay water temperatures were kept for the Massena Power Plant dating back to 1926. Unfortunately again, there appeared to be no relationship between freezeup on the power pool and that on the River. The U.S.L.S. considered that the immediate effect of ice is to reduce the Lake Ontario outflow and lower downstream river stages. Using the difference in flow estimates as given by the Oswego and Lock 25 rating curves, they estimated the commencement of ice effect as that day when there was a sudden jump in the difference, followed by consistent differences afterwards (to eliminate wind events). Estimates are given for the 1934-35 to 1951-52 ice seasons. See Table 4 of U.S.L.S., 1957 for more details.

Again, daily air temperatures at Cornwall have only been recorded since 1950. The Ogdensburg record extends back to 1926, but there is a minor sparsity problem with this record. Nonetheless, it was decided to use the Ogdensburg daily air temperature record for this analysis. Missing values were filled in with data from the Morrisburg daily air temperature record (which dates back to 1913).

An attempt was made to determine which isotherm offered the best relationship with the estimated date of first ice effect for each of these 18 ice seasons.

From Figure 6, it can be seen that a similar, though weaker, relationship appeared to exist between the -5.9 °C isotherm and the date of first ice effect for these preproject years. Unfortunately, the 1936-37 season proved too warm, and the -5.9 °C isotherm was not reached. This left 17 sets of data to perform the analysis with. Again, apparent upward trends existed in both sets of data, reiterating the possibility of climate change effects (even in the middle third of the 20th century). Here, the linear regression R^2 value fell to 0.50, with a t-statistic of 3.9. The -5.9 °C isotherms were found to, on average, occur a couple of days prior to the date of first effect (an average of 1.7 days earlier). This suggested that the best available model to estimate date of first ice effect under preproject conditions would be:

$$JD_{1fx} = JD_{-5.9iso}. + 1.7 \text{ (days)} \qquad (12)$$

Plots of the estimated dates of first ice effect to the actual dates (Figures 7 & 8) demonstrate that this is a fair relationship. Therefore, this model was used in later determinations to estimate the date of first ice effect under preproject conditions during postproject years, and is proposed as a satisfactory model for use in such determinations for future years.

3.4.6 The U.S.L.S. (1957) Method for Estimating Preproject Ice Retardation

As stated previously, the method put forth by the COL&F in 1956 was meant as a “satisfactory” technique which could be used until a new improved procedure could be developed. Eleven months later, the U.S. Lake Survey of the Corps of Engineers presented an alternative method based on degree days, “as a solution to the problem of determining the effects of ice on the flow of the St. Lawrence River ... to improve the system of determining the preproject flows ...”

(U.S.L.S., 1957). However, this method was not adopted for use by the ISLRBC (perhaps due to the suspected perception that only modest improvements would stem from this more complex procedure). The COL&F (1956) method remains in use by the ISLRBC to this day. With the advent of modern computer spreadsheets, it is now possible to make ready use of more sophisticated techniques such as that proposed by the U.S.L.S. authors. A comparison of the two methods was undertaken as the next phase of the current study. For a summary of the COL&F (1956) method, please see earlier.

The U.S.L.S. study presented three factors affecting the growth of ice:

1) The main factor is the loss of heat from the layer of water about to turn into ice due to conduction into the air. As such, for relatively constant air temperatures, the rate of growth of an ice sheet is strongly dependent on FDDs.

2) In a flowing river, the temperature of the water moving under the ice sheet plays an important part in limiting the ice thickness, as the addition or loss of heat to a layer of water about to turn into ice is considerable.

3) Atmospheric humidity and radiation are only important in the initial formation of ice. Their effects may be neglected with regard to the prediction of the rate of growth of an ice sheet.

The study used data from the period 1934-1952, during which time consistent channel conditions existed (in 1933, a self-registering gauge was established at Oswego to record continuous Lake Ontario levels and Gut Dam removal was completed in January 1953). Further, it was noted that, each year, ice cover between Ogdensburg and Lake Ontario tends to be a complete ice sheet, but, from Ogdensburg to the Galop Rapids, variable ice covers were observed. Hence, it was assumed that ice retardation from Lake Ontario to Ogdensburg was "relatively constant" each year (no mention is given to the duration of this ice, however). Ice conditions for the Ogdensburg-Galop Rapids reach were broken into two categories: Category I = complete ice sheet; Category II = greater than normal restriction (i.e., such as that caused by hanging ice dams, anchor ice, and/or frazil ice). Category I conditions were assumed to occur if the recorded river levels differed from the river levels which would have occurred under open-water conditions (computed using Oswego levels and the measured outflow) by less than 0.30 ft. (9.1 cm) at Ogdensburg. Backwater calculations demonstrated that a 1.00 ft. (30.5 cm) retardation effect at Ogdensburg equates to a 0.96 ft. (29.3 cm) retardation at Oswego, if the reach between is ice-free.

FDDs were computed using the mean of the daily maximum and minimum U.S. Weather Bureau air temperatures at Ogdensburg. Canadian Department of Transportation, Meteorological Division, readings at Brockville were used to fill in the record. Degree days were defined as degree-Fahrenheit days below freezing (32 °F). FDDs were computed from the estimated day of first effect to the estimated day of last effect. As stated previously, records on dates of freezeup were not kept, so dates of first ice effect were estimated (see earlier for method). The date of last ice effect was assumed to be the day that the average daily temperature rose permanently above freezing.

Results indicated that cumulative ice retardation, Q_i, in tcfs-days, could be obtained from computing FDDs (from day of first effect) based on the following (see Figure 9):

Category I $\quad Q_i = 80.5\ FDD^{1.25}$ (Imperial units) (13)

Category II $\quad Q_i = 54.2\ FDD^{1.42}$ (Imperial units) (14)

To apply these results, it was recommended that the Category II curve be used when the following two indicators are noted:

1) The average degrees below freezing, T_a, (i.e., the average temperature below freezing from first ice to last ice) minus one standard deviation of the daily air temperatures from first ice to last ice, σ, equals or exceeds 3.2 °F (i.e., if $T_a - \sigma \geq 3.2$ °F (1.8 °C)), and

2) There is a period (starting from the day of first ice effect) of 400 consecutive cumulative Fahrenheit FDDs (~222 CCFDDs) without a day with an above-freezing daily mean temperature.

The U.S.L.S. compared this method to that of the COL&F (1956) using total annual ice retardations, converted into the effect on Lake Ontario levels measured in feet. Findings indicated that the average cumulative seasonal error from 1934 to 1952 was reduced from 0.11 ft. (3.4 cm) to 0.06 ft. (1.8 cm). However, the minimum and maximum seasonal errors were larger (-0.20 ft. (-6.1 cm) in lieu of -0.19 ft. (-5.9 cm) and 0.28 ft. (8.5 cm) in lieu of 0.23 ft. (7.0 cm), respectively). Note that, in practice, monthly mean ice retardations are estimated, so monthly comparisons are generally more representative of the variability possible throughout the season (e.g., such as when the ice retardation decreases due to, say, a “January thaw”, then returns in February or March following a period of cold weather). A U.S.L.S. (1957) comparison for the months of January, February, and March showed minor improvements in average cumulative monthly errors (0.02, 0.04, and 0.04 ft. (0.7, 1.4, and 1.3 cm) in lieu of 0.03, 0.06, and 0.06 ft. (0.8, 2.0, and 1.8 cm), respectively).

A separate analysis was performed recently whereby individual monthly ice retardations were estimated for each method using data from 1934 through 1952. In this way, the cumulative effect of any trend in monthly errors was not carried forward. The objective here was to look at individual errors for each month of the winter. Note that Oswego levels were not adjusted for the effect of Gut Dam, since ice retardation estimates were compared to actual values. The COL&F (1956) ice retardation estimates were calculated using actual Lake Ontario levels (and not preproject ones). Actual ice retardation values (taken from Environment Canada Cornwall’s database) were calculated as the difference between the outflows resulting from the open-water Oswego relationship (Equation 2), and the recorded outflows (IGLLB, 1964)). Mean daily Ogdensburg air temperature values (filled in with Morrisburg data as necessary) were used in the determination. Retardations were considered from December to April each season. Though the COL&F (1956) method precludes estimates in December and April, the U.S.L.S. (1957) method does enable potential estimates in each of these “fringe” months.

Since the U.S.L.S. method requires knowledge or estimation of the dates of first and last ice effects, two separate determinations were considered for this method. The first one (Method 1) made use of the dates of first ice effect estimated using the approach used in 1957 (see earlier). The second (Method 2) made use of the model proposed earlier (Equation 12) in order to test the validity and accuracy of this relationship. For both approaches, the dates of last ice effect were estimated using the method proposed by U.S.L.S. (1957). That is, the date of last ice effect was presumed to be the day upon which the mean daily air temperatures generally rose above freezing for an extended period of time (normally four days or longer). In practice, Method 2 would be used since, for future (and all postproject) years, the hydraulics of the river have changed such that dates of first ice effect under a preproject hydraulic regime cannot be estimated from actual ice conditions now.

Figure 10 shows that the U.S.L.S. (1957) methodology affords better estimates, in general. Results with regard to the individual errors in terms of levels and flows are given in Tables 4 and 5, respectively. Of the 18 seasons considered, ice retardations could be estimated for all but two using the CoL&F (1956) procedure in the current study. All estimates could be determined for U.S.L.S. (1957) Method 1, and only the 1936-1937 season values could not be estimated for Method 2 (since the -5.9 °C isotherm was not reached that season).

As can be seen, results of these analyses suggested that the U.S.L.S. (1957) Method 2 offered a worthy approach for future consideration, and it appears that it could provide meaningful improvements over the CoL&F (1956) approach currently in use.

Table 4: Monthly Errors in Preproject Ice Retardation Estimates (cm)

	DECEMBER			JANUARY			FEBRUARY			MARCH			APRIL		
	CoL&F	USLS1	USLS2	CoL&F	USLS1	USLS2	CoL&F	USLS1	USLS2	CoL&F	USLS1	USLS2	CoL&F	USLS1	USLS2
Mean	0.1	0.1	-0.1	-0.2	-0.6	-0.7	-1.6	-0.9	-0.6	-1.3	-0.1	0.0	0.0	0.0	0.0
RMSE	0.3	0.3	0.4	1.4	1.1	1.2	1.8	1.4	2.0	1.9	0.9	1.0	0.0	0.0	0.0
Min	0.0	-0.2	-1.1	-2.4	-2.9	-2.8	-4.8	-3.9	-4.6	-4.4	-1.3	-1.3	0.0	-0.1	-0.1
Max	1.1	1.0	0.7	2.3	1.0	1.1	0.6	2.1	4.2	2.3	2.3	2.3	0.0	0.0	0.0

Table 5: Monthly Errors in Preproject Ice Retardation Estimates (m^3/s)

	DECEMBER			JANUARY			FEBRUARY			MARCH			APRIL		
	CoL&F	USLS1	USLS2	CoL&F	USLS1	USLS2	CoL&F	USLS1	USLS2	CoL&F	USLS1	USLS2	CoL&F	USLS1	USLS2
Mean	-6	4	-4	-11	-45	-50	-119	-67	-46	-99	-7	0	0	0	0
RMSE	20	19	27	105	81	86	136	103	146	142	70	75	0	1	1
Min	0	-17	-80	-176	-213	-206	-358	-292	-341	-326	-94	-97	0	-6	-5
Max	80	72	54	170	74	80	48	156	309	170	170	170	0	0	0

3.4.7 Effect of Change in Ice Retardation Methodology on Levels and Flows

It appears that the U.S.L.S. (1957) methodology, coupled with the date of first ice effect estimator model (i.e., Equation 12), provides significant improvements in accuracy over the CoL&F (1956) approach currently used. In order to estimate the effect that switching methods (i.e., from the latter to the former) might have on the estimation of preproject levels and flows during winter months, an analysis was performed for the winter periods from 1959-1960 to 1994-1995. Here, the magnitude of ice retardations were computed for each method in terms of both levels and outflows for Lake Ontario. Again, the Ogdensburg daily mean air temperature record was used (filled in where necessary with data from the Morrisburg station). Note that ice retardation factor, K, values for the CoL&F approach (as well as the monthly mean recorded Ogdensburg air temperatures used to determine them) were taken from an in-house database. For the U.S.L.S. approach, dates of first ice effect were again estimated with Equation 12 (after determination of the -5.9 °C isotherms), and the dates of last ice effect were again assumed to be the day each year whereon the mean daily temperature at Ogdensburg rose above freezing for an extended period of time (i.e, at least four days, without a subsequent period of well-below freezing temperatures). Though the analysis again encompassed individual monthly determinations from December to April each season, this time no ice retardation resulted for any month of April for the entire period used. There were, however, 12 instances where ice was indicated during December in the 36 years used using the U.S.L.S. approach. Remember, the CoL&F method precludes December and April ice retardation estimates. Keep in mind that this analysis did not illustrate the cumulative effect that any potential trends in monthly errors in preproject ice retardations would have, since only individual monthly ice retardations were considered.

From Figure 11, it can be seen that the results from the two methods are correlated. However, it appears that the CoL&F approach results in higher ice retardations the majority of the time. Given that the U.S.L.S. method is more accurate, this suggests that the method currently used may have a tendency to overestimate preproject ice retardations.

Results with regard to the differences (i.e., U.S.L.S. - CoL&F) between methods in terms of levels and flows are given in Tables 6 and 7, respectively.

Table 6: Monthly Estimates and Differences in Preproject Ice Retardations (cm)

	DECEMBER			JANUARY			FEBRUARY			MARCH			APRIL		
	CoL&F	USLS	Diff.	CoL&F	USLS	Diff.	CoL&F	USLS	Diff.	CoL&F	USLS	Diff.	CoL&F	USLS	Diff.
Mean	0.0	0.2	**0.2**	2.7	2.6	**0.0**	5.2	3.5	**-1.6**	2.8	1.1	**-1.7**	0.0	0.0	**0.0**
Std. Devn.	0.0	0.5	**0.5**	3.0	2.9	**1.0**	2.3	2.5	**2.7**	1.6	1.2	**1.1**	0.0	0.0	**0.0**
Min	0.0	0.0	**0.0**	0.0	0.0	**-2.8**	0.0	0.7	**-5.3**	0.0	0.0	**-3.7**	0.0	0.0	**0.0**
Max	0.0	2.4	**2.4**	9.9	10.5	**1.8**	10.3	5.3	**5.5**	5.7	4.8	**0.4**	0.0	0.0	**0.0**

Table 7: Monthly Estimates and Differences in Preproject Ice Retardations (m^3/s)

	DECEMBER			JANUARY			FEBRUARY			MARCH			APRIL		
	CoL&F	USLS	Diff.	CoL&F	USLS	Diff.	CoL&F	USLS	Diff.	CoL&F	USLS	Diff.	CoL&F	USLS	Diff.
Mean	0	18	**18**	199	197	**-3**	385	264	**-121**	210	85	**-126**	0	0	**0**
Std. Devn.	0	40	**40**	223	219	**78**	169	187	**198**	120	86	**80**	0	0	**0**
Min	0	0	**0**	0	0	**-205**	0	51	**-395**	0	0	**-277**	0	0	**0**
Max	0	178	**178**	739	786	**134**	709	769	**409**	423	361	**30**	0	0	**0**

As can be seen, adoption of the U.S.L.S. (1957) method can be expected to result in preproject level estimations which, on average, could be approximately 2 cm lower than would currently be predicted (e.g., for the months of February and March) equating to an increase in preproject outflow estimations on the order of 120-130 m^3/s. However, the difference would generally be much less during the remaining winter months.

In summary, the U.S.L.S. (1957) method has been demonstrated to offer better estimates of preproject ice retardations over the existing method (CoL&F, 1956). It is proposed that the estimation of preproject ice retardations be accomplished by use of the methodology proposed in 1957 by the United States Lake Survey.

3.5 Development of a New Preproject Relationship

As outlined in Section 3.2.1, it is believed that the development of Equation 2 appears reasonable, and it is believed that the authors likely fit the adjusted Oswego levels data directly to the computed flows in the 1953-1955 open-water periods. After thorough review of this existing equation, it was recommended that a new relationship take the same form as the old. As discussed in Section 3.3.1, modern techniques resulted in a revised estimate of the differential crustal movement rate between Oswego and the former Galop Rapids control section (i.e., 0.14 m/century in lieu of the currently adopted 0.17 m/century). Further, since benchmarks have been most recently brought to a common datum centred on the year 1985 (i.e., resulting from the adoption of IGLD 1985), the second term of the new relationship should take the form 0.0014(Year-1985). Finally, the exponent of the new equation was forced to 1.5 as per the currently adopted relationship.

Using the 16 monthly mean outflows and unadjusted Oswego levels for the open-water months of May to November from May 1953 to June 1955, inclusive, a stage-discharge equation was developed by multiple linear regression. The open-water preproject stage-discharge equation proposed for future use by the ISLRBC is:

$$Q_{pp} = 555.823\ (\text{Oswego Level} - 0.0014\ (\text{Year}-1985) - 69.474)^{1.5} \qquad (15)$$

where:

Q_{pp} = flow (m^3/s), and

Oswego Level is given in metres on IGLD 1985.

3.5.1 Comparison of New Relationship to Old Relationship

As demonstrated in Figure 12, both relationships fit the dataset used in their developments very well. Both result in excellent R^2 values of 0.997, and the new form offers just a slightly improved t-stat of 71.1 (in lieu of 71.0). The new relationship resulted in somewhat improved estimates in terms of residuals, however. The maximum and minimum residual were 30.9 and -36.3 m^3/s (in lieu of 40.9 and -50.6 m^3/s), the root mean squared error (RMSE) was 24.4 m^3/s (in lieu of 27.1 m^3/s), and the mean residual fell to just 0.1 m^3/s from -1.4 m^3/s.

In order to determine how sensitive the relationship was to the relative crustal movement rate, a separate relationship was developed using 0.17 m/century (the value used in the current relationship). This yielded the following open-water preproject stage-discharge relationship:

$$Q_{pp} = 556.129\,(\text{Oswego Level} - 0.0017\,(\text{Year}-1985) - 69.485)^{1.5} \quad (16)$$

This relationship again resulted in an excellent R^2 value of 0.997, and just a slightly lower t-stat of 70.9. The maximum and minimum residual were 30.3 and -37.4 m^3/s, the RMSE was 24.4 m^3/s, and the mean residual was -0.9 m^3/s.

Next, in order to compare the old and new relationships over a broad range of conditions, two separate comparisons were undertaken. The first considered the individual monthly mean estimates for the open-water period of May to November for the preproject years 1900-1955. Since recorded Oswego levels were used, the cumulative impact of routing errors in estimation was not considered. Further, since these relationships are valid only for the period after Gut Dam was removed, it was necessary to adjust open-water Oswego levels for the effect of Gut Dam from November 1903 to November 1952. The dam was estimated to have raised Lake Ontario levels by 4 to 4.75 inches (10.2 to 12.1 cm) dependent on flowrate (ILOBOE, 1958). Therefore, Oswego levels were adjusted linearly depending on the flowrate (from 10.2 cm at a flowrate of 4810 m^3/s to 12.1 cm at a flowrate of 8640 m^3/s).

As expected, both relationships yielded excellent results. The new relationship again resulted in somewhat improved estimates in terms of residuals. The maximum and minimum residual were 162.4 and -120.5 m^3/s (in lieu of 177.4 and -116.4 m^3/s), the RMSE was 39.3 m^3/s (in lieu of 43.8 m^3/s) and the mean residual was 4.3 m^3/s (in lieu of 5.4 m^3/s). Hence, the net effect of changing the relationship used would likely be almost negligible for both levels and flows.

Finally, a second comparison was undertaken for the entire period from 1900-1995, using "Basis of Comparison" (BOC) supply conditions. This BOC provides a benchmark dataset of consistent input parameters from which a variety of scenarios can be compared with regard to levels and flows during the current IJC Lake Ontario - St. Lawrence River Study. A continuous quarter-monthly series of Lake Ontario levels and flows were computed for the entire period from 1900-

1995 using the stage-discharge constant for Lake Ontario and the different preproject stage-discharge relationships. Since estimated levels and flows for each period depend upon the levels computed for the previous period, cumulative effects could be assessed. However, such estimates tend to be self-adjusting over time (for instance, if preproject outflow is overestimated for one quarter-month, the subsequently lower preproject level estimate the following quarter-month results in a lower corresponding outflow estimate, etc., such that cumulative errors tend to dampen quickly to negligible values).

Summaries of the effects of adopting the new proposed relationship (Equation 15; denoted "New_{14}") to replace Equation 2 are given in Tables 8 and 9 in terms of levels and flows, respectively. For comparison, results are also shown for Equation 16 A ("New_{17}")to provide a measure of the effect that a change in crustal movement rate has.

Table 8: Effect of Changing Relationships on Levels - BOC Period 1900-1995

	WATER LEVELS (m IGLD 1985)			CHANGE FROM CURRENT RESULT (cm)	
	"OLD"	"NEW_{14}"	"NEW_{17}"	"NEW_{14}"	"NEW_{17}"
Mean	74.87	74.87	74.86	-0.4	-0.6
Maximum	76.08	76.08	76.10	2.0	2.0
Minimum	73.78	73.74	73.74	-4.0	-4.0
Standard Deviation	0.43	0.44	0.44	1.2	1.2

Table 9: Effect of Changing Relationships on Flows - BOC Period 1900-1995

	OUTFLOWS (m^3/s)			CHANGE FROM CURRENT RESULT (m^3/s)	
	"OLD"	"NEW_{14}"	"NEW_{17}"	"NEW_{14}"	"NEW_{17}"
Mean	7020	7020	7020	0	0
Maximum	9490	9480	9490	50	40
Minimum	4600	4620	4610	-60	-70
Standard Deviation	862	858	858	15	14

Therefore, a change in the relationship used to estimate preproject levels and outflows would not affect the average quarter-monthly determinations (to the centimetre and cubic metre per second, respectively). The largest impacts expected would be on the order of 4 cm and 70 m^3/s, respectively.

Although the above analyses demonstrate that there is little or no change in the estimates derived from the relationships, it is proposed that the ISLRBC adopt Equation 15 for use in the determination of preproject levels and flows. It has been shown that a small improvement in accuracy is available, and it is believed that a relative crustal movement rate of 0.14 m/century at the former Galop Rapids relative to Oswego is more accurate that the 0.17 m/century rate used in the current relationship.

4 CONCLUSIONS

A comprehensive review of the hydraulic relationship for the Lake Ontario preproject outlet control section that existed at the head of the Galop Rapids near Cardinal, Ontario was undertaken. No known deficiencies in the method currently used to estimate the outflows under preproject outlet conditions were found. Nonetheless, an updated preproject outflow relationship was developed that offers slightly improved accuracy. The current relationship was developed in the mid-1950s using an earlier datum and English units, and no known reference is available describing its development. Therefore, the following open-water stage-discharge equation is proposed for use in studies and operation by the ISLRBC:

$$Q_{pp} = 555.823\ (\text{Oswego Level} - 0.0014\ (\text{Year}-1985) - 69.474)^{1.5}$$

where:

Q_{pp} = flow (m^3/s), and
Oswego Level is given in metres on IGLD 1985.

The above proposed relationship reflects improvements in the estimation of the relative crustal movement rate between the former Galop Rapids section and Oswego, NY. Further, the above relationship was developed using modern linear regression software whereas it is unknown how the currently adopted method was developed in the 1950s.

Finally, a comprehensive review of the current method used (i.e., CoL&F, 1956) to estimate ice retardations for use with the above relationship demonstrated that a previously proposed approach (U.S.L.S., 1957) yields improved estimates. It is proposed that preproject ice retardation estimates under the postproject hydraulic regime be determined using the approach detailed by the U.S. Lake Survey in their August 1957 report. In practice, results from the above (open-water) relationship will be reduced by an amount equivalent to the ice retardation estimated in order to arrive at estimates of preproject flows in the winter. Dates of first ice effect should be estimated using Equation 12, coupled with the use of daily mean Cornwall air temperatures for determination of the -5.9 °C isotherms. Cornwall daily mean air temperatures should be corrected by +0.6 °C to simulate estimation of Ogdensburg air temperatures. Dates of last ice effect should be estimated as the day upon which the daily mean air temperature at Cornwall rises above freezing for a prolonged period of at least four days, with no significant period of well-below freezing temperatures thereafter.

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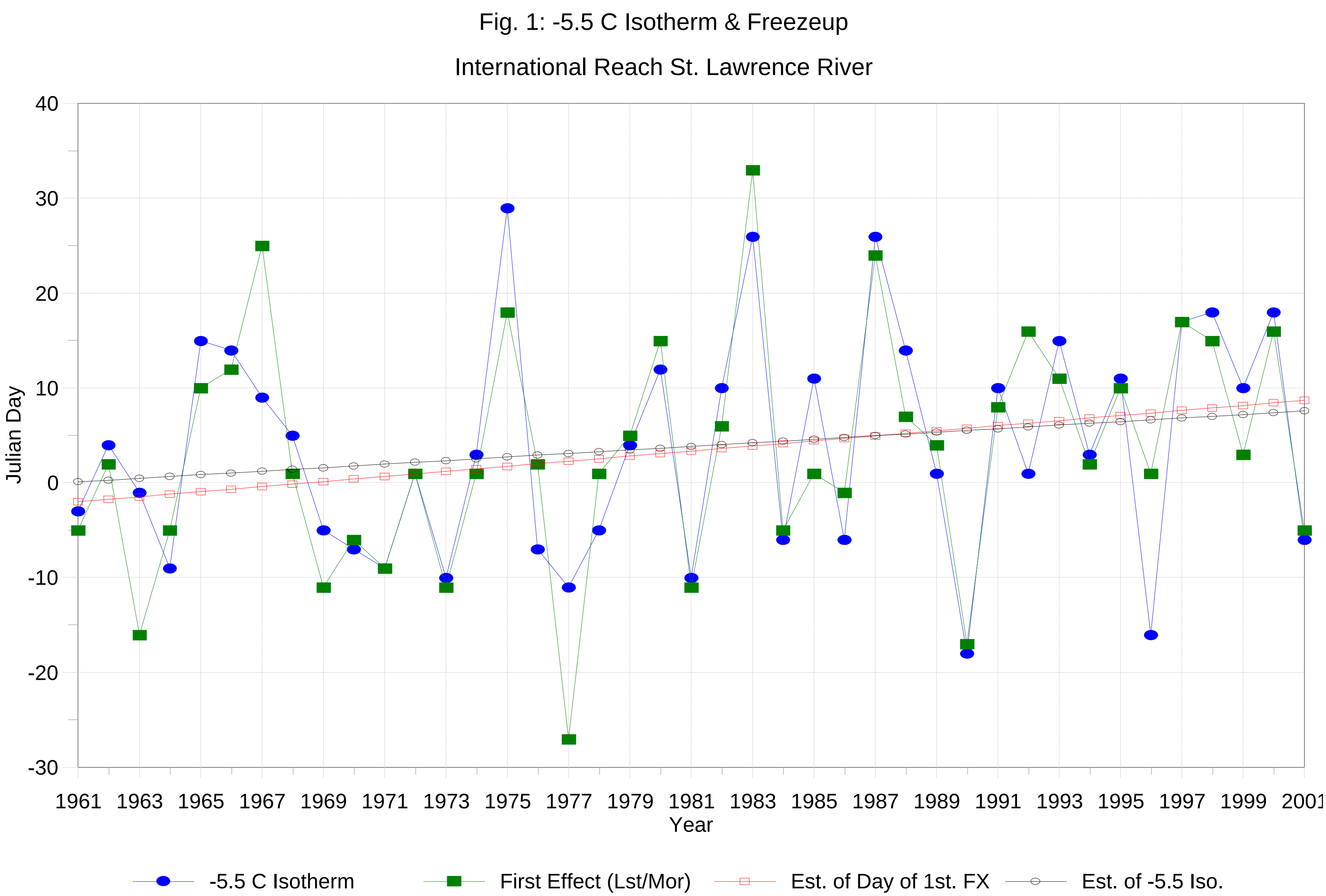
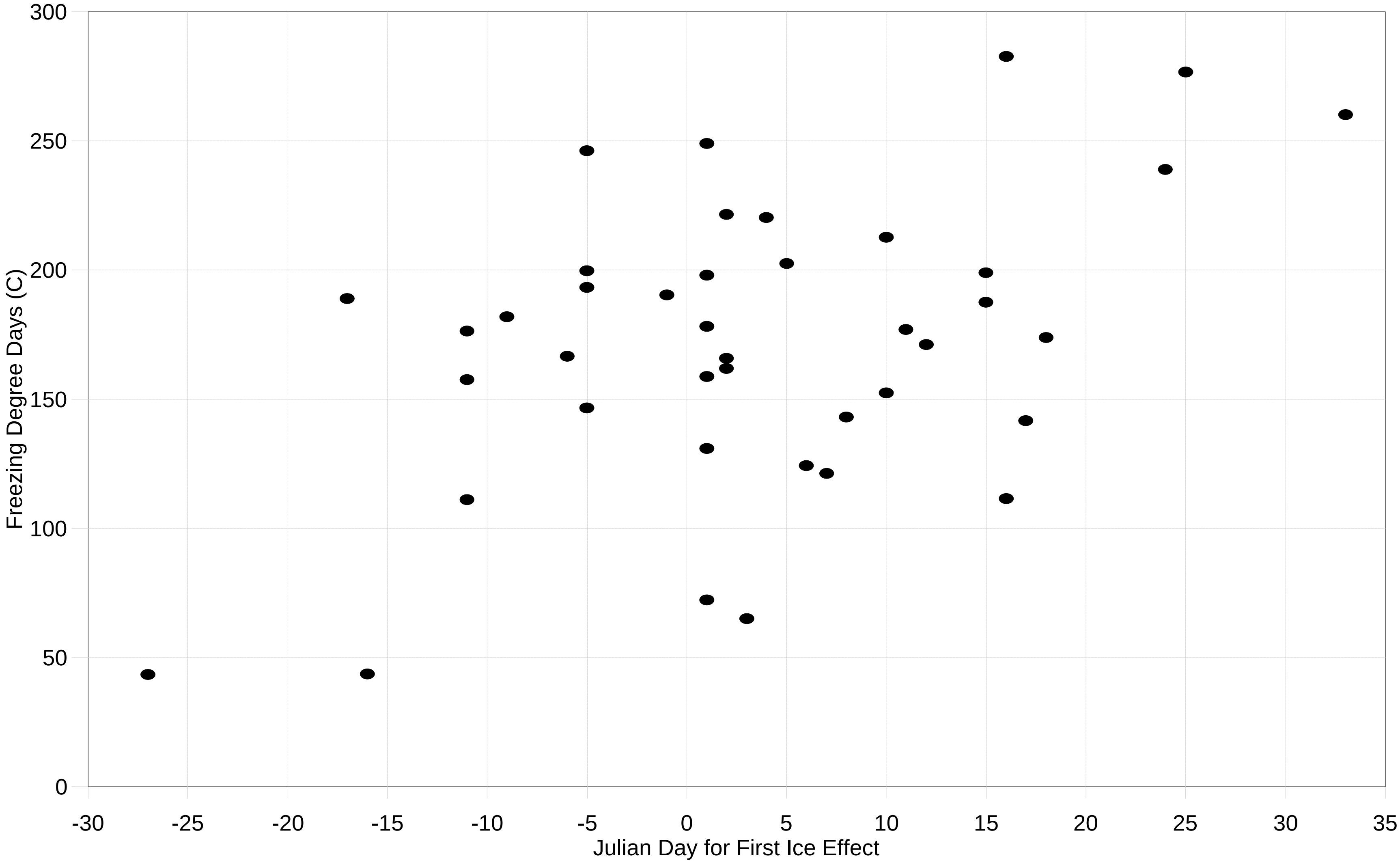


Fig. 1: -5.5 C Isotherm & Freezeup
International Reach St. Lawrence River
Julian Day
40
30
20
10
0
-10
-20
-30
1961
1963
1965
1967
1969
1971
1973
1975
1977
1979
1981
1983
1985
1987
1989
1991
1993
1995
1997
1999
2001
Year
-5.5 C Isotherm
First Effect (Lst/Mor)
Est. of Day of 1st. FX
Est. of -5.5 Iso.

Fig. 2: Postproject FDDs &

Date of First Ice Effect



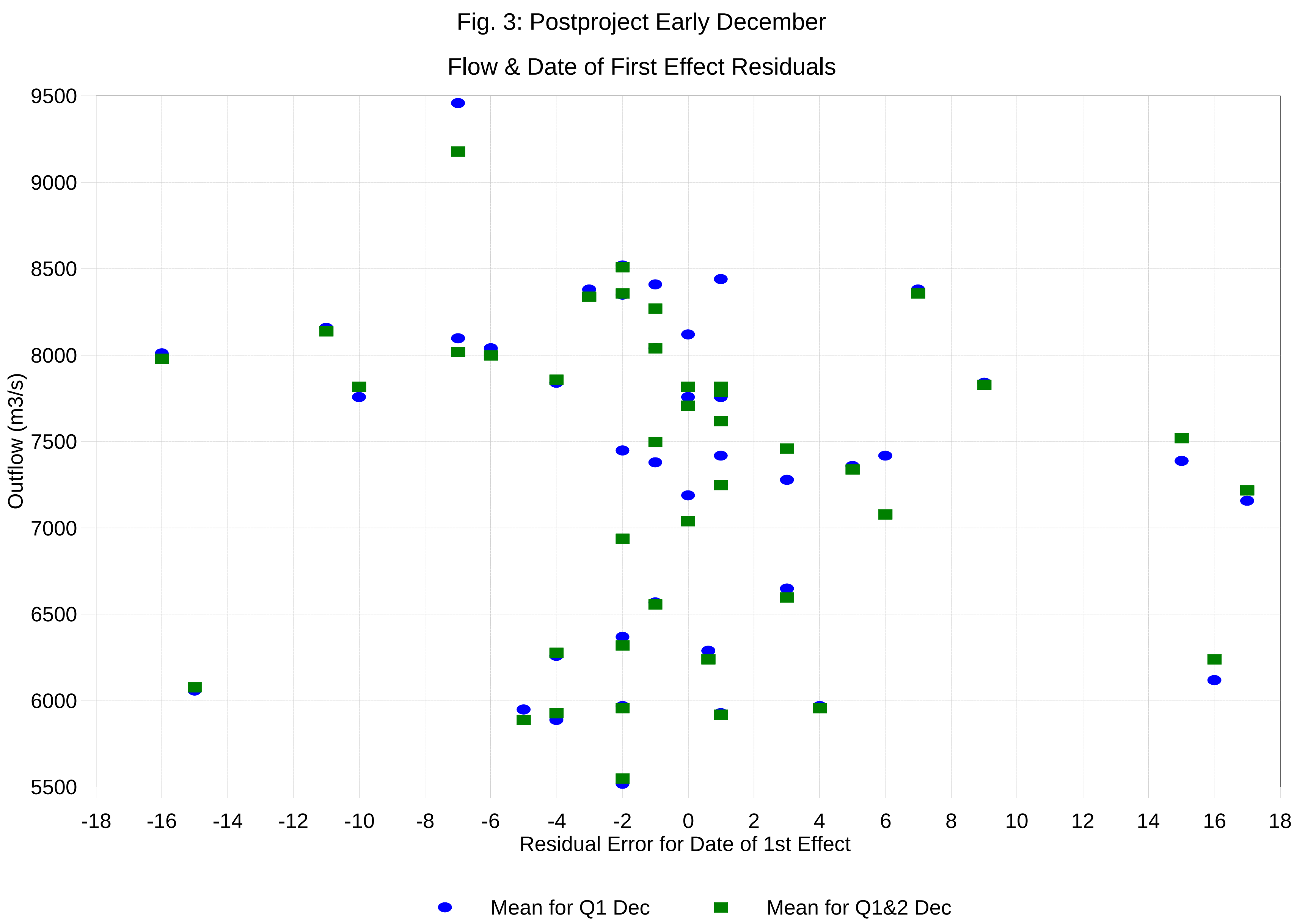


Fig. 3: Postproject Early December
Flow & Date of First Effect Residuals
Outflow (m3/s)
9500
9000
8500
8000
7500
7000
6500
6000
5500
-18
-16
-14
-12
-10
-8
-6
-4
-2
0
2
4
6
8
10
12
14
16
18
Residual Error for Date of 1st Effect
Mean for Q1 Dec
Mean for Q1&2 Dec

Fig. 4: Air Temperature Distribution

Winter 1964-65

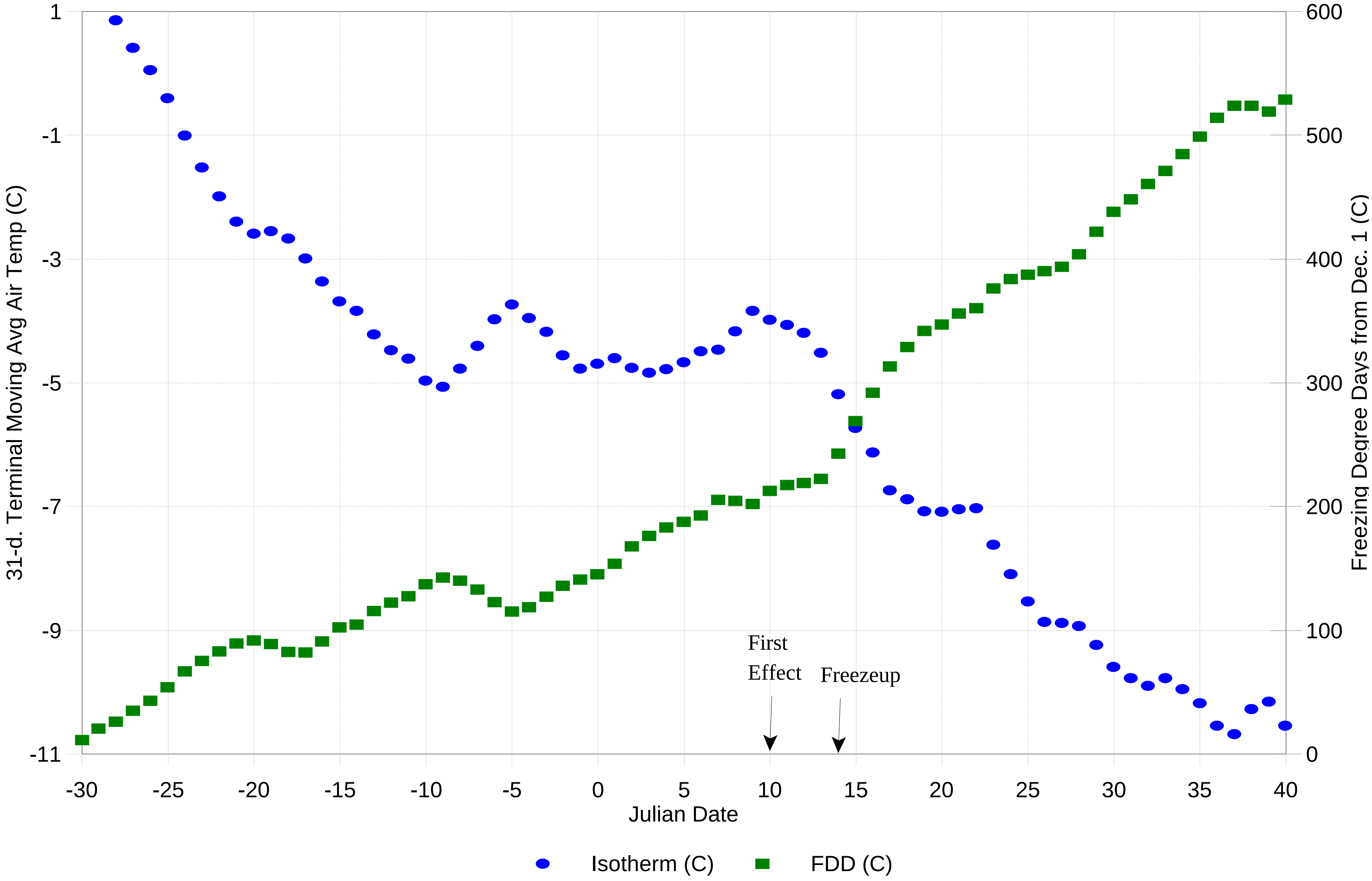
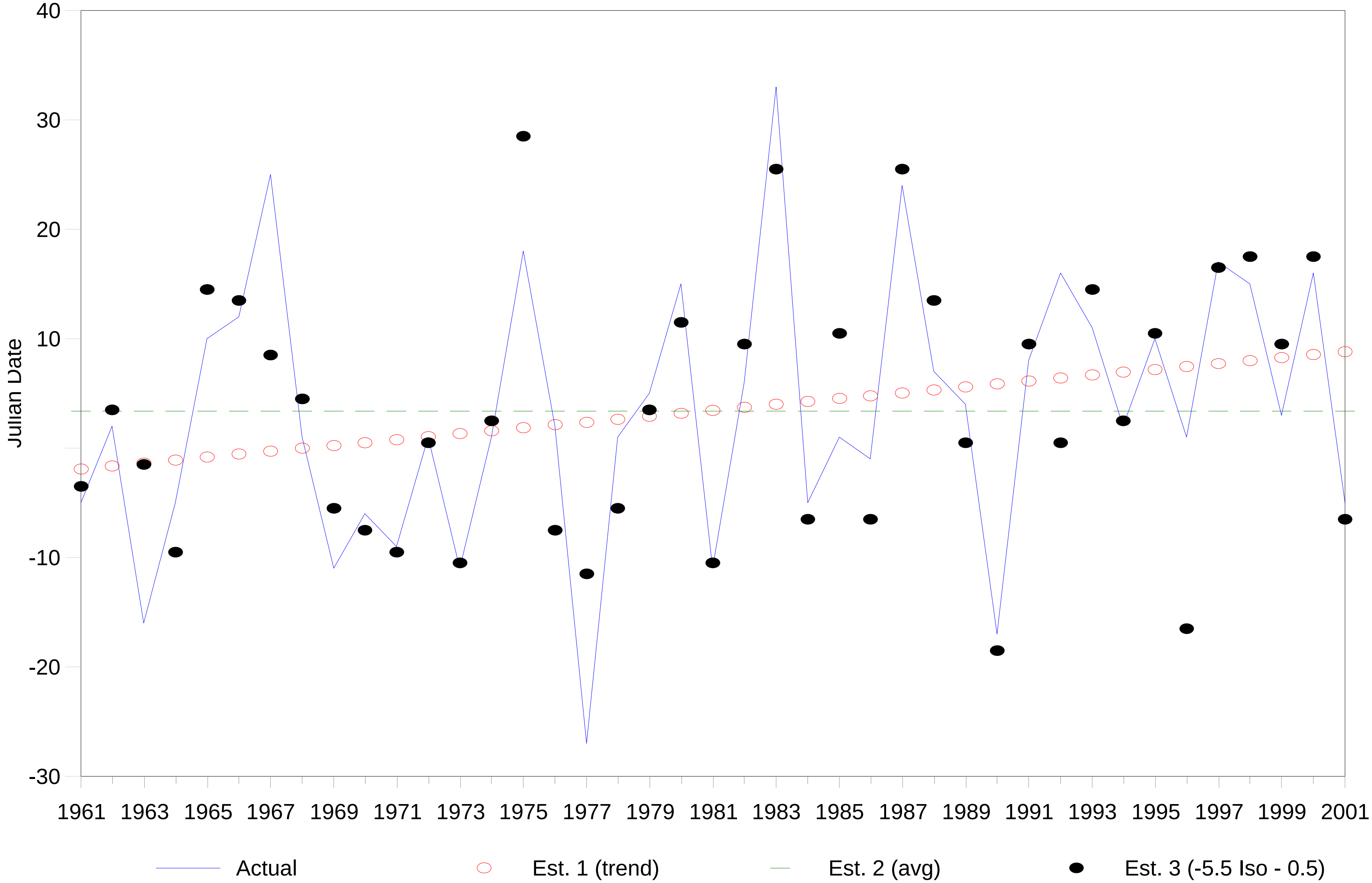


Fig. 5: Estimating Date of First

Ice Effect (L. St. Lawrence)



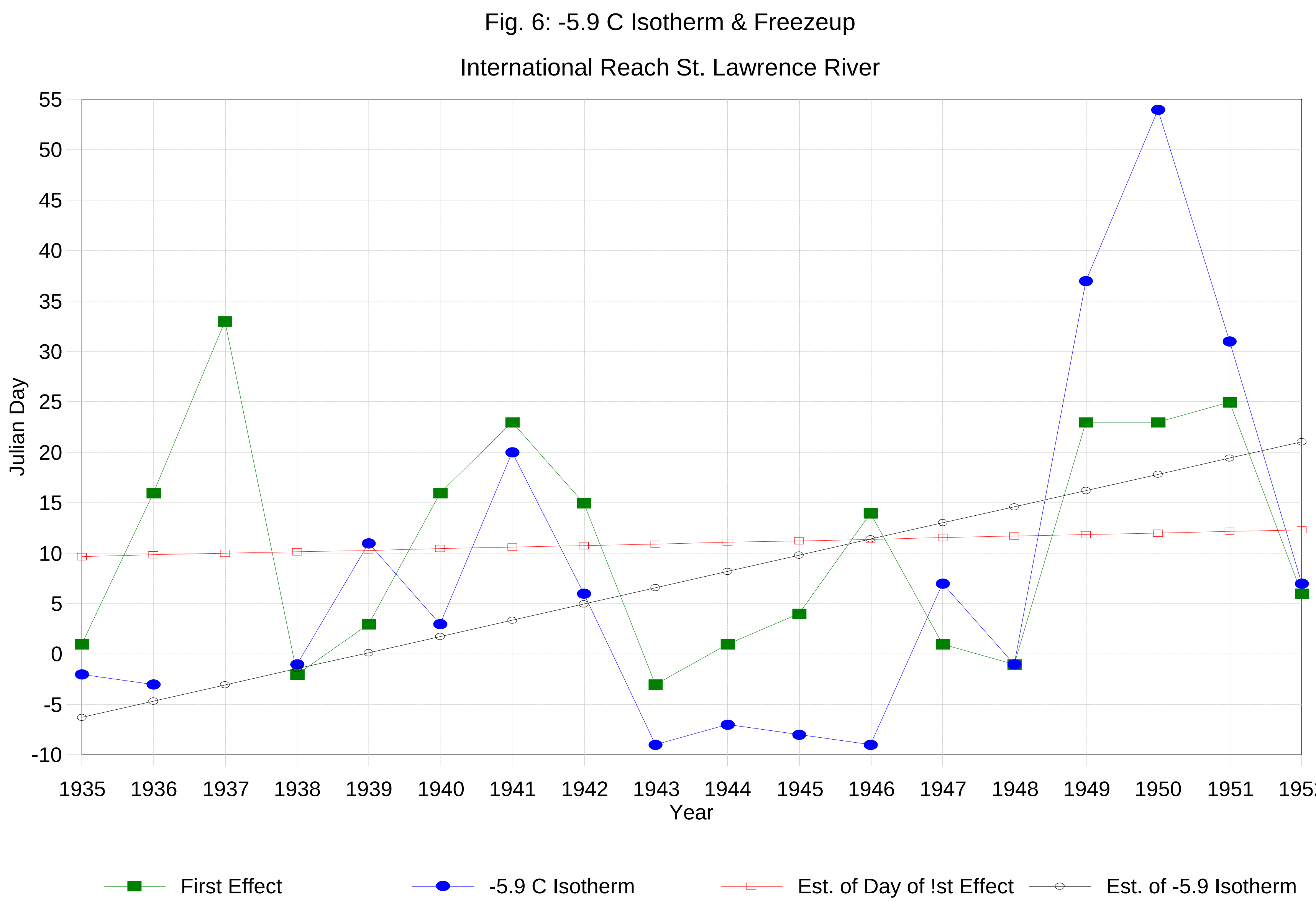
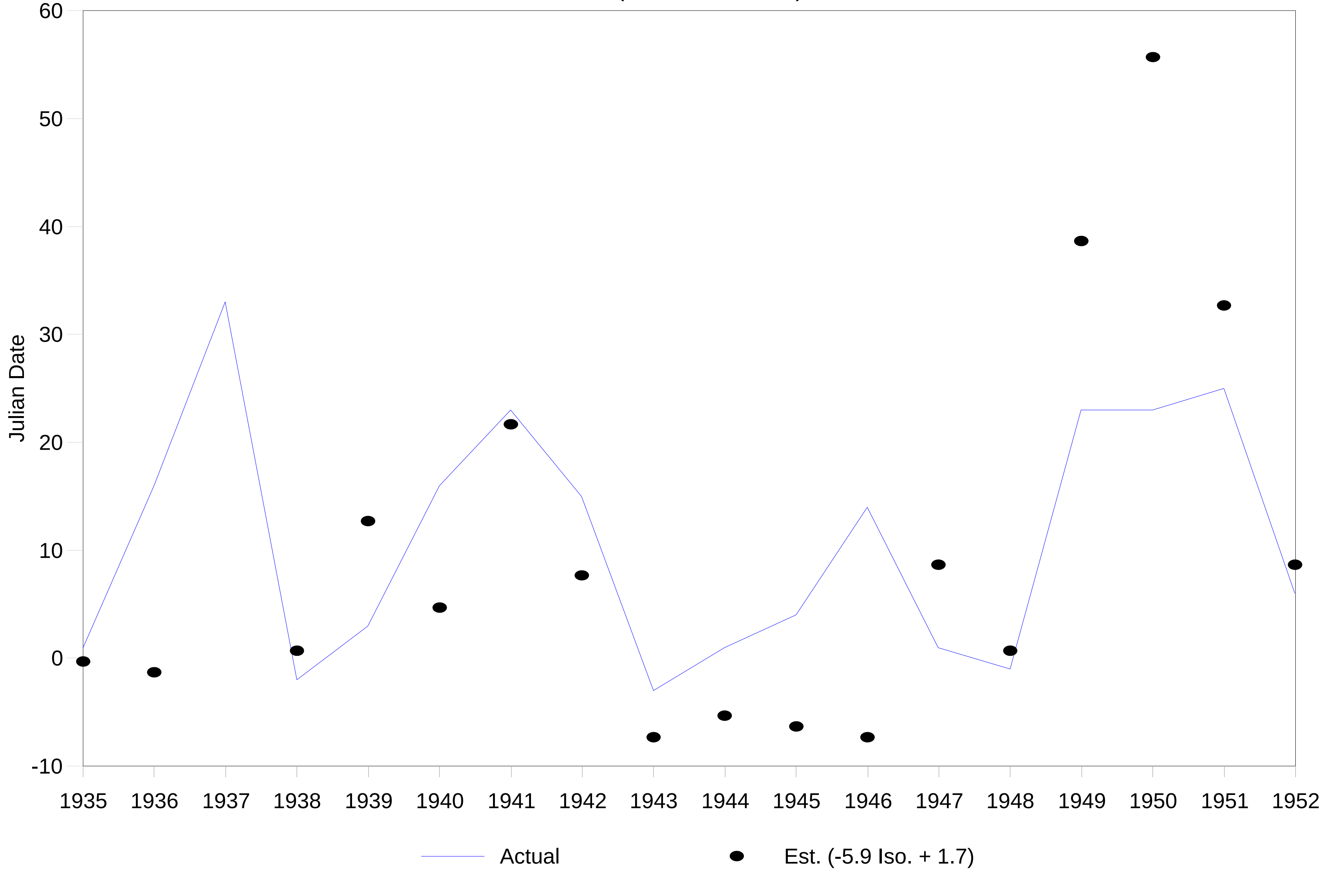


Fig. 6: -5.9 C Isotherm & Freezeup
International Reach St. Lawrence River
Julian Day
55
50
45
40
35
30
25
20
15
10
5
0
-5
-10
1935
1936
1937
1938
1939
1940
1941
1942
1943
1944
1945
1946
1947
1948
1949
1950
1951
1952
Year
First Effect
-5.9 C Isotherm
Est. of Day of !st Effect
Est. of -5.9 Isotherm

Fig. 7: Estimating Date of First

Ice Effect (L. St. Lawrence)



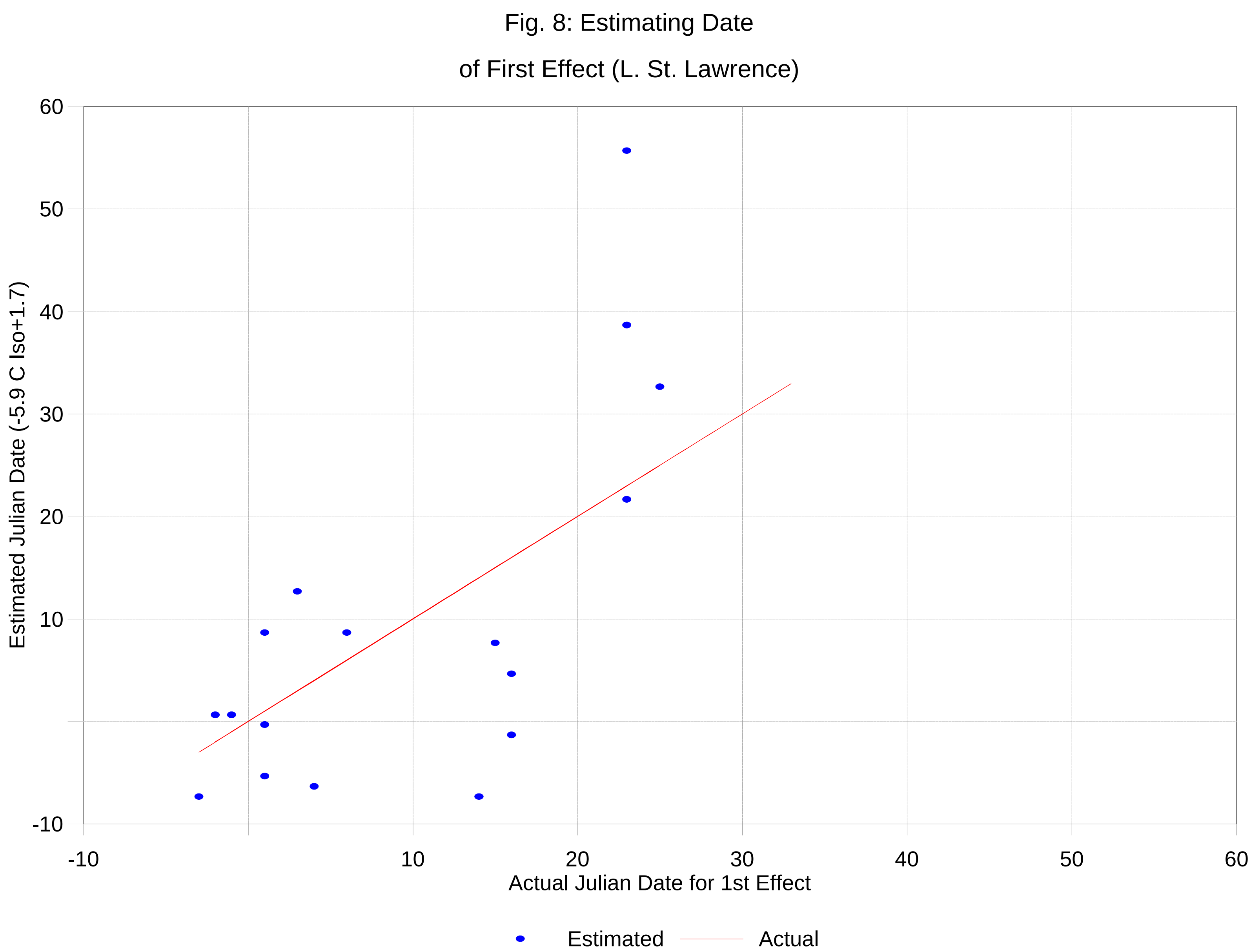
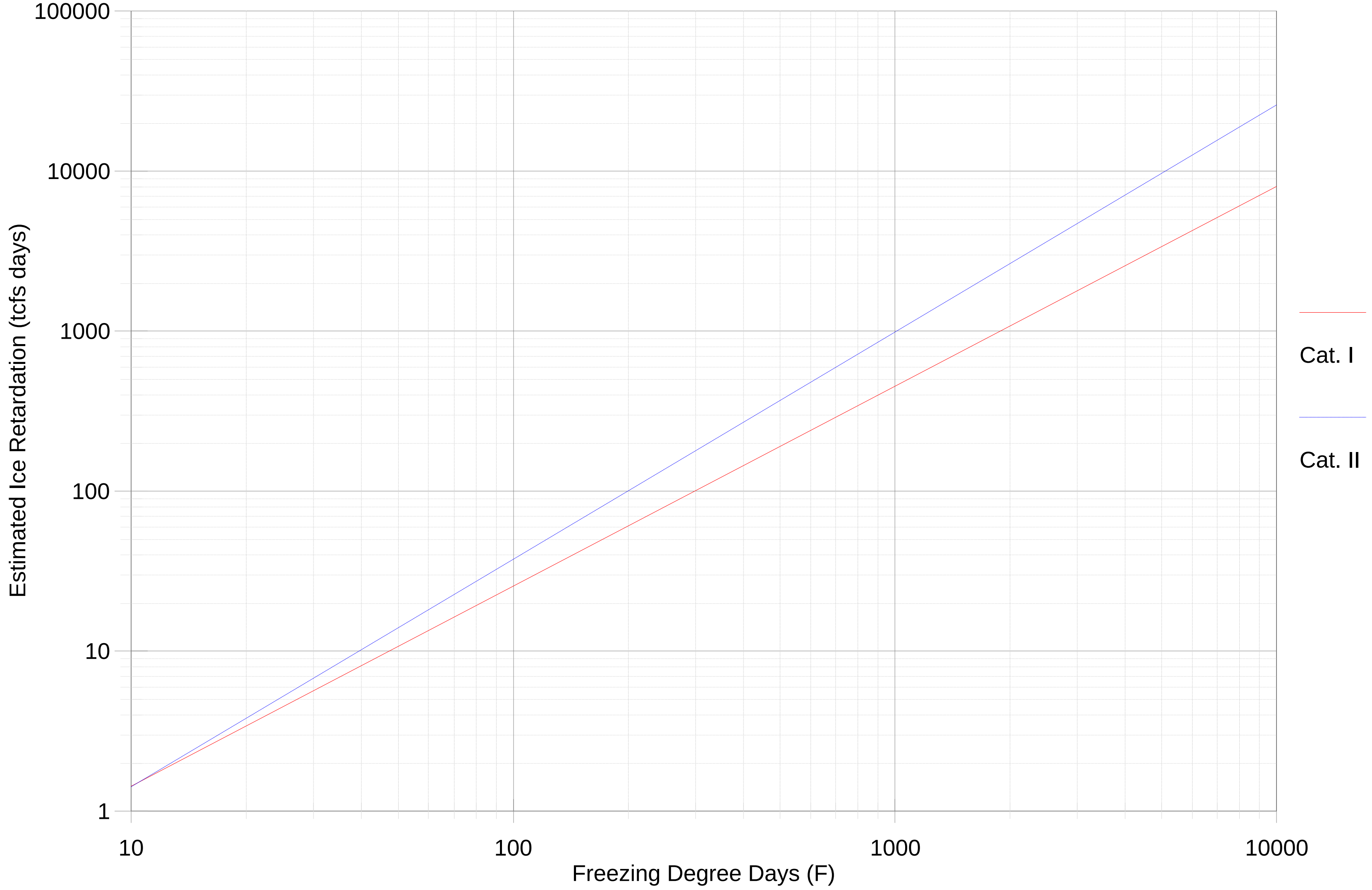


Fig. 8: Estimating Date
of First Effect (L. St. Lawrence)
60
50
40
30
20
10
-10
Estimated Julian Date (-5.9 C Iso+1.7)
-10
10
20
30
40
50
60
Actual Julian Date for 1st Effect
Estimated
Actual

Fig. 9: U.S.L.S. (1957) Relations

Categories I & II



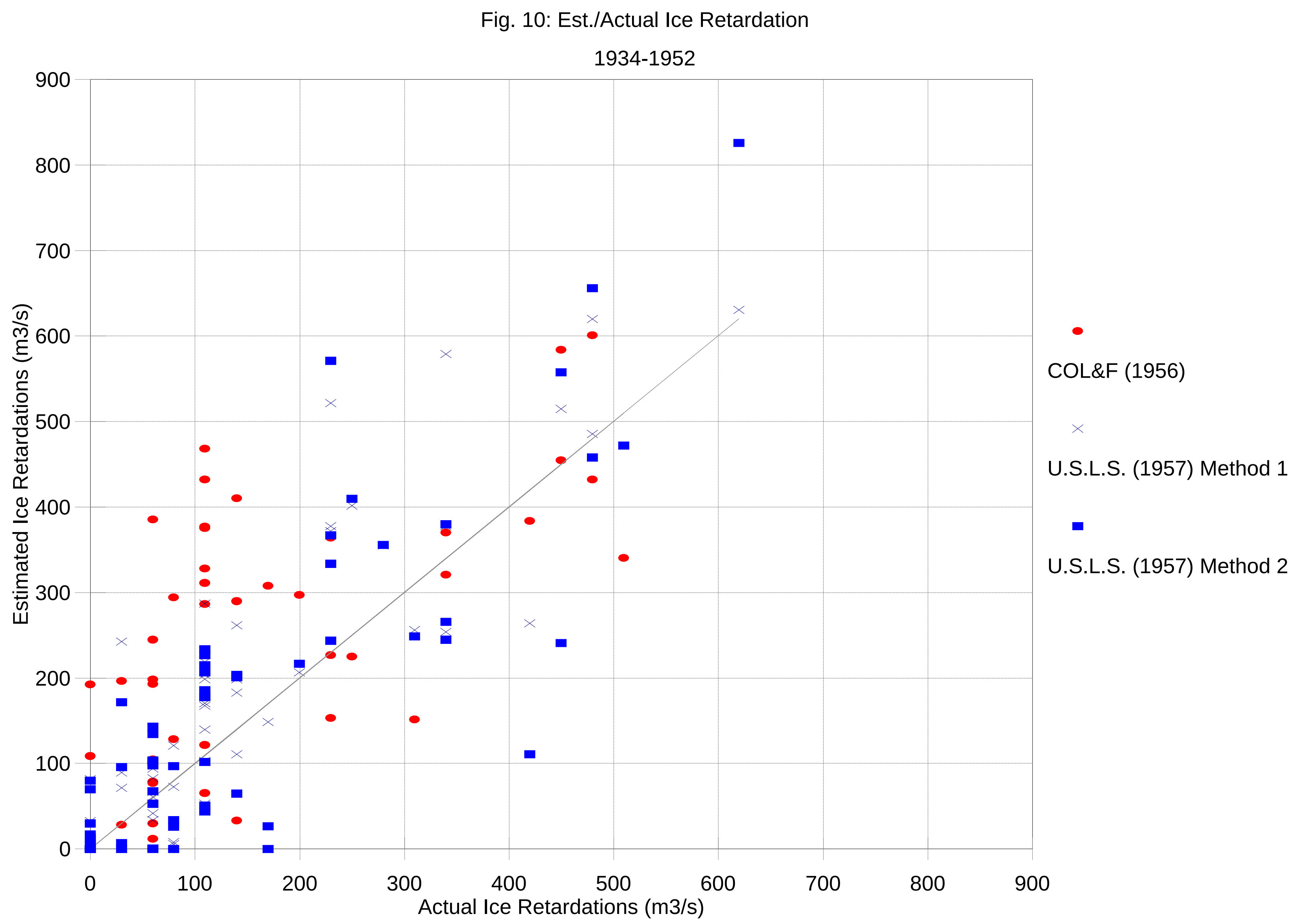


Fig. 10: Est./Actual Ice Retardation
1934-1952
Estimated Ice Retardations (m3/s)
Actual Ice Retardations (m3/s)
0
100
200
300
400
500
600
700
800
900
COL&F (1956)
U.S.L.S. (1957) Method 1
U.S.L.S. (1957) Method 2

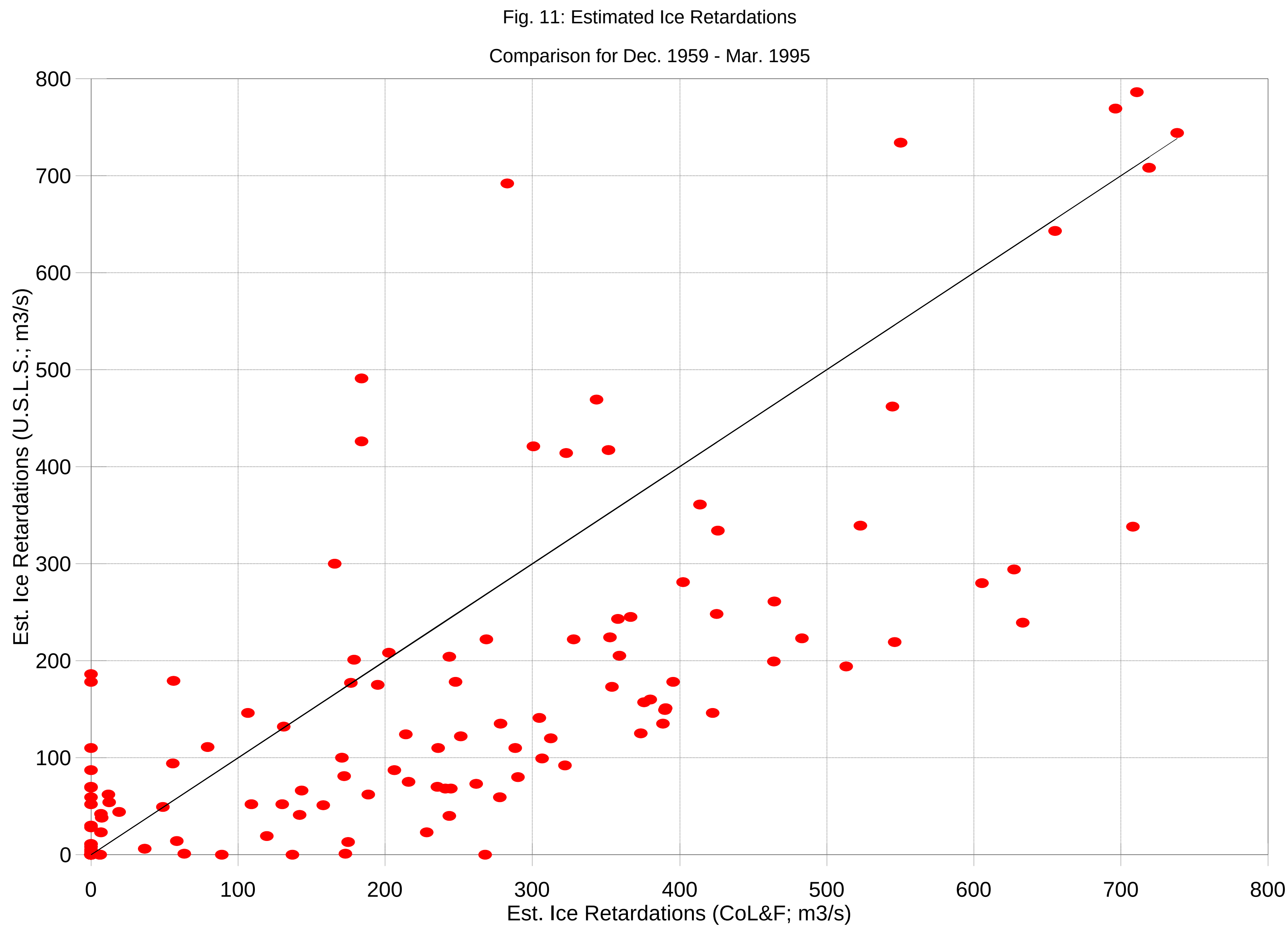
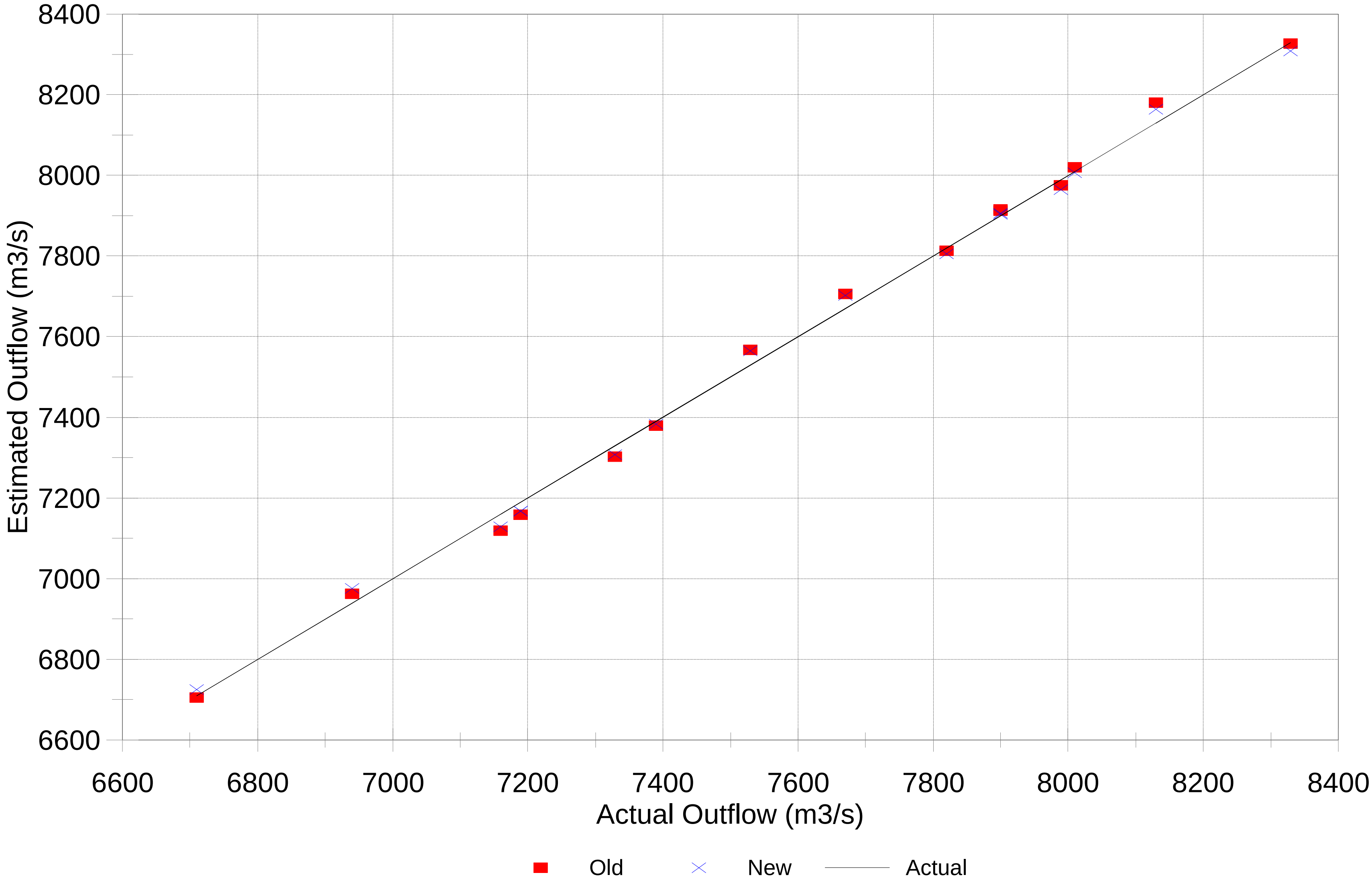


Fig. 11: Estimated Ice Retardations
Comparison for Dec. 1959 - Mar. 1995
Est. Ice Retardations (U.S.L.S.; m3/s)
0
100
200
300
400
500
600
700
800
Est. Ice Retardations (CoL&F; m3/s)

Fig. 12: New vs. Old Relations

Open-Water Preproject Outflows (53-55)



07/09/2004

Plan Formulation and Evaluation Group

Deterministic Forecasts for Lake Ontario Plan Formulation

Time Series Analysis and Stella® Model Implementation

by D. H. Lee

Deterministic Forecasts for Lake Ontario Plan Formulation

Time Series Analysis and Stella® Model Implementation

Introduction

Incorporating hydrologic forecasting into a new regulation plan is being explored as part of the International Joint Commission's Lake Ontario-St. Lawrence River Study. The objective of the Study is to assess and evaluate the current criteria used for regulating water levels on Lake Ontario and in the St. Lawrence River. New regulation plans that strive to meet the current and proposed criteria are being developed and assessed as part of the Study.

Forecasting work conducted for the Study was initially performed under the Hydrologic and Hydraulic Technical Work Group. This work primarily focused on assessments of current forecast methodologies, reviews of operational forecast systems, and needed improvements. Forecasting work then moved to the Plan Formulation and Evaluation Group (PFEG) as regulation plan development was initiated. The focus of the work shifted from operational methodologies to developing forecast methodologies suitable for plan development and simulation. This shift introduced the difficult requirement that the hydrologic forecast methodologies be suitable for simulation not only with the historical water supply series, but also with the stochastically generated series and climate change series. Because the hydrometeorological data and weather forecasts required by the current operational methods are not available for the entire historical period, and are non-existent for the stochastic and climate change series, an approach based solely on antecedent water supplies was selected. A further requirement was that the methodology fit within the STELLA® modeling framework. A final requirement was that the simulation forecast methodologies have comparable performance to the operational forecast methodologies. Time series modeling met these requirements; auto-regressive (ARMA) and auto-regressive-integrated-moving-average (ARIMA) time series models were developed for Lake Erie outflows, Lake Ontario net basin supplies, Lac St. Louis – Lake Ontario flows and annual Lake Ontario net total supplies.

This report details the development of those models and their implementation within the STELLA® modeling framework. It should be noted that the time-series forecast methodology produces a deterministic forecast appropriate for plans like Plan 1958D, Plan 1998, and the IS model. Forecast methodologies for risk-based plans and quasi-optimization plans will be reported in a follow-on report.

Background

Previous Studies

Numerous studies dating back to the mid-1960's report on statistical and time series analyses of Great Lakes net basin supplies, lake levels, outflows and other causative variables such as precipitation and temperature. Megerian (1964), DeCooke and Megerian (1967), and Gburek and Berry (1967) developed multiple regression and trend models of monthly net basin supplies based on antecedent monthly net basin supplies, temperature, and precipitation. These studies found that including antecedent data of more than 6 months did not improve the regression relationships and that the accuracy of monthly weather outlooks was the limiting factor in obtaining reliable forecasts of monthly net basin supply. In 1972, Yevjevich (1972) suggested an AR(1) model of annual Lake Ontario outflows, and in 1975, Yevjevich (1975) produced a lag-2 autoregressive AR(2) model for simulating monthly net basin supplies for each Great Lake using data from 1900 to 1968. Buchberger (1990, 1994) provides a summary of these early studies.

In 1990, Buchberger[1] explored the application of autoregressive-moving average models [ARMA(p,q)] for predicting monthly Lake Superior net basin supplies, using the techniques of Box and Jenkins (1976). He developed and tested 16 models ranging from ARMA(0,1) to ARMA(3,3), developed with data from 1900 through 1986. He used the minimum Akaike Information Criterion (AIC) to select the candidate model:

$$AIC = N \ln\left[(\sigma_e)^2\right] + 2(p+q)$$

where σ_e^2 is the normalized residual (error) variance and N is the sample size. He selected an ARMA(1,1) model as the candidate. He then compared forecast values for the period January 1987 to December 1989 to operational US and Canadian forecast methods using the measures of correlation, root mean squared error, mean absolute error and bias. He demonstrated that the ARMA(1,1) model performed on par with the operational forecast methods with slightly smaller RMSE for all months of a 6 month forecast horizon for the limited test period.

Buchberger (1991, 1992) later extended his work to develop monthly net basin supply ARMA(1,1) and ARMA(2,0) models for each of the Great Lakes and programmed forecasting software. The models were tested operationally for a period of time by the Detroit District, US Army Corps of Engineers but they never superceded the trend/regression methodology developed by Megerian and DeCooke.

During 1991-1992, Hydro-Québec undertook a spillway capacity study of the Beauharnois-Les Cèdres control structures located in the St. Lawrence River above Montreal, Québec. Rasmussen, et al. (1992) produced a 49,950 year time series of Great Lakes net basin supplies. The supplies were simulated using a shifting-level, multivariate autoregressive (SL/AR(1)) model using the methods described by Salas and Boes (1980). Based upon the 1900-1989 historical water supply series, the model was designed to preserve the annual

[1] As a historical side note, Buchberger's study was commissioned by the Detroit District, Corps of Engineers. E. Megerian, Chief of the Hydraulics Studies Section was the project manager of the study, the same person who conducted the original 1964 work.

statistical characteristics of spatial cross correlation (order zero), the serial correlation, shifts (evident in the Lakes Erie and Ontario supplies), means and standard deviations. In addition, the model preserved the monthly means and standard deviations. The supply sequence was routed through a hydraulic model of the Great Lakes, modified for robustness under extreme supply scenarios. The lake levels and outflows were retained for analysis, particularly to determine a probable maximum Lake Ontario outflow (Lee, et al., 1994). While the model's simulated series preserved key statistical characteristics of the historical series, no causative effect for the shifts was explored.

Under a grant provided by the Cooperative Institute for Limnology and Ecosystems Research of the National Oceanic and Atmospheric Administration, Buchberger (1994) investigated the covariance properties of annual net basin supplies to the Great Lakes. His data analysis showed that AR(1), AR(2), and ARMA(1,1) models proved adequate descriptions of the annual autocorrelation and that no single model emerged as a top candidate. However, the AR(1,1) models worked best on the upper lakes (Superior and Michigan-Huron) while the AR(1) models worked best on the lower lakes (Erie and Ontario).

Current Studies

Additional stochastic modeling work is ongoing as part of the Study. Sveinsson and Salas (2002) are fitting multivariate contemporaneous models to annual Great Lakes net basin supplies with disaggregation to the monthly and quarter-monthly timescales. Contemporaneous ARMA [CARMA(p,q)] models are being considered for Lakes Superior and Michigan-Huron and contemporaneous shifting mean AR(1) [CSMAR(1)] models are being considered for Lakes St. Clair, Erie and Ontario. Preliminary results are available at ftp:// wtoftpa.on.ec.gc.ca /ijcstudy/h&h/reports/Stochastic Hydrology. The stochastic series of net basin supplies will be used to test and evaluate Lake Ontario regulation plans.

Similar to the earlier Hydro-Québec study, a causative effect for the shifts and their durations remains unidentified. This prevents adapting the CSMAR(1) models for deterministic forecasting for use in regulation plans (personal communication, L. Fagherazzi, 2004). The models may have potential for generating probabilistic forecasts via Monte Carlo simulation for use in risk-based or quasi-optimization plans. However, the observed low and high frequency signals, shifts in means and variability, random events, and long–term trends evident in the Great Lakes water supply series are the result of complex interactions between the cool, dry air of polar fronts interacting with the warm moist air advected from the temperate climate of the Gulf region, influenced to some degree by the North Atlantic Oscillation and El Niño/Southern Oscillation sea surface temperature anomalies, tropical storm activity, and long-term climate change. These complex interactions can best be captured in a predictive way through the use of meteorologic forecasts coupled with operational hydrologic models.

Time Series Analysis

Data

A basic hydrologic dataset was developed for the Study by the Hydrologic and Hydraulic Technical Work Group (2004). The dataset is comprised of a 101 year sequence of quarter-monthly hydrologic variables representing the period of 1900-2000, adjusted for present system hydraulic conditions. The dataset includes Lake Erie outflows, Lake Ontario net basin supplies, and Lac St. Louis minus Lake Ontario flows, as well as local tributary flows, river tidal signal, and ice factors. PFEG developed time series models of the first three variables for regulation plan development as these are the dominant water supply inputs to the Lake Ontario-St. Lawrence River system. Because these water supplies are the responses of large-scale temporal and spatial hydrologic processes (large regional watershed integrations), they can be well modeled using linear reservoir theory which in turn can be represented by several well-known time series methods. Because the tributary flows respond quickly to localized precipitation events (on a daily time scale) and the flows are generally small in comparison to the regional water supplies, deterministic forecast models of the tributary flows were not created for incorporation into objective weekly regulation plan rules. However, this is not to say that operational forecasts of tributary flows should be neglected in lake regulation. Operational forecasts that consider watershed initial conditions and weather outlooks and use continuous hydrologic models will provide important information on a daily and weekly basis to lake regulators when making deviations from plan flows.

The models developed here are based directly on the quarter-monthly data, unlike many of the earlier studies which used annual or monthly data with disaggregation to finer time scales. It is known that net basin supplies generated from an ARMA approach applied directly to monthly data have been found to perform poorly when used to simulate monthly water levels over long time periods (decadal and longer) (Buchberger, 1994). The poor performance is due to the loss of inter-annual persistence. But this is not an issue here as the quarter-monthly models are being used to forecast for short time horizons.

Methodology

The time series analysis methodologies used here are developed and presented in Brockwell and Davis (2002). Their software ITSM2000 was used to perform the analysis. Readers unfamiliar with time series analysis are referred to this text. Briefly, time series analysis is comprised of identifying signals, trends, and random components of serial data, choosing an appropriate family of models and estimates of their parameters, and then checking (verifying) the goodness of fit. The most predictable signal in Great Lakes hydrologic data is the seasonal cycle.

Lake Erie Outflows

The quarter monthly Lake Erie outflows for the 1900-2000 Study hydrologic dataset provided 4,848 sample data points for analysis (Figure 1). A variety of model structures (ARMA and ARIMA) and data transformations (Box-Cox, classical, and differencing) were investigated. These models assume stationarity of mean and variance, an assumption not wholly satisfactory for this data, but necessary for practical application. Based on the selection criteria of minimum AIC, two candidate models were considered for further evaluation. The first candidate model was an ARMA(21,0) where $p=21$ was determined by Yule-Walker estimation. The corresponding data transformation consisted of subtracting the mean of the series (6,026 cms) to obtain a series with $\mu=0$, then removing the seasonal signal (enumerated in Appendix A). See Figure 2 for the deseasonalized time series. By visual inspection of the series' histogram, the series was determined to be normally distributed with negligible skew (Figure 3). The data and model autocorrelation functions (ACF) and partial autocorrelation functions (PACF) are shown in Figure 4.

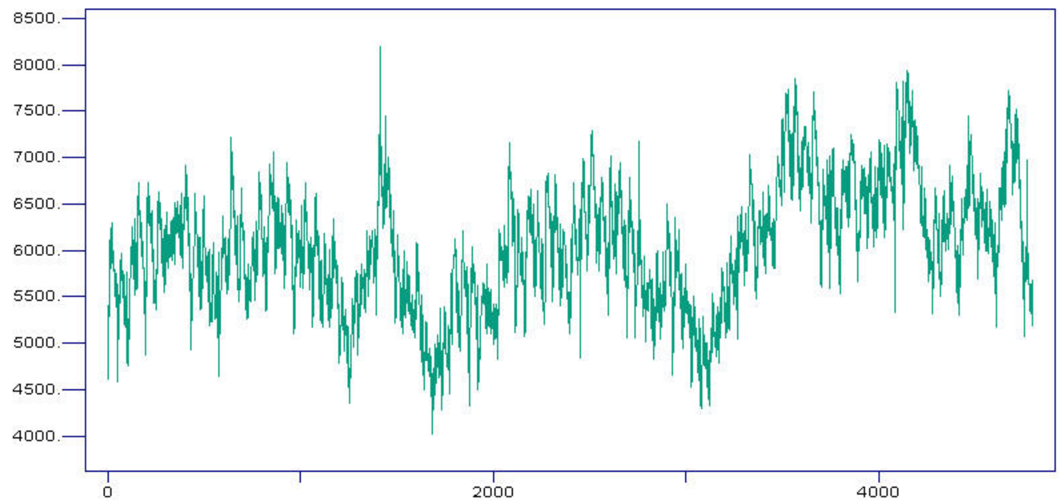


Figure 1. Lake Erie Outflow (cms) from the Study hydrologic dataset.

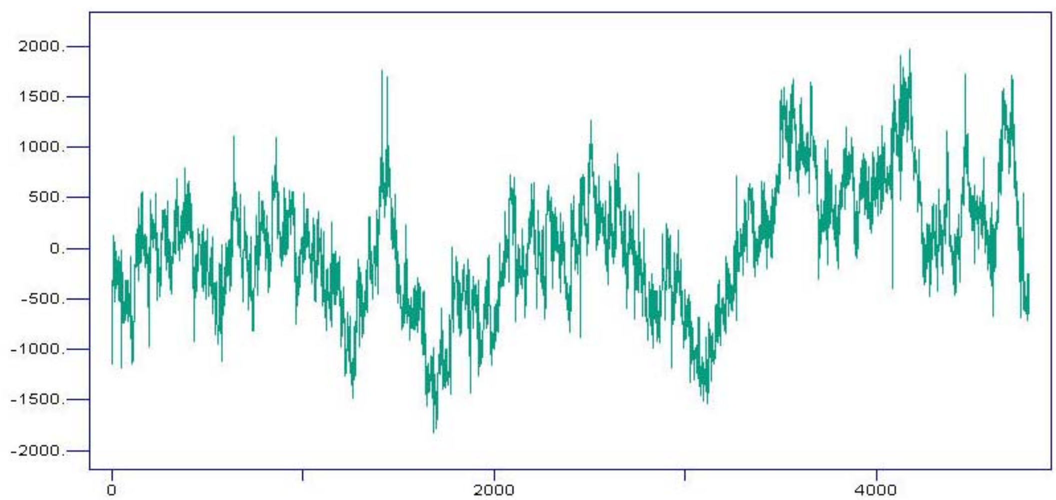


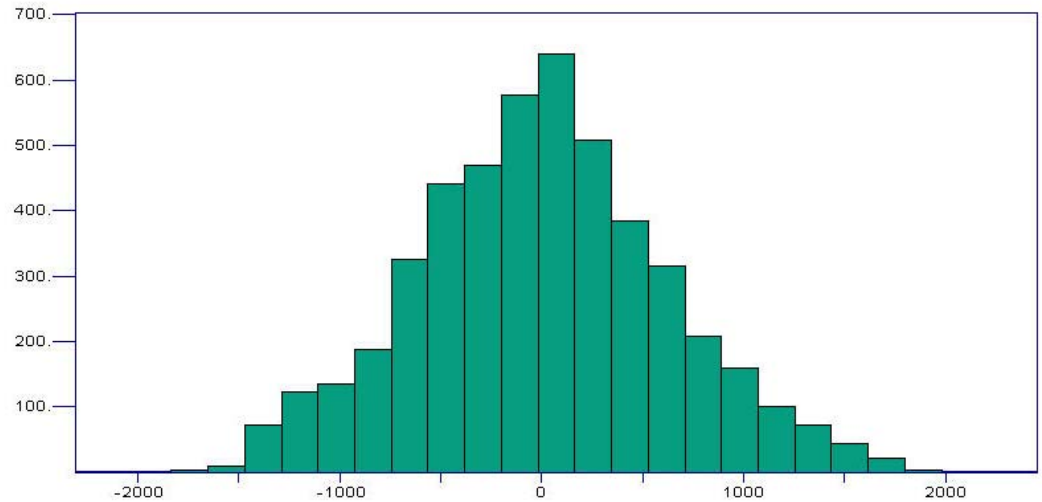
Figure 2. Lake Erie Outflow Deseasonalized Series (mean = 0) (cms) - ARMA(21,0) model.

The ARMA(21,0) model is:

$$X(t) = 0.5688*X(t-1)+0.2137*X(t-2)+ 0.04085*X(t-3)+ 0.01850*X(t-4)+ 0.02194*X(t-5) + 0.03984*X(t-6)+0.02599*X(t-7)+0.03943*X(t-8)-0.02275*X(t-9)+0.01456*X(t-10) + 0.009643*X(t-11)-0.007157*X(t-12)+0.04090*X(t-13)+0.005263*X(t-14) - 0.01658*X(t-15)-0.02585*X(t-16)-0.02521*X(t-17)+0.003007*X(t-18) - 0.01591*X(t-19)+0.01666*X(t-20)+0.03470*X(t-21)+Z(t)$$

where X(t) is the deseasonalized Lake Erie outflow series with μ=0 and Z(t) is a random component with a variance of 33,464 (standard deviation of 183 cms).

Figure 3. Lake Erie Outflow Deseasonalized Series (mean =0) Histogram – ARMA(21,0)



model.

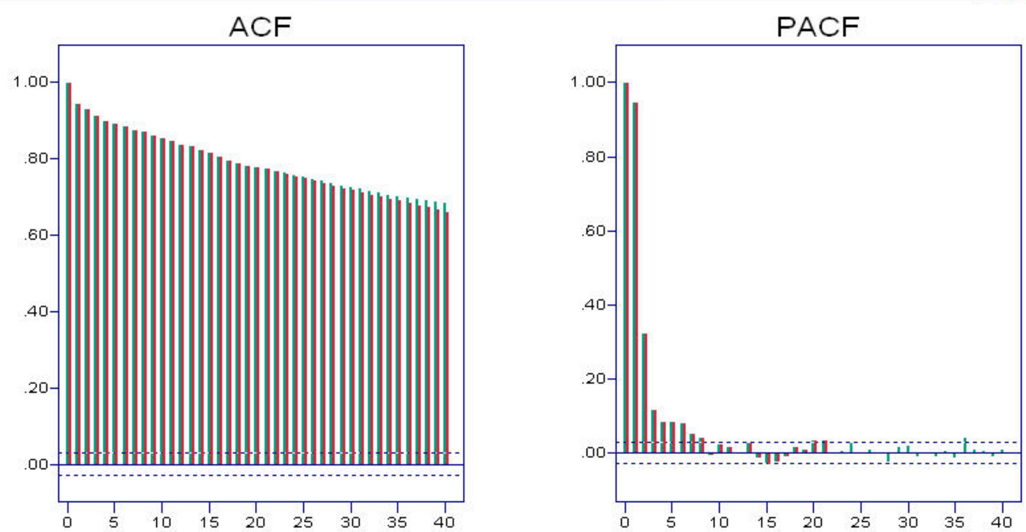


Figure 4. Lake Erie Outflow Deseasonalized Data (mean =0) (green) and Model (red) ACF and PACF - ARMA(21,0) model.

The second candidate model was based on the quarter-monthly Lake Erie outflow series differenced at a lag of 48. The differencing is an alternative means of deseasonalizing the data and leads to the ARIMA class of models (Brockwell and Davis, 2002). The mean of the differenced series (μ=-0.7927) was then subtracted. The series is shown in Figure 5. Note that the differencing reduces the sample size by 48. The ARIMA(16,0) had the minimum AIC score of the models tested for the differenced series, with p=16 determined by Yule-Walker estimation. By visual inspection of the series' histogram, the series was determined to be normally distributed with negligible skew (Figure 6). The data and model ACF and PACF are shown in Figure 7. The ARIMA(16,0) model is:

$$
\begin{aligned}
X(t) = {} & 0.5587*X(t-1) + 0.1970*X(t-2) + 0.02315*X(t-3) + 0.02463*X(t-4) \\
& + 0.007590*X(t-5) + 0.05533*X(t-6) + 0.01699*X(t-7) + 0.04978*X(t-8) \\
& - 0.01721*X(t-9) - 0.0002321*X(t-10) + 0.01507*X(t-11) + 0.005387*X(t-12) \\
& + 0.04879*X(t-13) - 0.004092*X(t-14) - 0.02376*X(t-15) - 0.04014*X(t-16) + Z(t)
\end{aligned}
$$

where X(t) is the differenced (lag 48) Lake Erie outflow series with μ=0 and Z(t) is a random component with a variance of 69,447 (standard deviation of 264 cms).

The models were verified by implementing them in the Stella® systems programming framework (see the following section 'Stella Model Implementation') and computing Lake Erie outflow forecasts 1 quarter-month into the future for the 1900-2000 period. The forecasts' statistical characteristics are compared with the Lake Erie outflows of the Study hydrologic dataset. A reference forecast consisting of a simple linear regression (LR) model [X(t)=0.9863*X(t-1) where X(t) is the Lake Erie outflow] was also included for comparison. Table 1 summarizes the comparison statistics.

Table 1. Lake Erie Outflow Model Verification and Comparison.

Statistic	*Study Dataset*	*ARMA(21,0)*	*ARIMA(16,0)*	*LR*
Mean	6,026	6,026	6,039	5,944
Stan. Dev.	658	632	671	649
Maximum	8,190	7,896	7,948	8,078
Minimum	4,028	4,321	4,128	3,973
Correlation		0.9565	0.8359	0.9496
Bias		0	12	-83
RMSE		192	381	224
MAE		142	252	167
Max. Error		1,507	1,624	1,565
Min. Error		-900	-1,689	-977

The ARMA(21,0) model was selected as the best model based on having zero bias, the minimum mean absolute error (MAE), the minimum root mean squared error (RMSE), the smallest maximum positive and negative errors, and the highest correlation. The ARIMA(16,0) and the LR seemed to marginally better preserve the variability of the Study hydrologic dataset as measured by the standard deviation and maximum and minimum values (or range), but the overall performance of the models as measured by the correlation, bias, RMSE, and MAE was deemed more important. Both the ARMA(21,0) and the LR model are included in the Stella® implementation.

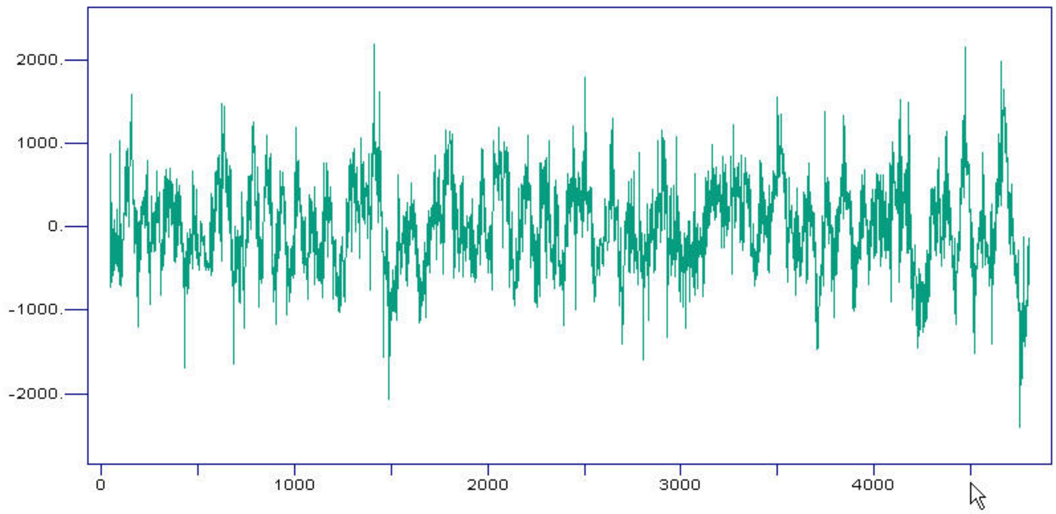


Figure 5. Erie Outflow Differenced Series (mean =0) (cms) - ARIMA(16,0) model.

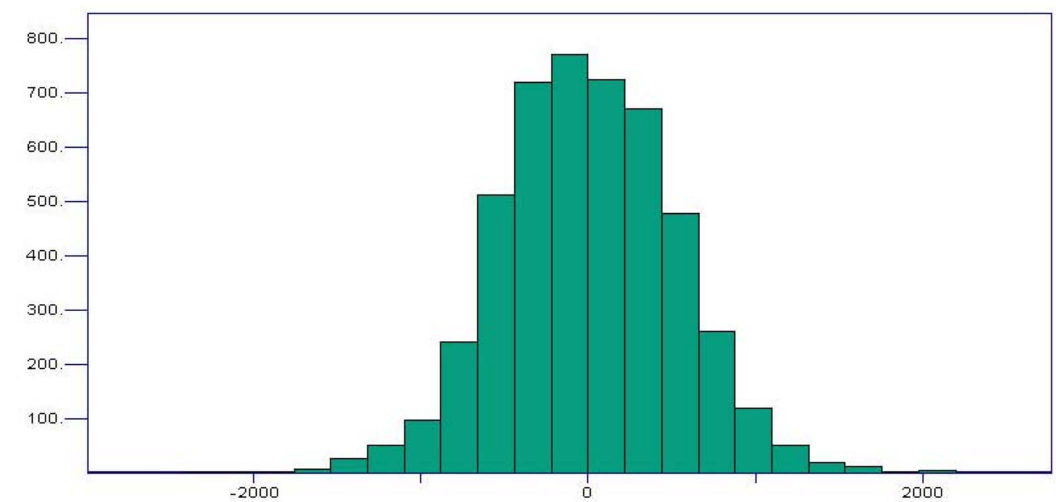


Figure 6. Erie Outflow Differenced Series (mean =0) Histogram – ARIMA*(16,0) model.*

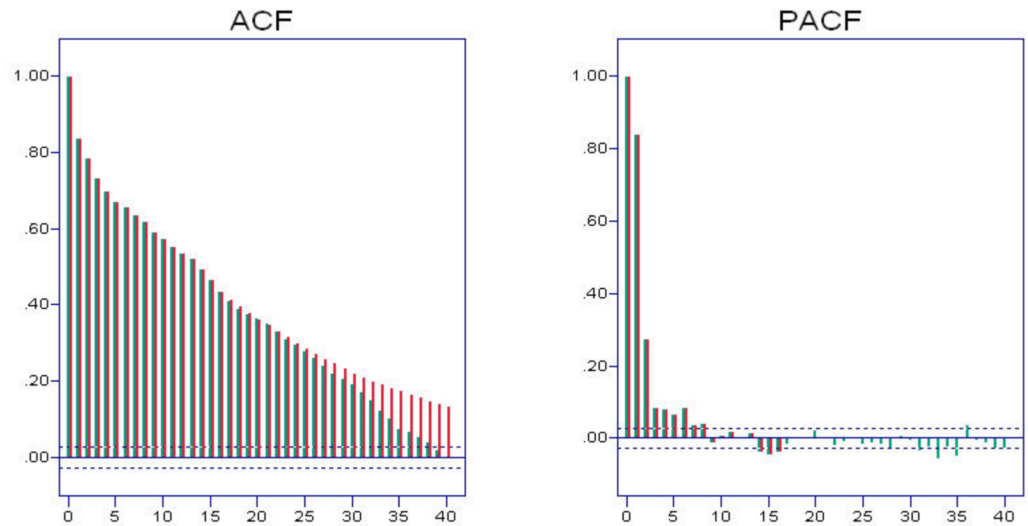


Figure 7. Lake Erie Outflow Differenced Data (mean = 0) (green) and Model (red) ACF and PACF - ARIMA(16,0) model.

Lake Ontario Net Basin Supplies

The quarter monthly Lake Ontario net basin supplies for the 1900-2000 Study hydrologic dataset provided 4,848 sample data points for analysis (Figure 8). Similar to the analysis of Lake Erie outflows, a variety of model structures (ARMA and ARIMA) and data transformations (Box-Cox, classical, and differencing) were investigated. Several candidates were selected for further testing. The candidate models are an ARMA(1,0), ARMA(26,0), ARIMA(1,1), and an ARIMA(15,2). Two other forecasts were also explored, a simple average of the preceding two quarter-months net basin supplies (sometimes called the "naïve" forecast), and a variation of the average with different weights determined by multiple linear regression (MLR). A reference forecast consisting of the 1900-2000 quarter-monthly mean (QMM) net basin supplies was also included in the comparison.

The models were verified by implementing them in the Stella® systems programming framework (see the following section 'Stella Model Implementation') and computing Lake Ontario net basin supply forecasts 1 quarter-month into the future for the 1900-2000 period. The forecasts' statistical characteristics are compared with the Lake Ontario net basin supplies of the Study hydrologic dataset in Table 2.

An additional statistic, a measure of skill, evaluates how well the models forecast extreme events. The skill statistic weights extreme event forecast error more heavily than normal supply forecast error. Values less than 1 indicate more skill relative to the reference (climatological) forecast. Values greater than 1 indicate less skill. See Croley and Lee, 2002 and 1993 for additional discussion of the statistic.

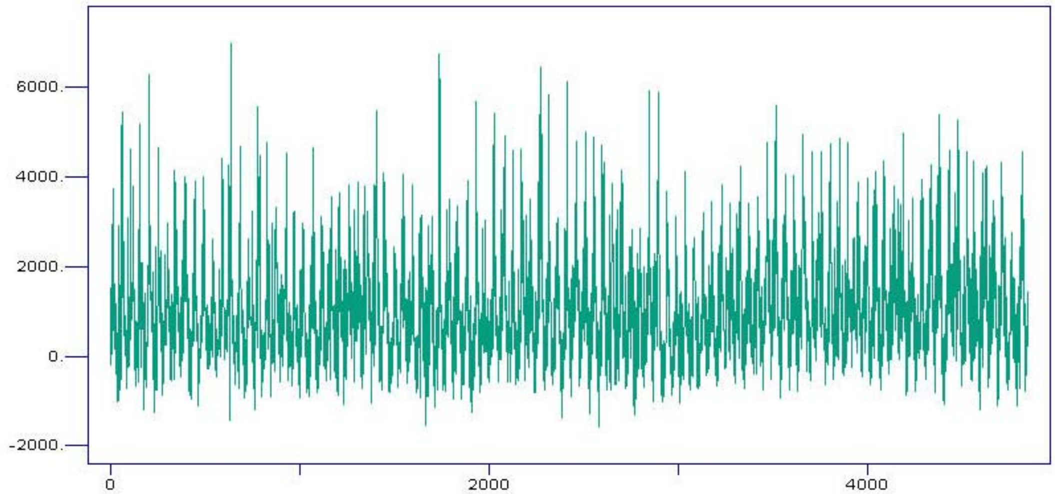


Figure 8. Lake Ontario Net Basin Supply from the Study Hydrologic Dataset.

Table 2. Lake Ontario Net Basin Supply Model Verification and Comparison.

Statistic	*Study Dataset*	*ARMA(1,0)*	*ARMA(26,0)*	*ARIMA(1,1)*	*ARIMA(15,2)*	*naive*	*MLR*	*QMM*
Mean	1,033	1,037	1,034	1,041	1,024	1,033	1,033	1,033
Stan. Dev.	1,153	1,713	800	1,034	1,088	1,047	916	775
Maximum	6,970	8,150	4,466	5,708	5,859	6,200	5,369	3,234
Minimum	-1,560	-4,284	-651	-1,567	-1,709	-1,130	-888	16
Correlation		0.4145	0.6963	0.6488	0.6211	0.6639	0.6771	0.6746
Bias		4	1	8	-9	0	0	0
RMSE		1,619	825	921	975	905	857	848
MAE		1,266	620	708	747	681	645	643
Max. Error		5,919	2,716	3,000	3,731	3,485	2,953	3,004
Min. Error		-6,524	-4,675	-4,933	-5,072	-5,195	-5116	-5,123
Skill		1.29	0.83	0.87	0.90	0.83	0.81	1

Because the number of models and statistics made it difficult to discern the 'best' model, a rank of 1 to 7 (best to worst) was then assigned to each evaluation statistic for each model, then the ranks summed for each model. The model with the lowest total sum is considered to have the best overall performance. The ranks and sums are shown in Table 3. A rank was not assigned to the mean as the same information is contained in the bias. Based on this procedure the leading models are the ARMA(26,0), the MLR, the naïve, and the ARIMA(1,1).

Table 3. Ontario Net Basin Supply Model Rankings (1=best, 7=worst, lowest rank sum is the overall best performer).

Statistic	*ARMA(1,0)*	*ARMA(26,0)*	*ARIMA(1,1)*	*ARIMA(15,2)*	*naive*	*MLR*	*QMM*
Stan. Dev.	7	5	3	1	2	4	6
Maximum	3	6	4	2	1	5	7
Minimum	7	5	1	2	3	4	6
Correlation	7	1	5	6	4	2	3
Bias	5	4	6	7	3	2	1
RMSE	7	1	5	6	4	3	2
MAE	7	1	5	6	4	3	2
Max. Error	7	1	3	6	5	2	4
Min. Error	7	1	2	3	6	4	5
Skill	7	2	4	5	3	1	6
Rank Sum	64	27	38	44	35	30	42

For the ARMA(26,0) model, the data transformation consisted of subtracting the mean of the series (1,035 cms) to obtain a series with $\mu=0$. The seasonal signal was not removed. The parameter p=26 was determined by Yule-Walker estimation. The model is

$$
\begin{aligned}
X(t) = {} & 0.4746*X(t-1) + 0.1493*X(t-2) + 0.01923*X(t-3) + 0.03424*X(t-4) \\
& + 0.01025*X(t-5) - 0.006960*X(t-6) - 0.03209*X(t-7) + 0.05757*X(t-8) \\
& + 0.00007484*X(t-9) - 0.01390*X(t-10) - 0.0007310*X(t-11) - 0.01017*X(t-12) \\
& - 0.02105*X(t-13) - 0.009959*X(t-14) - 0.01256*X(t-15) + 0.01011*X(t-16) \\
& - 0.008653*X(t-17) - 0.03989*X(t-18) - 0.01719*X(t-19) - 0.01100*X(t-20) \\
& - 0.02326*X(t-21) - 0.02640*X(t-22) - 0.01341*X(t-23) - 0.006209*X(t-24) \\
& - 0.01959*X(t-25) - 0.04441*X(t-26) + Z(t)
\end{aligned}
$$

where X(t) is the Lake Ontario net basin supply series with $\mu=0$ and Z(t) is a random component with a variance of 681,265 (standard deviation of 825 cms).

The naïve model, a simple average of the preceding 2 quarter-months supply, is:

$$X(t) = 0.5*X(t-1) + 0.5*X(t-2).$$

This forecast model, based on Lake Ontario net total supplies, has been effectively used in the development of the IS series of plans (ISLRBC 1997).

In exploring ways to improve on the naïve model, different coefficients were derived using multiple linear regression:

X(t) = 0.5936*X(t-1) + 0.2989*X(t-2) + 142.

For the ARIMA(1,1) model, the quarter monthly net basin supplies were differenced with a lag of 48 (each net basin supply had the corresponding prior year's net basin supply subtracted) (see Figure 9). Note that differencing reduces the sample size by 48. The mean of the differenced series was subtracted (μ=2.8125). An ARIMA(1,1) model was fit to the data using Hannan-Rissanen estimation (Brockwell and Davis, 2002). The resulting model is:

X(t) = 0.6052*X(t-1)+ Z(t)-0.2564*Z(t-1)

where X(t) is the differenced quarter monthly net basin supply with μ=0, and Z(t) is the random component with a variance of 1,171,607 (standard deviation of 1,082 cms). By visual inspection of the series' histogram, the series was determined to be normally distributed with negligible skew (Figure 10). The data and model autocorrelation functions (ACF) and partial autocorrelation functions (PACF) are shown in Figure 11. The ACF indicates that a higher AR order is desirable; but although the ARIMA(15,2) model had the lowest AIC, the model did not perform as well as the ARIMA(1,1) model in forecast comparisons.

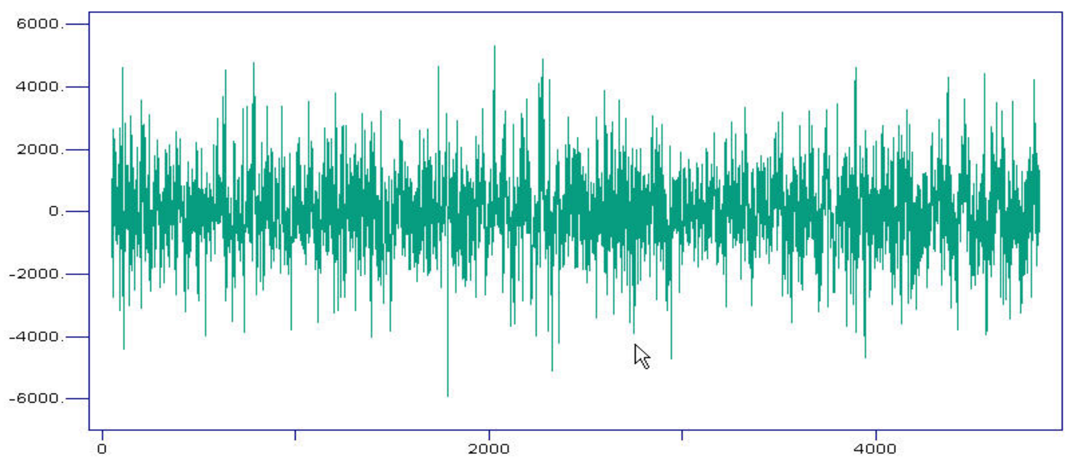


Figure 9. Differenced Net Basin Supply Series with Mean =0 - ARIMA(1,1) model.

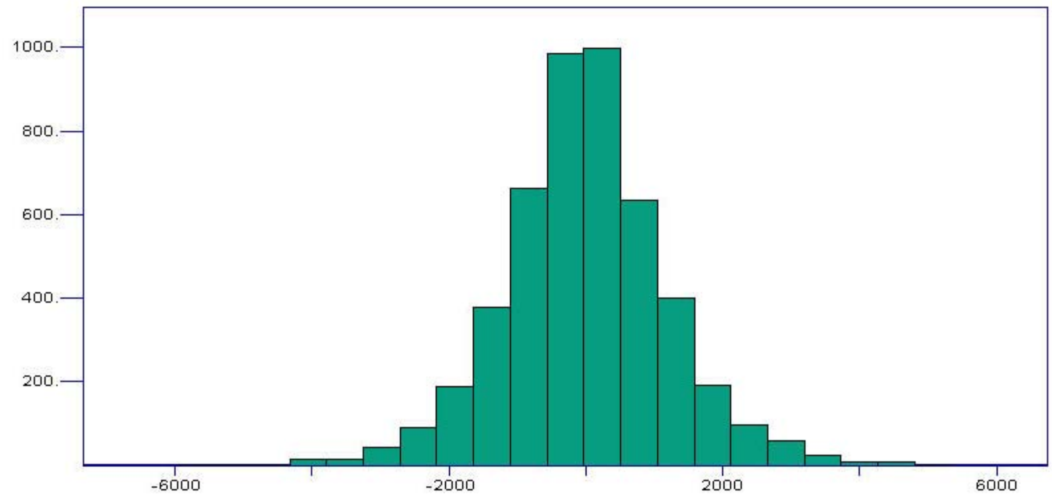


Figure 10. Differenced Series (mean = 0) Histogram - ARIMA(1,1) model.

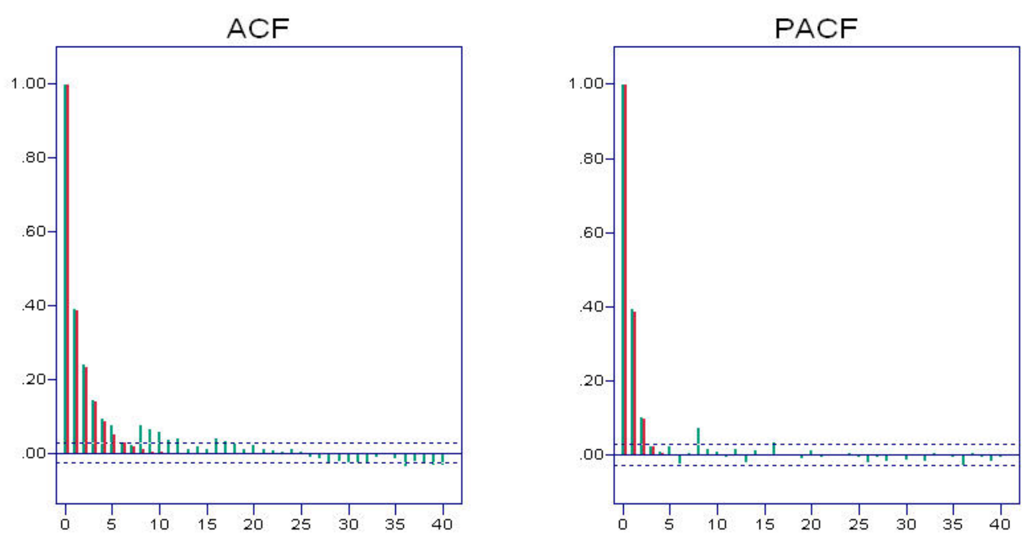


Figure 11. Lake Ontario Net Basin Supply Differenced Data (mean =0) (green) and Model (red) ACF and PACF - ARIMA(1,1) model.

Because other methods of ranking the net basin supply forecast models could yield different results, all four models are included in the Stella® implementation for plan regulation development.

Lac St. Louis – Lake Ontario Outflows

The quarter monthly Lac St. Louis – Lake Ontario outflows for the 1900-2000 Study hydrologic dataset provided 4,848 sample data points for analysis (Figure 12). Of all the models explored, only one candidate model was selected for further evaluation, an ARMA(5,0) where p=5 was determined by Yule-Walker estimation. The corresponding data transformation consisted of subtracting the mean of the series (μ=1,185 cms) to obtain a series with μ=0, then removing the seasonal signal (enumerated in Appendix B). See Figure 13 for the deseasonalized time series. By visual inspection of the series' histogram, the series was determined to have some skew (Figure 14), but this was ignored in the analysis. The data and model autocorrelation functions (ACF) and partial autocorrelation functions (PACF) are shown in Figure 15.

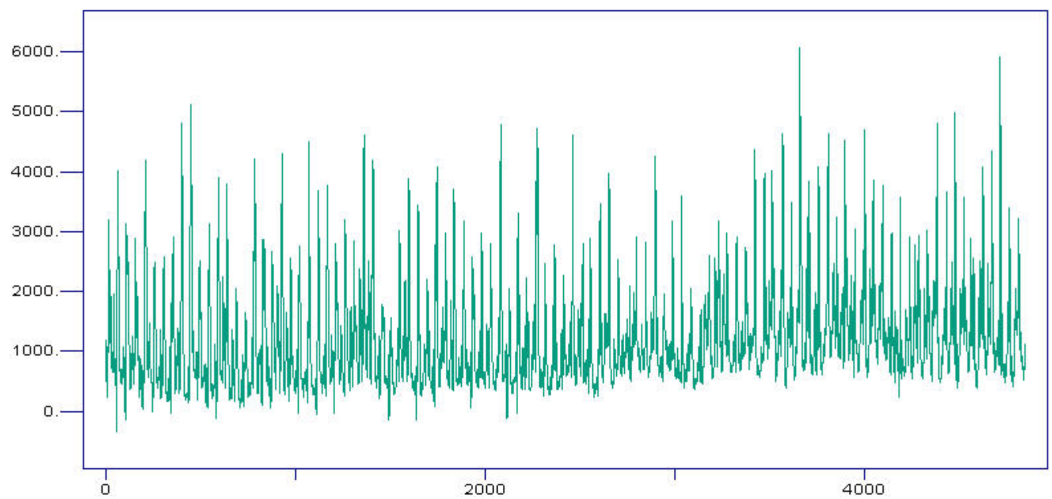


Figure 12. Lac St. Louis minus Lake Ontario Outflows (cms).

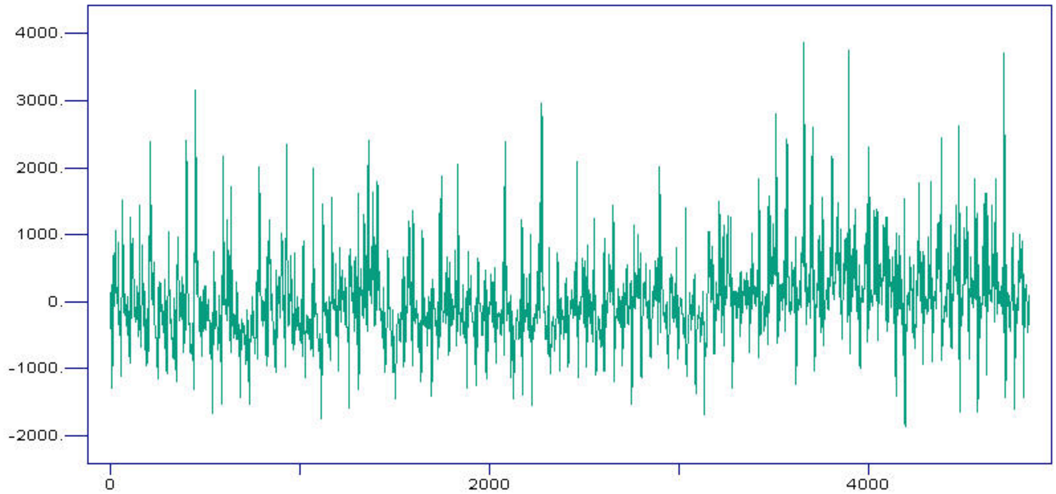


Figure 13. Lac St. Louis - Lake Ontario Outflow Deseasonalized Series (mean =0) - AR(5,0) Model.

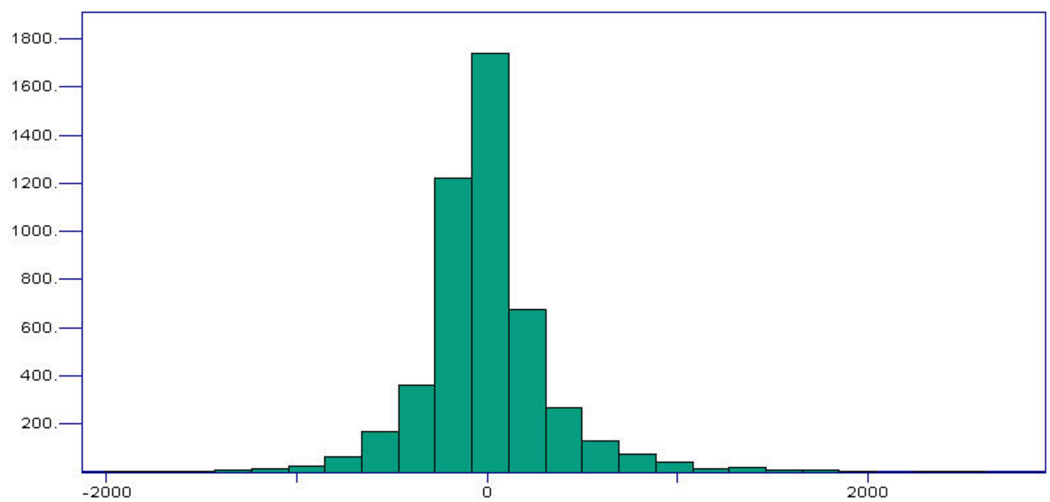


Figure 14. Deseasonalized Series (mean = 0) Histogram of Lac St. Louis - Lake Ontario Outflows - AR(5,0).

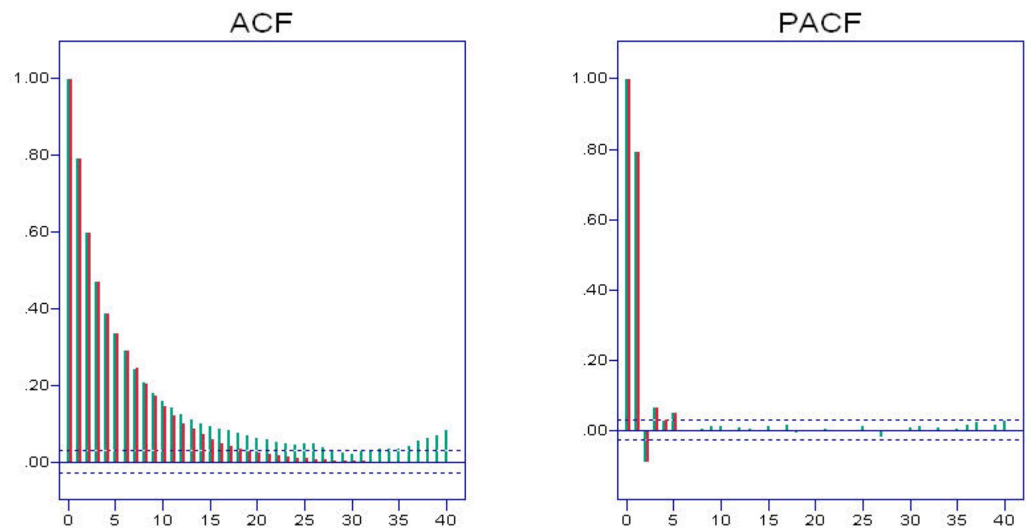


Figure 15. Lac St. Louis – Lake Ontario Deseasonalized Outflows (mean =0) Data (green) and Model (red) ACF and PACF - ARMA(5,0) model.

Table 4 summarizes the comparison and verification statistics of the ARMA(5,0) model and a reference forecast with the Study hydrologic dataset. The reference forecast is based on the quarter-monthly means (QMM). The ARMA(5,0) model preserves the time series mean and is well correlated with the Study hydrologic dataset values. The RMSE of 375 cms is very similar to that of the operational Ottawa River flow forecasts of 336 cms (PFEG, 2004). While a direct comparison between the ARMA(5,0) model statistics and the operational forecasts is not strictly valid, the results are encouraging. The results cannot be compared directly as the operational forecasts are on a weekly basis, the operational analysis is based on a much shorter time period (1995-2003), and the operational forecasts do not include the local tributary flows below Carillion, Québec and Cornwall, Ontario.

Table 4. Lac St. Louis – Lake Ontario Outflow Model Verification and Comparison.

Statistic	*Study Dataset*	*ARMA(5,0)*	*QMM*
Mean	1,185	1,185	1,185
Stan. Dev.	813	736	575
Maximum	6,060	5,271	2,530
Minimum	-330	-97	583
Correlation		0.8874	0.7071
Bias		0	0
RMSE		375	575
MAE		244	415
Maximum Error		2,005	1,855
Minimum Error		-2,818	-3,871

Lake Ontario Net Total Supplies

Lake Ontario net total supply is the sum of the Lake Erie outflow and the Lake Ontario net basin supply. To evaluate forecasts of net total supply, the sum of the forecast Lake Erie outflow [ARMA(21,0)] and the forecast Lake Ontario net basin supply [ARMA(26,0)]are compared to that of the Study hydrologic data set. A "naïve" forecast (the average of the preceding two quarter-months net total supply) and a reference forecast (quarter-monthly means - QMM) are also compared. Table 5 summarizes the results.

Table 5. Lake Ontario Net Total Supply Verification and Comparison.

Statistic	*Study Dataset*	*ARMAs*	*naive*	*QMM*
Mean	7,059	7,060	7,072	7,059
Stan. Dev.	1,432	1,077	1,343	840
Maximum	13,462	11,116	12,222	9,341
Minimum	3,220	4,250	3,955	6,073
Correlation		0.7916	0.6395	0.5865
Bias		1	13	0
RMSE		877	1,181	1,160
MAE		660	863	907
Maximum Error		2,741	6,164	3,542
Minimum Error		-5,065	-5,490	-5,460

Stella® Model Implementation

The Stella® model implementation is available via ftp from:

ftp:// wtoftpa.on.ec.gc.ca///ijcstudy/pfeg/modeling/ForecastSVM_20040709.STM.

At the interface level (shown in Figure 16), switches allow the user to select among the multiple models for Lake Erie outflows, Lake Ontario net basin supply and Lake Erie net total supply.

At the modeling level (shown in Figure 17), a frame entitled 'Deterministic Forecasts' encompasses the sub-frames for the Lake Erie outflow, Lake Ontario net basin supply, Lac-St. Louis – Lake Ontario outflow, and Lake Ontario net total supply models. Variable names are self-explanatory, and documentation is provided in main variable dialog boxes (Figure 18).

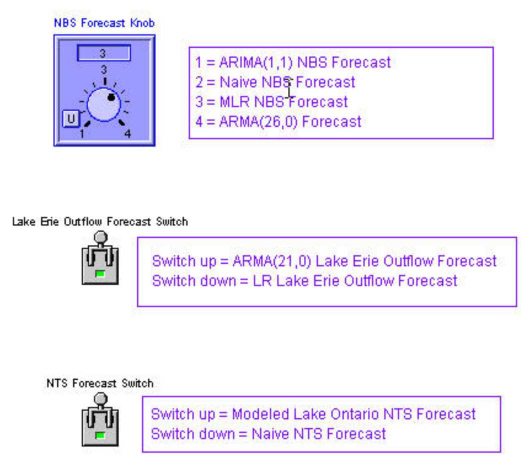


Figure 16. ForecastSVM Interface Level.

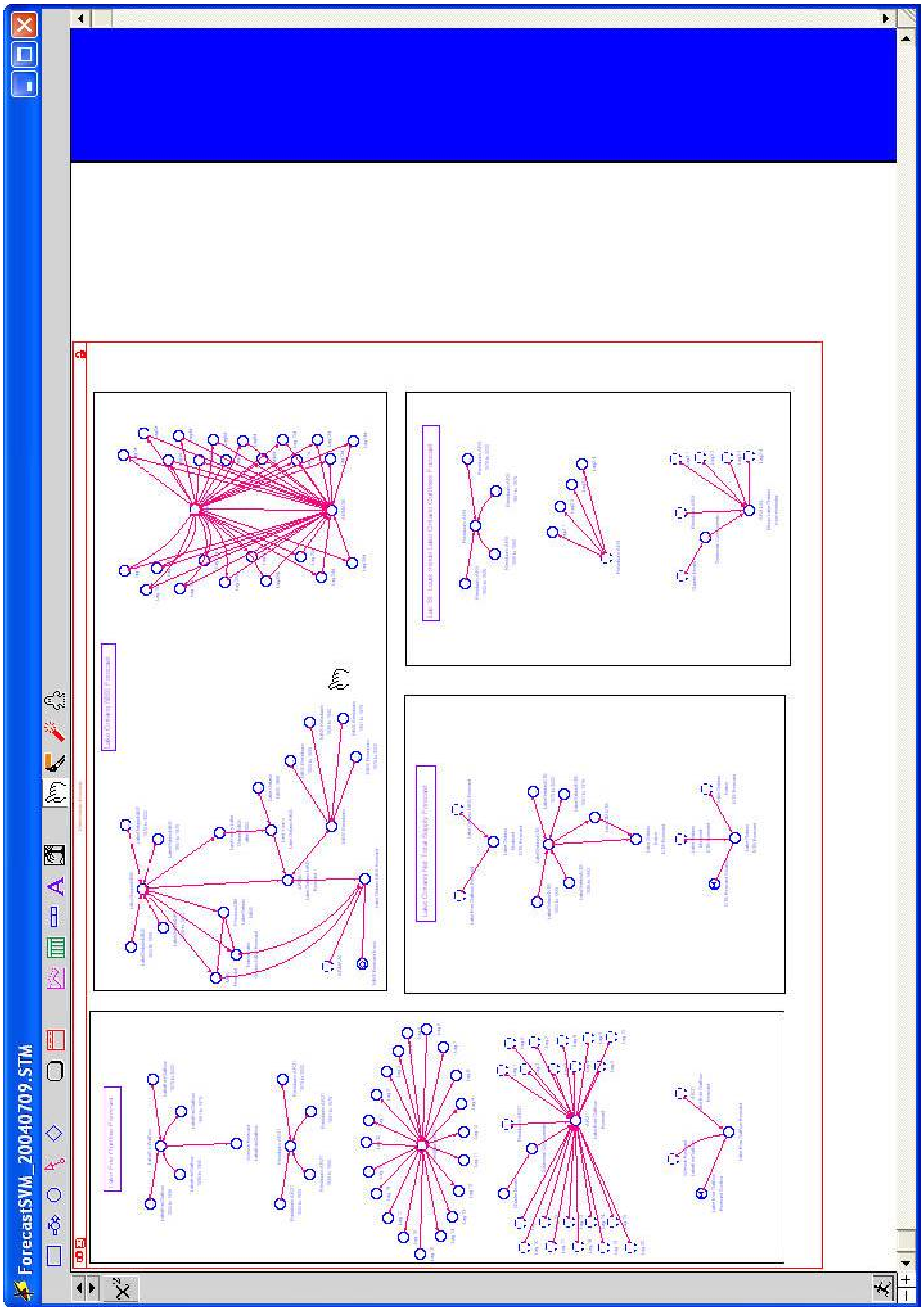


Figure 17. Stella® Model Level – Deterministic Forecast Implementation.

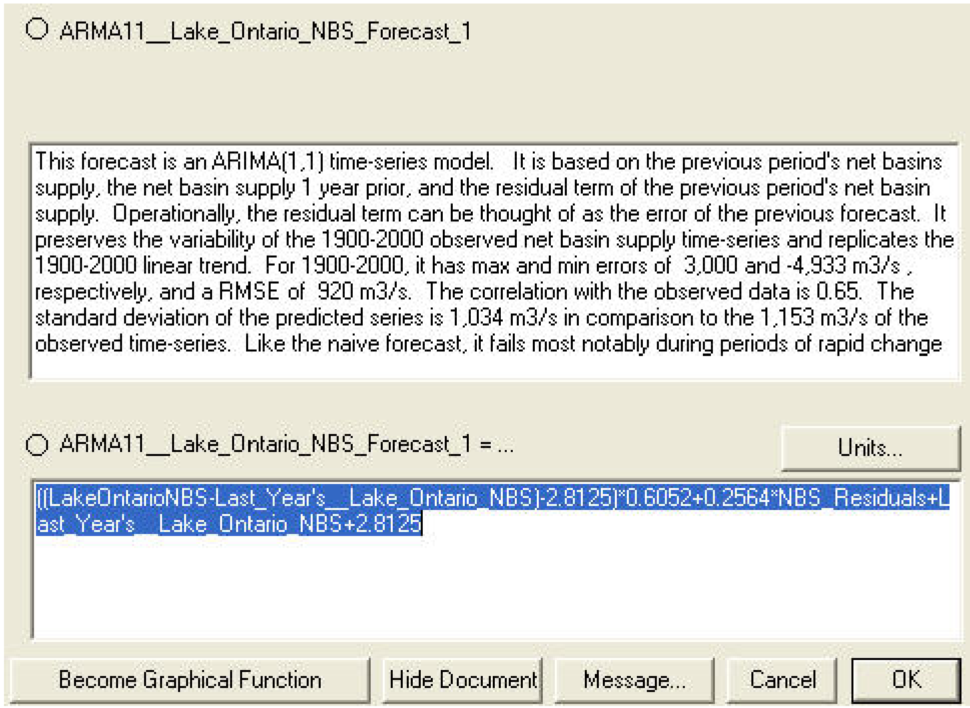


Figure 18. Variable dialogue box.

Summary

Several models are developed and presented for forecasting Lake Erie outflow, Lake Ontario net basin supply, Lac St. Louis – Lake Ontario flows, and Lake Ontario net total supply. The models are implemented in the Stella® modeling framework. The sole purpose of the models is for use in Lake Ontario regulation plan development. The models are not intended as a replacement of current operational forecast methods. The models have yet to be calibrated and tested with the climate change scenarios.

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Appendix A

Lake Erie Outflow Seasonal Components

[quarter month, value (cms)]

1, -180	17, 314	33, 32
2, -273	18, 376	34, 18
3, -271	19, 387	35, -41
4, -295	20, 369	36, -38
5, -370	21, 404	37, -4
6, -376	22, 301	38, -102
7, -338	23, 231	39, -82
8, -287	24, 255	40, -150
9, -290	25, 259	41, -134
10, -214	26, 221	42, -175
11, -99	27, 181	43, -65
12, -47	28, 164	44, -84
13, 78	29, 125	45, -120
14, 67	30, 110	46, -182
15, 149	31, 96	47, -103
16, 192	32, 78	48, -86

The seasonal components are the 1900-2000 quarter monthly means of the Lake Erie outflow with the 1900-2000 mean of 6,026 cms subtracted.

Appendix B

Lac St. Louis – Lake Ontario Outflow Seasonal Components

[quarter month, value (cms)]

1, -279	17, 1327	33, -599
2, -157	18, 1209	34, -603
3, -134	19, 1021	35, -575
4, -167	20, 778	36, -540
5, -126	21, 549	37, -485
6, -252	22, 336	38, -455
7, -363	23, 163	39, -415
8, -410	24, 24	40, -298
9, -211	25, -102	41, -228
10,-207	26, -229	42, -172
11, 35	27, -328	43, -117
12, 468	28, -403	44, -115
13, 1013	29, -461	45, -160
14, 1175	30, -520	46, -137
15, 1337	31, -548	47, -174
16, 1321	32, -574	48, -208

The seasonal components are the 1900-2000 quarter monthly means of the Lac St. Louis – Lake Ontario outflow with the 1900-2000 mean of 1,185 cms subtracted.