REGULATION OF LAKE CHAMPLAIN

HYDRAULIC APPENDIX

Report to

The International Joint Commission
(under the Reference of 29 March 1973)

by

The International Champlain-Richelieu Engineering Board

REGULARISATION DU LAC CHAMPLAIN

ANNEXE HYDRAULIQUE

Rapport à

La Commission mixte internationale
(en vertu du mandat du 29 mars 1973)

par

Le Bureau technique international Champlain-Richelieu
This report has been prepared by Messrs. S. Khubchandani and M. Sydor of Environment Canada, under the direction of the Hydraulics Committee.

OTTAWA

FEBRUARY 1974
REGULATION ANALYSIS
FOR THE CONTROL OF
LAKE CHAMPLAIN DISCHARGES

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1.1 Purpose

The purpose of the regulation analysis, presented in this report, is to formulate and then evaluate a number of possible regulation schemes for the control of levels and outflows of Lake Champlain. Further, comparison based on the hydrologic, economic and environmental impacts would identify scheme/s which the International Richelieu-Champlain Engineering (IR-CE) Board can recommend in its report to the International Joint Commission.

1.2 Objectives of Regulation

Obviously the aim of any regulation is to benefit as many interests as possible while at the same time minimizing any potential damage to other interests. The planning objectives of regulating the Richelieu-Champlain system were identified earlier. (1)

Basically, a regulation scheme consists of:

a) a set of objectives to be satisfied,

b) a forecast of net basin supplies (inflows),

c) a decision process or rules of operation to meet the given objectives.

The primary objective of the proposed development is to reduce the high lake stages which cause flooding. By computing frequencies

(1) These numbers denote references listed on Page 54.
of lake stages under natural (base case) conditions, and also with regulation, and using the stage-damage functions developed by the Economics Committee, annual damages are computed. The difference between the two annual damages represents benefits due to regulation.

Secondary benefits result from raising and stabilizing the natural minimum lake levels, and augmenting the natural mean low outflows. The former would improve the recreation potential and environmental habitat around the lake. The latter will improve water supply and sanitation along the river. According to the Economics Committee, it is not possible to quantify these secondary benefits.

The changes from the natural variation of lake levels would affect the flora and fauna. While some species and vegetations might suffer, others might thrive. The Environmental Committee has identified the affected environmental resources and examined the effect of varying lake levels. For the Canadian portion of the lake, which covers only about four per cent of the total lake area, an environmental matrix has been prepared for each month by a Consultant. The matrix shows the most desirable lake level for each resource as well as all the resources considered together. Other lake levels are assigned (environmental) ratios with respect to the desired level. While similar methodology was reportedly used by the States of Vermont and New York for their portion of the lake, the Environmental Committee do not recommend using numerical figures for environmental assessment for the lake as a whole.
1.3 Approach

Historical data from 1937 to 1972 of monthly mean lake levels and outflows have been used in the study. The outflows in the Richelieu River are converted into the net basin supplies (also called inflows) into Lake Champlain by adding algebraically the corresponding change in lake storage. For a particular regulation scheme, these inflows are routed, subject to a set of established constraints, through the proposed regulatory works at St-Jean, Quebec. These works not only lower the entire natural stage-discharge curve due to increased channel carrying capacity as a result of dredging, but also enable regulation of outflows by operation of the gates at the control structure.

A number of alternative regulation schemes were tried, using as constraints the minimum lake levels during different parts of the year and the minimum outflows into the river. As the study advanced, increasing input was made by the environmental group in defining these constraints.

A computer program was developed for this regulation analysis. This program in addition to normal routing of inflows scans the historical data so as to optimize the benefits. Complete foresight is thus assumed. Optimization first considers economic functions for which peak daily lake levels associated with particular monthly mean levels are used. Next the program optimizes the accumulated environmental ratios for the Canadian side.
The computer output provides for each scheme a histogram of regulated monthly mean lake levels, benefit-cost analysis, environmental analysis relating to Canadian interests only, and stage-duration curves. Using this evaluation with the natural condition as a base case, it is possible to compare all the schemes.

Selection of the scheme/s is based on a trade-off of economic benefits in favour of acceptance by the Environmental Committee.

It is very unlikely that the past series of historical supplies would recur in future. Synthetic hydrologic series are generated to simulate future supplies. Ten such series of 100 years each are used to test the selected regulation scheme. Results of this study are contained in a separate report on simulation analysis.

Operation rule curves have been developed for a selected scheme. These would need to be refined when the watershed prediction model contemplated as part of the future work, is completed.
SECTION 2
DATA

2.1 Hydraulic

Mean daily stages of Lake Champlain have been recorded at Rouses' Point, N.Y. since 1871, at Burlington, Vt. since 1907 and at Philipsburg, P.Q. since 1964. The levels of the Upper Richelieu River in Quebec are being gauged at Cantic since 1937, at St-Jean since 1924, at Fryer's Island Dam (both upstream and downstream of the dam) since 1939 and at Fryer's Rapids since 1937. The locations of all these gauges are shown in Figure 1. The flows of the Upper Richelieu River are being gauged at the Route No. 1 bridge at Chambly since 1937.

Mean daily lake stages at Rouses' Point, N.Y. and streamflows gauged at Chambly, 29 miles downstream, are used in this study. Examination of topographic maps shows that there is no major inflow into the Richelieu River in this reach. The streamflows at Chambly are therefore taken to represent the outflows from the lake. Error, if any, in such an assumption would be within the accuracy of streamflow measurements. Further, no time lag is assumed between the daily stages at Rouses' Point and streamflows at Chambly since it is observed that the peaks of flows as well as lake stages occur within a day or so and do not fluctuate greatly.

The lake stages at Rouses' Point, N.Y. and at Burlington, Vt. relate to the U.S. G.S. datum.* Over the period of record, there have been changes in this datum. The historical data has been corrected to account for these changes.

* All elevations in this report relate to U.S. G.S. datum. To convert to Canadian Geodetic Datum (C.G.D.), deduct 0.37 feet from these elevations.
Stage discharge curves relating the lake stages at Rouses' Point to the river discharges have been prepared in the previous studies. These were updated using all the available historical data from 1937 to 1972. Figure 2 shows the natural stage-discharge curve fitted to all the data. As was noted in the previous study, there is a wide scatter at the lower end of the curve.

Since the stage-discharge relationship is the basic tool for flow routing through the system, maximum accuracy in its derivation is necessary. A detailed study of this was therefore undertaken. Rather than combining the stage-discharge data for the entire historical period of 36 years, data for each year were plotted separately. Further data points for each month were identified. An interesting phenomenon was observed in all years. For the same outflow, at low lake levels, lake stages are always lower during rising flow period than during the falling flood period. At higher lake levels, this effect is reversed, although the difference is less marked. The extent of this variation which results in a looped stage-discharge curve varies from year to year. A typical example of this looping effect for the year 1969 is shown in Figure 3. The reverse loop, at higher outflows, is a function of the maximum flow recorded during the particular year.
This so called looping of the stage-discharge curve has obviously some physical explanation. Different premises such as a long narrow sloping lake or some inflow between the lake outlet at Rouses' Point and the stream gauging station have been put forth. Study of these causes could be a subject of academic research. In the absence of any identifiable relationship, actual stage-discharge curves for each individual year have been used for converting outflows into net basin supplies (inflows). Third degree polynomials were fitted to the two limbs of the curve as shown in Figure 3.

Area-capacity curves for Lake Champlain are shown in Figure 4. Both these curves in the range in which the lake normally fluctuates (elevation 92 to 102) are approximately straight lines. The average area of the lake is \(485\) square miles or \(310,000\) acres. The capacity per foot depth of the lake is \(4,600\) cfs months or about \(12\) billion cubic feet. This capacity is equivalent to \(0.67\) inches of runoff from the total watershed area of \(7,760\) square miles drained by the lake.

The proposed regulatory construction works at St-Jean \(^1\) would alter the natural stage-discharge curve. The entire curve would be lowered due to dredging of the shoal at St-Jean. The gates at the proposed structure provide flexibility of operation above this stage-discharge curve. Figure 5 shows the stage-discharge curves with operation of all the gates at various elevations. It is of course possible to operate at any intermediate point by adjusting the crest level and/or the number of gates.
Mean monthly lake stages, outflows and inflows are used for all analytical work in this study. Such monthly averages however cannot be used for assessing the flood damage. The latter result from high peaks lasting only for a few days during any particular month.

A statistical analysis was made to correlate the maximum daily levels with the average monthly levels as observed during the historical period. Linear regression equations have been derived to develop maximum daily lake levels for each month from the monthly means. Two equations were derived. One equation is for the maximum daily lake levels for the spring months (March to May) applicable for mean monthly lake levels higher than elevation 98.5 feet. The other is for the remaining part of the year. The straight line relationships derived are shown in Figure 6. These have been incorporated in the computer programs for determining flood damages.
SPRING MONTHS

\[ D = -0.01017 \pm 1.00758M \]

\[ D = 0.2 + 1.13(M - 93.0) + 93.0 \]
2.2 Economic

The basic economic data used in this study for the benefit-cost analysis of alternative regulation schemes consists of lake stage versus damage figures. These figures were compiled for the Economics Committee by McGill University Industrial Research for Canada (4) and the New York District of the Corps of Engineers for the U.S. (5).

For the Canadian side, damage figures are grouped under residential, commercial and agricultural sectors. These stage damage figures are presented in Table 2.1. On the United States side, damage figures are classified into structural and non-structural sectors. Structural damage data has been compiled separately for the States of New York and Vermont. These stage damage figures are presented in Table 2.2.

Discrete values of damages at different lake stages, as extracted in the above tables, are used for computing average annual damages. The computed present average annual damages are converted into equivalent average annual damages for the economic life of the project by multiplying with an equivalent factor. This factor based on an annual interest rate of 7 per cent, project economic life of 50 years and varying sub-period growth rate has been estimated by the Economics Committee (4,5) as follows:

<table>
<thead>
<tr>
<th>Equivalent Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Canada</td>
</tr>
<tr>
<td>New York State</td>
</tr>
<tr>
<td>Vermont State</td>
</tr>
</tbody>
</table>
TABLE 2.1

FLOOD DAMAGES ALONG RICHELIEU RIVER IN CANADA

(Based on 1972 figures)

<table>
<thead>
<tr>
<th>Stage of Lake Champlain in Feet (U.S.G.S. Datum)</th>
<th>Damages in $ x 1000</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Residential and Commercial</td>
</tr>
<tr>
<td>97.0</td>
<td>0</td>
</tr>
<tr>
<td>97.5</td>
<td>0</td>
</tr>
<tr>
<td>98.5</td>
<td>0</td>
</tr>
<tr>
<td>98.5</td>
<td>0</td>
</tr>
<tr>
<td>99.0</td>
<td>80</td>
</tr>
<tr>
<td>99.5</td>
<td>250</td>
</tr>
<tr>
<td>100.0</td>
<td>430</td>
</tr>
<tr>
<td>100.5</td>
<td>620</td>
</tr>
<tr>
<td>101.0</td>
<td>840</td>
</tr>
<tr>
<td>101.5</td>
<td>1,095</td>
</tr>
<tr>
<td>102.0</td>
<td>1,300</td>
</tr>
<tr>
<td>102.5</td>
<td>1,600</td>
</tr>
<tr>
<td>103.0</td>
<td>1,900</td>
</tr>
<tr>
<td>103.5</td>
<td>2,270</td>
</tr>
<tr>
<td>104.0</td>
<td>2,720</td>
</tr>
<tr>
<td>104.5</td>
<td>3,374</td>
</tr>
<tr>
<td>Stage of Lake Champlain in Feet (U.S.G.S. Datum)</td>
<td>Damages in $ \times 1000$</td>
</tr>
<tr>
<td>-------------------------------------------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td></td>
<td>Structural</td>
</tr>
<tr>
<td></td>
<td>New York State</td>
</tr>
<tr>
<td>97.0</td>
<td>0</td>
</tr>
<tr>
<td>97.5</td>
<td>0</td>
</tr>
<tr>
<td>98.0</td>
<td>0</td>
</tr>
<tr>
<td>98.5</td>
<td>2</td>
</tr>
<tr>
<td>99.0</td>
<td>3</td>
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<td>99.5</td>
<td>40</td>
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</tr>
<tr>
<td>102.5</td>
<td>620</td>
</tr>
<tr>
<td>103.0</td>
<td>860</td>
</tr>
<tr>
<td>103.5</td>
<td>1,233</td>
</tr>
</tbody>
</table>
2.3 Environmental

Environmental data is required to evaluate alternative regulation schemes and/or to formulate schemes aimed especially at environmental enhancement.

For the Canadian portion of the basin, which incidently covers only about 4 per cent of the lake area, preliminary environmental study was carried out by a Consultant. (2) This study examined the effect of various lake stages during each month on different species of fish and wildlife inhabiting this area. Overall effect on all such resources was represented by a ratio with the aggregate of the assigned value of the resource in the numerator and relative value of resource in the area in the denominator. A matrix for each month was proposed, giving for the full range of lake stages, environmental ratios at each stage. This ratio is a measure of the estimated capacity to support available resources at a particular water level against the optimum capacity of the region to support the same resources. The environmentally most desirable level during the month has a ratio of 1.0; other levels are compared with this. Typical environmental matrices for May-June in the Canadian study are presented in Table 2.3.

Environmental matrices were formulated for studies in the States of New York and Vermont. However, the Environmental Committee recommended not to use such numerical matrices for evaluation of alternative regulation schemes for a lake as a whole. Instead, based on its studies, the Committee suggested criteria for desirable lake stages during different months and limitations on rates of drawdown.
# Environmental Resources Table 2.3

## For Canada

### Month of May

<table>
<thead>
<tr>
<th>Level</th>
<th>Eel</th>
<th>Bass</th>
<th>Pike</th>
<th>Perch</th>
<th>Walleye</th>
<th>Br. Bullhd</th>
<th>Breeding</th>
<th>Staging</th>
<th>Muskrat</th>
<th>Beaver</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>1.0/10</td>
<td>1.0/10</td>
<td>7.0/10</td>
<td>1.0/10</td>
<td>0.0/10</td>
<td>8.0/8</td>
<td>1.0/4</td>
<td>0.0/10</td>
<td>1.0/10</td>
<td>4.0/6</td>
<td>24.0/68 = 0.353</td>
</tr>
<tr>
<td>101</td>
<td>1.0/10</td>
<td>1.0/10</td>
<td>8.0/10</td>
<td>1.0/10</td>
<td>0.0/10</td>
<td>8.0/8</td>
<td>1.0/4</td>
<td>0.0/10</td>
<td>1.0/10</td>
<td>4.0/6</td>
<td>25.0/68 = 0.368</td>
</tr>
<tr>
<td>100</td>
<td>1.0/10</td>
<td>3.0/10</td>
<td>9.0/10</td>
<td>1.0/10</td>
<td>0.0/10</td>
<td>8.0/8</td>
<td>1.0/4</td>
<td>0.0/10</td>
<td>6.0/10</td>
<td>4.5/6</td>
<td>33.5/68 = 0.493</td>
</tr>
<tr>
<td>99</td>
<td>1.0/10</td>
<td>10.0/10</td>
<td>9.0/10</td>
<td>8.0/10</td>
<td>8.0/8</td>
<td>1.0/4</td>
<td>0.0/10</td>
<td>7.5/10</td>
<td>5.0/6</td>
<td>49.5/68 = 0.728</td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>1.0/10</td>
<td>10.0/10</td>
<td>10.0/10</td>
<td>9.0/10</td>
<td>8.0/8</td>
<td>1.0/4</td>
<td>0.0/10</td>
<td>8.0/10</td>
<td>5.0/6</td>
<td>52.0/68 = 0.765</td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>1.0/10</td>
<td>10.0/10</td>
<td>10.0/10</td>
<td>10.0/10</td>
<td>8.0/8</td>
<td>3.0/4</td>
<td>0.0/10</td>
<td>10.0/10</td>
<td>6.0/6</td>
<td>58.0/68 = 0.853</td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>1.0/10</td>
<td>10.0/10</td>
<td>10.0/10</td>
<td>10.0/10</td>
<td>8.0/8</td>
<td>4.0/4</td>
<td>0.0/10</td>
<td>10.0/10</td>
<td>5.0/6</td>
<td>58.0/68 = 0.853</td>
<td></td>
</tr>
<tr>
<td>95</td>
<td>10.0/10</td>
<td>10.0/10</td>
<td>9.0/10</td>
<td>10.0/10</td>
<td>8.0/8</td>
<td>4.0/4</td>
<td>0.0/10</td>
<td>7.0/10</td>
<td>4.0/6</td>
<td>62.0/68 = 0.912</td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>10.0/10</td>
<td>5.0/10</td>
<td>7.0/10</td>
<td>10.0/10</td>
<td>8.0/8</td>
<td>4.0/4</td>
<td>0.0/10</td>
<td>6.0/10</td>
<td>1.0/6</td>
<td>51.0/68 = 0.750</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>10.0/10</td>
<td>1.0/10</td>
<td>8.0/10</td>
<td>8.0/10</td>
<td>7.0/8</td>
<td>4.0/4</td>
<td>0.0/10</td>
<td>3.0/10</td>
<td>1.0/6</td>
<td>40.0/68 = 0.588</td>
<td></td>
</tr>
<tr>
<td>92</td>
<td>10.0/10</td>
<td>1.0/10</td>
<td>3.0/10</td>
<td>6.0/10</td>
<td>6.0/8</td>
<td>2.0/4</td>
<td>0.0/10</td>
<td>1.0/10</td>
<td>1.0/6</td>
<td>34.0/68 = 0.500</td>
<td></td>
</tr>
</tbody>
</table>

### Month of June

<table>
<thead>
<tr>
<th>Level</th>
<th>Eel</th>
<th>Bass</th>
<th>Pike</th>
<th>Perch</th>
<th>Walleye</th>
<th>Br. Bullhd</th>
<th>Breeding</th>
<th>Staging</th>
<th>Muskrat</th>
<th>Beaver</th>
<th>Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>1.0/10</td>
<td>-0.0/10</td>
<td>5.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>1.0/4</td>
<td>-0.0/10</td>
<td>1.0/10</td>
<td>2.0/6</td>
<td>10.0/40 = 0.250</td>
<td></td>
</tr>
<tr>
<td>101</td>
<td>1.0/10</td>
<td>-0.0/10</td>
<td>5.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>1.0/4</td>
<td>-0.0/10</td>
<td>1.0/10</td>
<td>2.0/6</td>
<td>10.0/40 = 0.250</td>
<td></td>
</tr>
<tr>
<td>100</td>
<td>1.0/10</td>
<td>-0.0/10</td>
<td>5.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>1.0/4</td>
<td>-0.0/10</td>
<td>1.0/10</td>
<td>2.0/6</td>
<td>10.0/40 = 0.250</td>
<td></td>
</tr>
<tr>
<td>99</td>
<td>1.0/10</td>
<td>-0.0/10</td>
<td>5.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>1.0/4</td>
<td>-0.0/10</td>
<td>2.0/10</td>
<td>2.0/6</td>
<td>13.0/40 = 0.325</td>
<td></td>
</tr>
<tr>
<td>98</td>
<td>1.0/10</td>
<td>-0.0/10</td>
<td>5.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>2.0/4</td>
<td>-0.0/10</td>
<td>7.5/10</td>
<td>4.5/6</td>
<td>23.0/40 = 0.575</td>
<td></td>
</tr>
<tr>
<td>97</td>
<td>1.0/10</td>
<td>-0.0/10</td>
<td>5.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>3.0/4</td>
<td>-0.0/10</td>
<td>8.0/10</td>
<td>5.0/6</td>
<td>25.0/40 = 0.625</td>
<td></td>
</tr>
<tr>
<td>96</td>
<td>1.0/10</td>
<td>-0.0/10</td>
<td>5.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>4.0/4</td>
<td>-0.0/10</td>
<td>10.0/10</td>
<td>6.0/6</td>
<td>29.0/40 = 0.725</td>
<td></td>
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<td>10.0/10</td>
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<td>-0.0/8</td>
<td>4.0/4</td>
<td>-0.0/10</td>
<td>10.0/10</td>
<td>5.0/6</td>
<td>39.0/40 = 0.975</td>
<td></td>
</tr>
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<td>10.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>4.0/4</td>
<td>-0.0/10</td>
<td>7.0/10</td>
<td>2.0/6</td>
<td>32.0/40 = 0.800</td>
<td></td>
</tr>
<tr>
<td>93</td>
<td>10.0/10</td>
<td>-0.0/10</td>
<td>10.0/10</td>
<td>-0.0/10</td>
<td>-0.0/8</td>
<td>4.0/4</td>
<td>-0.0/10</td>
<td>3.0/10</td>
<td>1.0/6</td>
<td>26.0/40 = 0.650</td>
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2.4 Other

Snow survey data are collected and compiled every two to four weeks by the U.S. Geological Survey at about 20 stations in the States of New York and Vermont. Most of these stations have been recently established and the data tapers off quickly in the past. Snow survey data publications also give water equivalent measurements. This snow equivalent estimate expected to be the spring runoff was examined for each year with respect to the net basin inflows as already calculated. A plot of these is shown in Figure 7. The correlation in this plot indicates that a reliable technique for forecasting the net basin inflow can be achieved with a more precise analysis. Such analysis would consider temperature and rainfall along with water equivalent.

A long-term physiographic characteristic of this basin may be pointed out. The earth's crust in North America after being surcharged by glaciers thousands of years ago are slowly rebounding. This uplift is, however, not uniform. In the Lake Champlain Basin, the uplift is occuring at a faster rate in the north than in the south. Thus the north end of the Lake at the mouth of Richelieu River is estimated to be rebounding at 0.25 feet per century more than the southern end at Whitehall, N.Y.

The greater uplift in the north tends to act as a dam and causes the water levels to rise with respect to land in the south.
NOTE: 1960-65 DATA LESS ACCURATE
This is a dynamic natural phenomenon that is expected to continue. This long-term trend should be considered in planning as it affects discharges, natural marsh development and recession.
SECTION 3
COMPUTER MODEL

3.1 Development

A computer model was developed which routes the average monthly inflows (net basin supplies) through the system subject to the specified hydraulic constraints both in time and space. The following basic equation is used for reservoir routing:

\[
\frac{(I_t + I_{t+1})}{2} - \frac{(O_t + O_{t+1})}{2} = S_{t+1} - S_t
\]

where:
- \(I_t\), \(I_{t+1}\) are inflows at time intervals (months) \(t\) and \(t+1\)
- \(O_t\), \(O_{t+1}\) are corresponding outflows
- \(S_t\), \(S_{t+1}\) are corresponding lake storages.

The system is checked to ascertain the manner in which the control gates on the structure should be operated so as to respect the specified constraints. The constraints checked are firstly the specified outflow, secondly the lake stage and thirdly the rate of change in lake stage. For each set of constraints, the program determines the required crest elevation of control gates which in turn gives the cost of regulatory works.

In addition to simple routing, the dynamic programming technique is used to optimize objective functions. Two functions are examined in this case - economic and environmental. The economic function aims

* All computer work was carried out at Environment Canada in Ottawa.
at minimizing the flood damages, while the environmental function aims at maximizing the accumulated environmental ratio applicable to the Canadian portion of the basin only. The latter is assumed to be a measure of environmental enhancement.

At each stage of forward routing, the objective function is evaluated and time dependent functions are accumulated. By examining the accumulated function, the optimum function is determined by comparing all possible combinations of month \( t_{i+1} \) with month \( t_i \). This procedure is carried out until the final period \( t_n \). The path is then retraced backward through time \( (t_n, t_{n-1}, \ldots, t_1) \) to arrive at the most optimum route. It may be noted that this technique thus assumes perfect foreknowledge of the available inflows.

The process has thus complete certainty over the 37 years of historical occurrences. Other less complex analyses such as mass diagrams, frequency curves, duration curves use base of historical data in a similar fashion.

The above mathematical solution process can be thought of as a recursive search for the optimum path of achieving defined objectives within constraints. The model searches forward and retraces back after final computation is made, to determine the best solution. Mathematical approximations can be applied to minimize search areas. The continuous time element is required and enables interrelated constraints to be analyzed.

Hence for a regulation scheme with specified hydraulic criteria, the computer program determines the optimal route through...
the hydrologic time series so as to:

1. minimize total accumulated flood damage
2. minimize the construction cost of regulatory works (gates)
3. maximize total accumulated environmental ratio

For the optimal solution, the program then carried out a statistical analysis to determine the frequency of lake stages as described in paragraph 3.2. Using these frequencies, the program computes the average annual damages for each regulation scheme. It then makes a benefit-cost analysis. The results of this benefit-cost analysis and the environmental analysis (for the Canadian Portion only) as well as the specified hydraulic constraints of each scheme are abstracted in a computer printout at the end of the program.

Plotting routines provide computer plots of:

1. Histograms of average lake levels (to the tenth of a foot) for each month. These histograms show the number of times each level was reached, mean* and median** levels during each month, and levels with one standard deviation*** on either side of the mean.
2. Duration curves of lake stages as well as lake outflows for each month and maximum, minimum

* Arithmetic average of all values.
** Corresponding to average number of events.
*** Assuming normal distribution.
and average during the year.

3. Continuous hydrograph of monthly mean lake levels for the entire period of record examined.

3.2 Frequency Analysis

The purpose of frequency analysis is to determine the frequency (or the probability) of annual high lake stages both under the natural condition and with any regulation scheme. These frequencies and the stage-damage figures are then used to compute average annual damages in each case.

The time series of high lake stages is statistically analyzed and a specific frequency distribution is fitted to evaluate the frequency of extreme events beyond those in the data. Selection of an appropriate frequency (distribution) curve has to be based on an understanding of the hydrologic system and experience with other similar frequency series.

Initially, frequency analysis was made of lake stages using the method of maximum likelihood. On probability paper, the frequency curve was a straight line. The extension of the data series for extreme values was thus based on linear extrapolation of all the data. It was seen that this resulted in very high frequencies of extreme values. Also there were anomalies in that the frequency of extreme high events was in some regulation schemes higher than under natural conditions. An example of this plot is shown in Figure 8.

Obviously a more refined method of frequency analysis was thus called for. After discussions and studies, the following technique based on the method of plotting position was evolved.
All the annual high lake stages are ordered in magnitude of their flood stage. The frequency of each stage is computed on the basis of its plotting position. A linear regression using the least squares method was made for a set of six frequency points at a time. For the extreme values, a line through the last six points was extrapolated. At intermediate stages, three points above and three points below the stage were used for the straight line relationship. This eliminates different frequencies for stages that occur more than once in the time series. A typical step frequency curve resulting from this technique is illustrated in Figure 9.

The above revised method of frequency analysis is used in this study for computing economic effects of regulation. This method is believed to provide accurate estimates of frequency of lake stages.

For the United States, stage-damage figures have been given under structural and nonstructural sectors. The latter occur only during the summer period of June to October (inclusive). Two separate frequency analyses have thus been made - one for high annual lake stages (all year) which result in structural damage and the other for lake stages during summer only.
3.3 Economic Analysis

Stage-damage curves including equivalent factors are combined with the frequency of lake levels under each regulation scheme to compute damage frequency relationship. Step integration of damage frequencies provides average annual damages. Typical calculations which form part of the computer program are extracted from the Economics Committee Report \(^{(4,5)}\) and are illustrated in Table 3.1 and 3.2 for Canada and the United States respectively. The estimated annual damages are then compared with similar damages under the natural unregulated condition to compute net annual benefits under each scheme.

3.4 Environmental Analysis

The most desirable environmental levels during each month as given in the environmental matrix referred to in paragraph 2.3 are input in the computer program as target levels. Regulating the system as a function of these targets, the program optimizes by maximizing the accumulated environmental ratio. The optimized accumulated ratio is thus worked out for each regulation scheme. Each regulation scheme is compared with the natural unregulated condition by an index as follows:

\[
\text{Index} = \frac{\text{Accumulated ratio with regulation}}{\text{Accumulated ratio under natural condition}}
\]

This index is at best a very subjective measure of environmental impact. Some obvious deficiencies in the above analysis are:
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<th>FLOOD DISCH. STAGE (FT.) USGS (CFS)</th>
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<th>AT STAGE</th>
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<th>AVE. ANNUAL DAMAGES</th>
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<th>TOTAL (3)</th>
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**NOTE (1) = DAMAGES EXCLUDE AGRICULTURE INTERESTS (EQUIVALENT FACTOR = 1.71)**

**NOTE (2) = DAMAGES FOR AGRICULTURE ONLY (EQUIVALENT FACTOR = 1.71)**

**NOTE (3) = TOTAL ACCUMULATIVE AVERAGE ANNUAL DAMAGES (INCLUDES EQUVALENT FACTOR)**
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**NOTE (1) = DAMAGES IN NEW YORK STATE (EQUIVALENT FACTOR = 1.49)**

**NOTE (2) = DAMAGES IN VERMONT STATE (EQUIVALENT FACTOR = 1.56)**

**NOTE (3) = TOTAL ACCUMULATIVE AVERAGE ANNUAL DAMAGES (INCLUDES EQUIVALENT FACTOR)
1. It considers each month in isolation, disregarding residual or carry over effect from month to month.

2. It does not take into account mortality and recovery rate of species.

3. It is not related specifically to the critical period for each resource. This could be less than a month or may overlap between months.

In spite of the above shortcomings, the index does provide an additional tool for comparing various regulation schemes.

3.5 Operational Criteria

The development of the regulation schemes, as stated in Paragraph 3.1, was based on perfect fore-knowledge of the historic time series. In actual operation no such fore-knowledge is available, although some capability for forecasting spring net basin supplied could be developed. In the absence of any such capability at present, the following operational criteria was proposed mainly to illustrate the difference that the actual operation would make to the economics of the optimized scheme.

1. Complete flexibility of gate operation at any desired crest elevation throughout the year, with adjustment being made as required.

2. Defining as monthly targets the mean monthly lake levels of the optimized regulation scheme.

3. Continual adjustment of the gates so as to correct any deviation from the monthly target levels.
It will be noted that the above operational criteria represent a lower boundary. These could be improved by assuming greater forecasting capability. In fact, the operational criteria based on shorter time interval and forecasting capability will very likely improve the economics of optimized scheme based on mean monthly regulation.
SECTION 4
REGULATION SCHEMES

4.1 Formulation

All the regulation schemes formulated for this study are listed in Table 4.1. The table gives the hydraulic constraints for each scheme and the crest elevation of control gates at St-Jean required to meet these constraints. The latter has been determined by computer analysis.

Initially, 20 schemes in Series A through F were formulated, mainly to cover the full range of lake stage and flow parameters that could be varied. The histograms of these schemes (Plates 2 through 18) showed that as a result of the optimization process, the minimum specified lake levels became necessary during the pre-spring flood period of February - March. The lake levels drop gradually from July to January.

In nature, as the histogram of long-term mean lake levels presented in Plate 1 shows, minimum lake levels occur during September-October. Further, the lake levels start rising from January. This natural pattern of fluctuations would be altered by the regulation schemes which were aimed primarily at reducing flood damage.

The Environmental Committee does not favour any drastic alteration of the long-term natural histogram. While lowering of lake levels during the pre-spring flood period of February - March is essential to effect any moderation of extreme high stages, it was considered to be detrimental to aquatic life, particularly pike.
The Environmental Committee recommended a stable pattern of lake levels throughout the year except during spring floods. To formulate regulation schemes specifically to maintain and improve the lake environs such as aquatic, wildlife and wetland considerations, the Environmental Committee was asked to recommend the required hydraulic criteria. Its first attempt, designated scheme G-1 was a set of target maximum and minimum lake levels for each month of the year. These constraints were too broad and a scheme which could respect these could not be formulated.

The criteria of stable lake levels was used in the formulation of 12 schemes in Series H through K. Each scheme is designed to attain a particular more or less stable lake level, with a reduced range of fluctuations from year to year. The histograms of these schemes are presented in Plates 19 to 30. Later on schemes in Series M and N, were suggested by the Environmental Committee. Histograms of these appear in Plates 31 and 33.

At the meetings of the Board during the period of this study, a concept of minimum possible regulation on the lake was advanced. This concept was to formulate a scheme which would eliminate five extreme peaks and five extreme lows during the historical period of 1937 to 1972 being examined in this study. A histogram of natural lake levels, with five years of high peaks and five years of extreme lows deleted, is shown in Plate 32. As will be noted, this is almost identical to the natural histogram (Plate 1), thus indicating that there would be no flood damage benefits with such a regulation.
Thus, altogether 31 alternative regulation schemes as indicated in Table 4.1 were formulated.
### TABLE 4.1
HYDRAULIC CONSTRAINTS OF REGULATION SCHEMES

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<th>SCHEME IDENTIFICATION</th>
<th>MINIMUM LAKE LEVEL (USGS) IN FEET, DURING SUMMER (1)</th>
<th>MINIMUM LAKE OUTFLOW IN CFS</th>
<th>REQUIRED ELEVATION OF GATE CREST AT ST-JEAN IN FEET (USGS)</th>
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(1) Summer period is from May-October (inclusive)
(2) Winter period is from November - April (inclusive)
* These schemes have not been run.
4.2 Hydraulic Effects

The hydraulic effects of regulation may be examined with respect to extreme (both high and low) lake stages and extreme low lake-outflows.

a) Extreme high lake stages

The moderation of extreme high lake stages, which occur in April - May, is a direct function of the specified lake stage during February - March. Lake stages prior to February have almost no effect on the extreme high stages. Figure 10 shows a plot of regulated lake stages in February - March versus the corresponding high lake stages. The hydraulic criteria for minimum winter level specified in the regulation schemes as formulated could have been limited to stipulate such levels during only February - March.

The lowering of extreme high stage is accompanied by a shift in time of the rising limb of the flood hydrograph. However, it is estimated that even with maximum lowering, the peak flood would probably be delayed by less than a week.

b) Extreme low lake stages

Extreme summer low lake stages, which occur in September - October, can be prevented from falling below any desired elevation.

c) Minimum lake outflow

The long term mean of the minimum lake daily outflow, which occurs in September - October, is about 3,000 cfs. To increase this outflow beyond 3,000 cfs., storage is required on the lake. The amount of such storage is a function of the specified low lake stage and increases with the increase in the desired minimum flow.
Regulation of Lake Champlain
Pre-Spring Flood Lake Stage vs. Peak Flood Lake Stage

Environment Canada
Engineering Division

Figure 10

Drwg: RJT Date: Feb '74
In addition to the histogram of lake levels contained in Plates 1 to 36, the following plots illustrate the hydraulic effects of the regulation schemes:

- **Frequency Curves**: Plates H, I and J
- **Continuous Hydrograph of Lake levels**: Plates H-2-4, I-2-4 and J-2-4.

The last two have been prepared only for some selected regulation schemes.
4.3 Economic Effects

Three tangible benefits resulting from the regulation of Lake Champlain are:

1. Reduction in flood damages due to lowering of extreme high lake stages.

2. Recreational and environmental enhancement due to raising of low lake stages.

3. Improvements in water quality in the Richelieu River due to low flow augmentation.

The Economics Committee has provided stage-damage relationships which identify damages due to floods only. Based on this data, average annual flood damages have been worked out under natural unregulated conditions and under each regulation scheme, as per the method described in paragraph 3.3. The average annual flood benefits under each scheme consist of the reduction in the annual flood damages due to regulation.

Table 4.2 presents the results of benefit-cost analyses for all the regulation schemes. The total capital cost of regulatory work is allocated for each scheme to the three tangible benefits identified above.

The cost of regulatory works up to gate crest elevation of 92, the natural sill elevation of the St. Jean shoal, is proposed to be allocated to flood control. Incremental costs of providing higher gates above elevation 92 in order to raise the minimum lake level is proposed to be allocated to recreation and environmental enhancement. Further incremental costs of raising the gates so as to provide...
### TABLE 4.2

**ECONOMIC AND ENVIRONMENTAL ANALYSIS**

(All figures for benefits and costs are in thousands of dollars)

<table>
<thead>
<tr>
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| BENEFITS | |
| Average Annual Flood Damages, Natural Condition | 1358 | 1358 | 1358 | 1358 | 1358 | 1358 | 1358 | 1358 |
| Average Annual Flood Damages with Regulation | 381 | 380 | 382 | 402 | 380 | 381 | 380 | 386 |
| Average Annual Flood Benefits | 977 | 978 | 976 | 956 | 978 | 977 | 978 | 972 |

| COSTS | |
| Required Gate Crest Elevation (USGS) | 6287 | 6407 | 6456 | 6612 | 6176 | 6272 | 6390 | 6485 |
| Capital Cost of Regulatory Works | 92.9 | 93.8 | 94.15 | 95.2 | 92.0 | 92.78 | 93.68 | 94.35 |
| Capital Cost Chargeable to | |
| - Flood Control | 6174 | 6174 | 6174 | 6174 | 6174 | 6174 | 6174 | 6174 |
| - Recreation and Environment | 113 | 233 | 233 | 233 | 2 | 98 | 98 | 98 |
| - Water Quality | 0 | 0 | 49 | 205 | 0 | 0 | 118 | 213 |
| Annual Cost of Flood Control | 494 | 494 | 494 | 494 | 494 | 494 | 494 | 494 |

| BENEFIT-COST ANALYSIS | |
| Net Annual Flood Benefits | 483 | 484 | 482 | 462 | 484 | 483 | 484 | 478 |
| Benefit-Cost Ratio (for flood control only) | 1.97 | 1.97 | 1.97 | 1.94 | 1.97 | 1.97 | 1.97 | 1.96 |

<p>| ENVIRONMENTAL ANALYSIS | Canada only | |
| Accumulated Environmental Ratio under Natural Conditions | 347.8 | 347.8 | 347.8 | 347.8 | 347.8 | 347.8 | 347.8 | 347.8 |
| Accumulated Environmental Ratio with Regulation | 371.4 | 370.6 | 365.3 | 356.7 | 376.1 | 370.4 | 366.2 | 356.1 |
| Environmental Index | 1.07 | 1.06 | 1.05 | 1.03 | 1.07 | 1.07 | 1.05 | 1.02 |</p>
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#### ECONOMIC AND ENVIRONMENTAL ANALYSIS

(All figures for benefits and costs are in thousands of dollars)

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#### BENEFITS

- Average Annual Flood Damages, Natural Condition: 1358, 1358, 1358, 1358, 1358, 1358
- Average Annual Flood Damages with Regulation: 417, 418, 443, 448, 437, 502
- Average Annual Flood Benefits: 941, 940, 915, 911, 921, 856

#### COSTS

- Required Gate Crest Elevation (USGS): 92.0, 92.78, 95.42, 92.38, 95.36, 95.83
- Capital Cost of Regulatory Works: 6176, 6272, 6646, 6622, 6347, 6712
- Capital Cost Chargeable to:
  - Flood Control: 6174, 6174, 6174, 6174, 6174, 6174
  - Recreation and Environment: 2, 98, 98, 48, 173, 173
  - Water Quality: 0, 0, 374, 0, 0, 365
- Annual Cost of Flood Control: 494, 494, 494, 494, 494, 494

#### BENEFIT-COST ANALYSIS

- Net Annual Flood Benefits: 447, 446, 421, 417.4, 427.8, 362
- Benefit-Cost Ratio (for flood control only): 1.59, 1.90, 1.85, 1.84, 1.86, 1.73

#### ENVIRONMENTAL ANALYSIS (Canada only)

- Accumulated Environmental Ratio under Natural Conditions: 347.8, 347.8, 347.8, 347.8, 347.8, 347.8
- Accumulated Environmental Ratio with Regulation: 382.1, 382.4, 367.9, 387.0, 384.6, 368.3
- Environmental Index: 1.10, 1.10, 1.06, 1.11, 1.11, 1.06
### TABLE 4.2 (Cont’d)

**ECONOMIC AND ENVIRONMENTAL ANALYSIS**

(All figures for benefits and costs are in thousands of dollars)

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#### BENEFITS

- Average Annual Flood Damages, Natural Condition: 1358, 1358, 1358, 1358, 1358, 1358, 1358
- Average Annual Flood Damages with Regulation: 490, 491, 587, 529, 530, 699, 584
- Average Annual Flood Benefits: 868, 867, 771, 829, 828, 659, 774

#### COSTS

- Required Gate Crest Elevation (USGS): 92.9, 93.80, 96.49, 93.86, 94.49, 97.03, 95.13
- Capital Cost of Regulatory Works: 6287, 6047, 6822, 6415, 6505, 6915, 6601
- Capital Cost Chargeable to:
  - Flood Control: 6174, 6174, 6174, 6174, 6174, 6174, 6174
  - Recreation and Environment: 113, 233, 233, 243, 331, 331, 427
  - Water Quality: 0, 0, 415, 0, 0, 410, 0
- Annual Cost of Flood Control: 494, 494, 494, 494, 494, 494, 494

#### BENEFIT-COST ANALYSIS

- Net Annual Flood Benefits: 374, 373, 277, 335, 334, 165, 280
- Benefit-Cost Ratio (for flood control only): 1.75, 1.75, 1.56, 1.67, 1.67, 1.33, 1.36

#### ENVIRONMENTAL ANALYSIS (Canada only)

- Accumulated Environmental Ratio under Natural Conditions: 347.8, 347.8, 347.8, 347.8, 347.8, 347.8, 347.8
- Accumulated Environmental Ratio with Regulation: 361.1, 389.9, 362.2, 374.0, 360.5, 354.9, 344.1
- Environmental Index: 1.12, 1.12, 1.04, 1.07, 1.06, 0.96, 0.99
**TABLE 4.2 (Cont’d)**

**ECONOMIC AND ENVIRONMENTAL ANALYSIS**

(All figures for benefits and costs are in thousands of dollars)

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<td>Minimum River Discharge (CFS)</td>
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**BENEFITS**

Average Annual Flood Damages, Natural Condition | 1,358 | 1,358 |
Average Annual Flood Damages with Regulation | 802 | 1,176 |
Average Annual Flood Benefits | 556 | 182 |

**COSTS**

Required Gate Crest Elevation (USGS) | 96.12 | 96.64 |
Capital Cost of Regulatory Works | 6,760 | 6,847 |
Capital Cost Chargeable to
- Flood Control | 6174 | 6174 |
- Recreation and Environment | 586 | 673 |
- Water Quality | 0 | 0 |
Annual Cost of Flood Control | 494 | 494 |

**BENEFIT-COST ANALYSIS**

Net Annual Flood Benefits | 62 | -312 |
Benefit-Cost Ratio (for flood control only) | 1.12 | 0.36 |

**ENVIRONMENTAL ANALYSIS** (Canada only)

Accumulated Environmental Ratio under Natural Conditions | - |
Accumulated Environmental Ratio with Regulation | - |
Environmental Index | - |
storage to assure minimum lake outflows above 3,000 cfs, is proposed to be allocated to water quality benefits accruing in the downstream reach.

For flood control, the highest benefit-cost ratio (over 2.30) is attained for the schemes in Series B with minimum specified winter lake level of 92.0. This ratio decreases progressively with higher specified minimum lake stages as shown in Figure 11.

The incremental costs of regulatory construction works charged to recreation and environment and water quality, as depicted in Figure 12, are relatively very small. The benefits due to these, although not quantified, will no doubt be higher. However, in the absence of data, economically optimum regulation schemes in respect to these specific benefits cannot be identified.

4.4 Environmental Effects

Environmental effects of regulation schemes, for the Canadian portion only, are evaluated by an environmental index computed as described in paragraph 3.4. This index compares the effect of changes in lake stages on its environs with regulated conditions versus the same under natural condition.

The results of the environmental analysis for all regulation schemes are shown in Table 4.2. The highest value of environmental index is about 1.12 for schemes in Series J which call for a minimum lake stage of 94.0 all through the year.

It may be re-emphasized that this measure of environmental effects is subjective.
BENEFIT-COST RATIO = \( \frac{\text{ANNUAL FLOOD BENEFITS ONLY}}{\text{COST OF REGULATORY WORKS UP TO ELEVATION 92.0' ONLY}} \)

3000 CFS

ENVIRONMENT CANADA ENGINEERING DIVISION
REGULATION OF LAKE CHAMPLAIN BENEFIT-COST ANALYSIS FOR FLOOD CONTROL

DRWG: RJT DATE: DEC '73

FIGURE 11
ADDITIONAL CAPITAL COST OF REGULATORY WORKS IN $X,1000

MINIMUM SUMMER LAKE LEVEL IN FEET (USGS)

CHARGEABLE TO WATER QUALITY

ENVIRONMENT CANADA
ENGINEERING DIVISION

REGULATION OF LAKE CHAMPLAIN CAPITAL COST OF RECREATION AND WATER QUALITY IMPROVEMENT

FIGURE 12

DRAW: RJT  DATE: DEC '75
SECTION 5

CONCLUSIONS

5.1 Evaluation of Regulation Plans

All the 35 alternative regulation schemes have been evaluated on the basis of their economic and other considerations.

Scheme 1-2 with specified minimum lake level of 93.5 and minimum lake outflow of 3,000 cfs presents the best balance between benefit-cost ratio, minimum lake levels and lake outflows. It has therefore been selected in this study for developing an operational rule curve.

5.2 Operational Plan

Based on the criteria devised in Paragraph 3.5, optimized regulation scheme 1-2 was transformed into the corresponding operational scheme. It was seen that the flood benefits would be somewhat lower. Also to meet the required hydraulic criteria, some minor structural modifications were necessary. As a result of both these factors, the benefit-cost ratio was lowered by about 10 per cent. Similar reduction in the case of other schemes may also be expected.

5.3 Further Work Suggested

The current study reported herein is considered adequate for the feasibility stage. However, the following further work as shown in Table 5.1 would be necessary before the selected regulation scheme can be approved for operation.

It is recommended that the above work items be undertaken in the next phase of the study concurrently with the detailed engineering designs for the regulatory works. The U.S. Corps of Engineers, New York District and Environment Canada could be the lead agencies in the two
countries. The personnel already familiar with this study would probably be the best for the continuing phase. Depending on the manpower allocation, the next phase of the study can be completed within one year at a cost of about $150,000.
### TABLE 5-1

**FURTHER WORK RECOMMENDED FOR REGULATION STUDY**

<table>
<thead>
<tr>
<th>Work Item</th>
<th>Purpose</th>
<th>Estimated Time required in months</th>
<th>Cost in $</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Physical Model</td>
<td>To determine</td>
<td>6</td>
<td>50,000</td>
</tr>
<tr>
<td>Scale 1:50, to reproduce the proposed regulatory works on Richelieu River</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>i) Suitable configuration</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ii) Hydraulic factors</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iii) Desirability of fixed overflow section</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>iv) Construction arrangement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Prediction Model</td>
<td>To establish</td>
<td>4</td>
<td>30,000</td>
</tr>
<tr>
<td></td>
<td>i) Supply indicators</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>ii) Flood runoff correlations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3. Operation Rule Curve</td>
<td>To devise rules of reservoir operation to attain the regulation objectives, by examining synthetically generated series.</td>
<td>4</td>
<td>20,000</td>
</tr>
<tr>
<td>4. Regulation Analysis Based on Weekly Period</td>
<td>For some critical periods during the year, use weekly flows for better environmental assessment.</td>
<td>2</td>
<td>20,000</td>
</tr>
<tr>
<td>5. Sensitivity Analysis</td>
<td>To determine the tradeoff of economic benefits for obtaining specific environmental benefits.</td>
<td>2</td>
<td>15,000</td>
</tr>
<tr>
<td>6. Water Quality Benefits</td>
<td>To quantify the benefits due to low flow augmentation in the Richelieu River.</td>
<td>2</td>
<td>15,000</td>
</tr>
<tr>
<td>TOTAL</td>
<td></td>
<td></td>
<td>$150,000</td>
</tr>
</tbody>
</table>
REFERENCES


< 0.34% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -0.34% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION USGS
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION
PLATE 3

REGULATION HISTOGRAM

SCHEME A-2

02/02/76

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 94.00 USGS

WINTER MINIMUM ELEVATION = 92.00 USGS

RICHIEU R. MINIMUM FLOW = 3000. CFS

< +3% = ONE STANDARD DEVIATION ABOVE THE MEAN

< -3% = ONE STANDARD DEVIATION BELOW THE MEAN

< MEAN = LONG TERM MEAN MONTHLY ELEVATION

< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS.
PLATE 5

REGULATION HISTOGRAM
SCHEME A
03/02/74

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 94.00 USGS
WINTER MINIMUM ELEVATION = 92.00 USGS
RICHELIEU R. MINIMUM FLOW = 5000. CFS

< 34% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -34% = ONE STANDARD DEVIATION BELOW THE MEAN
MEAN = LONG TERM MEAN MONTHLY ELEVATION
MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS.
Plate 7

Regulation Histogram

Scheme 9-2

02/02/74

Constraints

Summer minimum elevation = 93.00 USGS
Winter minimum elevation = 92.00 USGS
Richelieu R. minimum flow = 3000. CFS

WINTER MINIMUM ELEVATION:

RICHELIEU R.

FLOH = 3000. CFS

MEOIAN = LONG TERM MEAN

MEDIAN = LONG TERM MEDIAN

MONTHLY ELEVATION USGS

< +3% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -3% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS

JAN.  FEB.  MAR.  APR.  MAY.  JUNE.  JULY.  AUG.  SEPT.  OCT.  NOV.  DEC.
PLATE 8

REGULATION HISTOGRAM

SCHEME 9-1

83/87/74

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 91.00 USGS
WINTER MINIMUM ELEVATION = 92.00 USGS
RICHELIEU R. MINIMUM FLOW = 4000.0 CFS

< +3% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -3% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS
PLATE 11
REGULATION HISTOGRAM
SCHEME C-2
03/02/74

CONTAINTS
SUMMER MINIMUM ELEVATION = 95.00 USGS
WINTER MINIMUM ELEVATION = 93.00 USGS
RICHELIEU R. MINIMUM FLOW = 3000. CFS

< +34% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -34% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS.
PLATE 12

REGULATION Histogram

SCHEME G-3

01/02/74

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 95.00 USGS
WINTER MINIMUM ELEVATION = 93.00 USGS
RICHELIEU R. MINIMUM FLOW = 4000. CFS

<++34% = one standard deviation above the mean
<--34% = one standard deviation below the mean
< MEAN = Long Term Mean Monthly Elevation
< MEDIAN = Long Term Median Monthly Elevation USGS
PLATE 13

REGULATION HISTOGRAM

SCHLME C-4
01/3/74

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 99.00 USGS
WINTER MINIMUM ELEVATION = 93.00 USGS
RICHELIEU R. MINIMUM FLOW = 5000. CFS

< +3% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -3% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS.
PLATE 14

REGULATION HISTOGRAM

SCHEME 0-1

01/02/74

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 95.00 USGS
WINTER MINIMUM ELEVATION = 94.00 USGS
RICHELIEU R. MINIMUM FLOW = 1000. CFS

< +34% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -34% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS
PLATE 18
REGULATION HISTOGRAM
SCHEME R-1
15/07/74

CONSTRAINTS
SUMMER MINIMUM ELEVATION = 95.00 USGS
WINTER MINIMUM ELEVATION = 95.00 USGS
RICHELIEU R. MINIMUM FLOW = 3000. CFS

< 34% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -34% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS.

JAN.  FEB.  MAR.  APR.  MAY  JUNE  JULY  AUG.  SEP.  OCT.  NOV.  DEC.
REGULATION HISTOGRAM

SCHEME 1-1
02/92/74

CONSTRUCTIONS

SUMMER MINIMUM ELEVATION = 93.50 USGS
WINTER MINIMUM ELEVATION = 93.50 USGS
RICHELIEU R. MINIMUM FLOW = 1000. CFS

MEAN = LONG TERM MEAN MONTHLY ELEVATION
MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS

*+34% = ONE STANDARD DEVIATION ABOVE THE MEAN
*-34% = ONE STANDARD DEVIATION BELOW THE MEAN

MONTHLY ELEVATION USGS.
PLATE 23
REGULATION HISTOGRAM
SCHEME 1-7
02/02/74
CONSTRAINTS
SUMMER MINIMUM ELEVATION = 93.50 USGS
WINTER MINIMUM ELEVATION = 93.50 USGS
RICHELIEU R. MINIMUM FLOW = 3000 CFS

<+34% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -34% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS.
PLATE 24

REGULATION HISTOGRAM

SCHEME 1-3

07/02/74

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 94.50 USGS
WINTER MINIMUM ELEVATION = 92.50 USGS
RICHELIEU R. MINIMUM FLOW = 5000. CFS

< +3% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -3% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS.

JAN. FEB. MAR. APR. MAY. JUNE JULY AUG. SEPT. OCT. NOV. DEC.
PLATE 25

REGULATION HISTOGRAM

SCHHE J-1

02/02/74

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 94.00 USGS
WINTER MINIMUM ELEVATION = 94.00 USGS
RICHELIEU R. MINIMUM FLOW = 1000. CFS

<+34% = ONE STANDARD DEVIATION ABOVE THE MEAN
<+34% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS
PLATE 26

REGULATION HISTOGRAM
SCHNEE D-2

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 94.88 USGS
WINTER MINIMUM ELEVATION = 94.00 USGS
NECHFEED D. MINIMUM FLOW = 1000, CFS

< +34% = ONE STANDARD DEVIATION ABOVE THE MEAN
< -34% = ONE STANDARD DEVIATION BELOW THE MEAN
< MEAN = LONG TERM MEAN MONTHLY ELEVATION
< MEDIAN = LONG TERM MEDIAN MONTHLY ELEVATION USGS

JAN.  FEB.  MAR.  APR.  MAY.  JUNE  JULY  AUG.  SEPT  OCT.  NOV.  DEC.
PLATE 27

REGULATION HISTOGRAM
SCHEME J-3
8/1/62/74

CONSTRAINTS

SUMMER MINIMUM ELEVATION = 94.00 USGS

WINTER MINIMUM ELEVATION = 94.00 USGS

RICHELIEU R. MINIMUM FLOW = 5000. CFS
PLATE 30

REGULATION HISTOGRAM

SUMMER MINIMUM ELEVATION = 94.50 USGS
WINTER MINIMUM ELEVATION = 94.50 USGS
RICHELIEU R. MINIMUM FLOW = 6000, CFS

+34% = ONE STANDARD DEVIATION ABOVE THE MEAN
-34% = ONE STANDARD DEVIATION BELOW THE MEAN
MEAN = LONGTERM MEAN MONTHLY ELEVATION
MEDIAN = LONGTERM MEDIAN MONTHLY ELEVATION USGS
PLATE 36

NATURAL (Incomplete Record)
5 with 4 Low Years
Removed
STAGE - DISCHARGE RELATION H-2
AT THE BORDER (CROSS SECTION 109)

LAKE LEVEL U.S. DATUM
94.00
98.00
102.00

DISCHARGE IN 1000 CFS
0.00 5.00 10.00 15.00 20.00 25.00 30.00 35.00 40.00 45.00 50.00

DAM IN FULL OPEN POSITION
CREST AT ELEV. = 92.0
CREST AT ELEV. = 93.0
CREST AT ELFV. = 94.0

PLATE H-2-1
DURATION ANALYSIS OF LAKE CHAMPLAIN DISCHARGE H-2

PLATE H-2-2
STAGE - DISCHARGE RELATION I-2
AT THE BORDER (CROSS SECTION 109)

DAM IN FULL OPEN POSITION
CREST AT ELEV. = 92.0
CREST AT ELEV. = 93.0
CREST AT ELEV. = 94.0
LAKE CHAMPLAIN DISCHARGE AND LAKE LEVEL HYDROGRAPHS I-2
STAGE - DISCHARGE RELATION J-2
AT THE BORDER (CROSS SECTION 109)

DAM IN FULL OPEN POSITION
CREST AT ELEV. = 92.0
CREST AT ELEV. = 93.0
CREST AT ELEV. = 94.0