LAKE MEMPHREMAGOG
VERMONT
A HYDROLOGIC AND HYDRAULIC ANALYSIS

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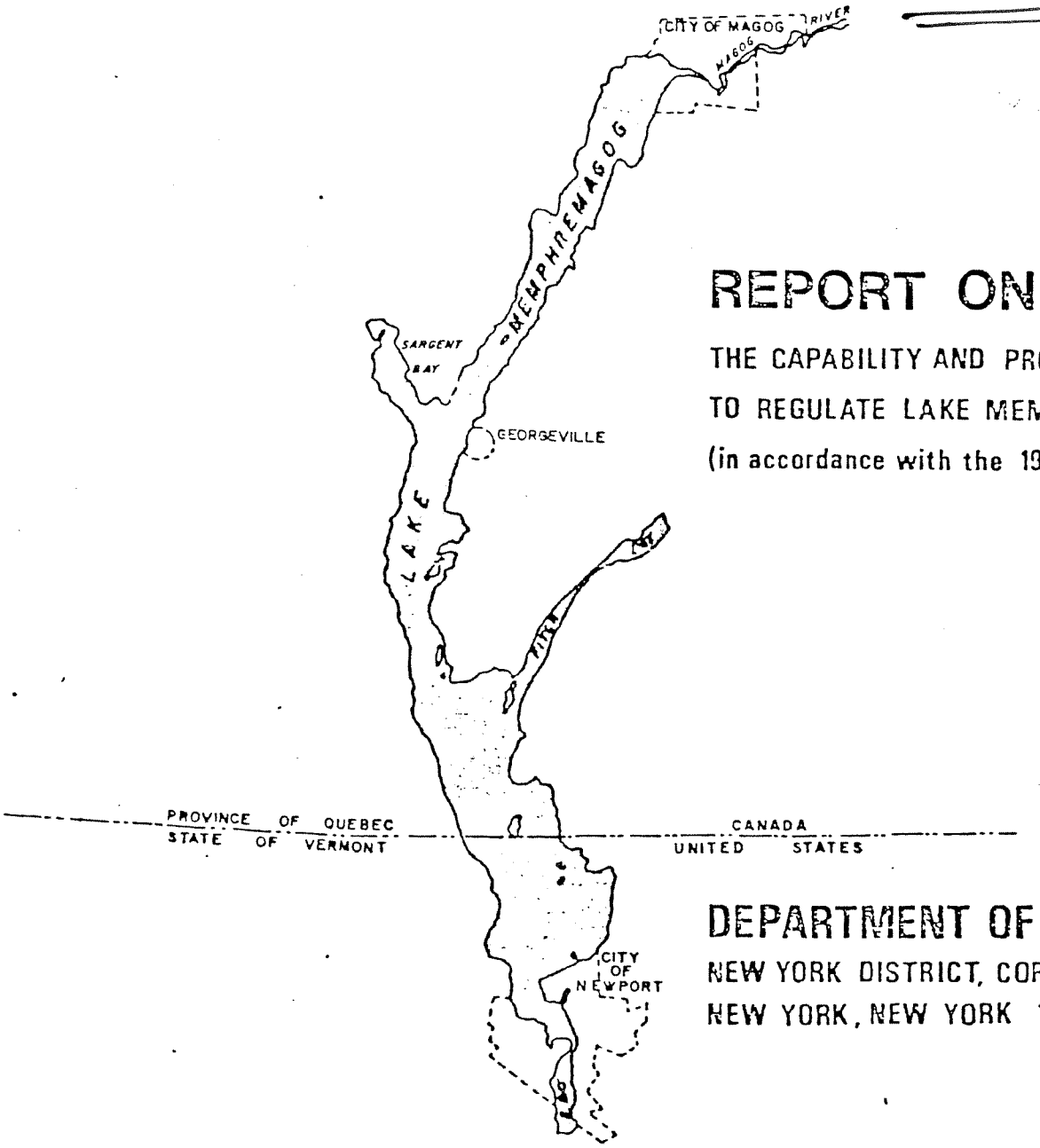

REPORT ON

THE CAPABILITY AND PROCEDURE
TO REGULATE LAKE MEMPHREMAGOG
(in accordance with the 1935 agreement)

DEPARTMENT OF THE ARMY
NEW YORK DISTRICT, CORPS OF ENGINEERS
NEW YORK, NEW YORK 10007

Anderson-Nichols & Co., Inc.
BARRE, VERMONT 05641

MARCH 1978

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VERMONT

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for

Department of the Army

New York District, Corps of Engineers

New York, New York 10007

Prepared By

Anderson-Nichols & Company, Inc.

Consulting Engineers

Contract No. DACW51-77-C-0067

March 1978

TABLE OF CONTENTS

	Page
INTRODUCTION	1
PURPOSE OF STUDY	1
SUMMARY OF FINDINGS	2
AUTHORITY	3
ACKNOWLEDGEMENTS	4
BACKGROUND	5
STUDY AREA	5
HISTORY	7
PARTIES OF INTEREST	10
OUTLET CONTROL	12
OUTLET DESCRIPTION	12
DOMINION TEXTILE DAM	14
Description of the Dam	14
Method of Operation	16
Discharge Analysis	16
OUTLET CHANNEL	21
Topographic Data	21
Hydraulic Analyses	22
Results of Analyses	24

LAKE HYDROLOGY 28

INFLOW ROUTING 28

PREDICTIVE MODEL 31

LAKE GRADIENT 37

CONCLUSIONS 39

REFERENCES 43

APPENDICES

1. Individual Sluice Gate Rating Curves Obtained from Dominion Textile, Ltd.

2. Mean Daily Water Levels, Lake Memphremagog at Newport, Vermont

LIST OF FIGURES

No.	Description	Page
1	Lake Memphremagog Drainage Basin Map	6
2	Magog River (Outlet Channel)	13
3	Dominion Textile Co. Ltd. Hydroelectric Dam	15
4	Stage Discharge Curve for Dominion Textile Co. Ltd. Hydroelectric Dam	20
5	Stage-Discharge Curve for Lake Memphremagog	25
6	Flow Profiles for Magog River	27
7	Stage-Area Curve for Lake Memphremagog	30
8	Rating Curve for Black River Stream Gage	34
9	Routing Curve for Lake Memphremagog	35

LIST OF TABLES

No.	Description	Page
I	Stage-Discharge Relationship for the Dominion Textile Co. Ltd. Hydroelectric Dam	19
II	Gaging Stations of the Lake Memphremagog Basin	28

LAKE MEMPHREMAGOG

VERMONT

A Hydrologic and Hydraulic Analysis

INTRODUCTION

PURPOSE OF STUDY

The purpose of this study was to improve the available information with regard to the capability and procedure to regulate the Lake Memphremagog water levels in accordance with the 1935 International Agreement.* More specifically, this Report is intended to provide the State of Vermont and other interested parites, with an analysis of the hydrologic and hydraulic characteristics of the lake which affect the water levels during periods of high runoff and flooding. In addition, the purpose of the study was to determine the physical limitations imposed by the Dominion Textile Dam and the outlet channel to the regulation of the lake levels, and to develop a model for a key tributary of the lake which will enable the regulation of the discharges from Lake Memphremagog to minimize the time the levels exceed the upper limit of the international agreement.

The primary emphases of this study were to:

a) Examine the hydraulic capabilities of the outlet structure for Lake Memphremagog.

b) Determine the hydraulic characteristics of the Magog River from the outlet structure to Lake

*Included on Page 7.

Memphremagog and compute the flow profiles through this reach to determine the effect of the channel on lake levels.

c) Develop a stage-discharge relationship for Lake Memphremagog.

d) Correlate the inflow with the outflow through reservoir routing procedures and define the basin inflow for selected years of record.

e) Correlate the routed inflow as computed above with the existing tributary stream gage data and establish a relationship which will enable the prediction of inflow and lake level stages.

f) Compare the lake levels as recorded at the gages on Lake Memphremagog at Newport, Vermont and Magog, Quebec to determine the gradient of the Lake.

SUMMARY OF FINDINGS

This Report presents the results of the hydrologic and hydraulic study of Lake Memphremagog. The discharge capacity of the Dominion Textile Dam was computed and the resulting rating curve has been included in the report as well as the stage-discharge relationship for the lake for the condition when all gates at the dam are open. From the analysis of the discharge capacity of the dam and the backwater computations for the outlet channel it is apparent that the outlet channel controls the level of the lake when all the gates are open at the dam. Substantial head losses occur

in the outlet channel at the site of the old dam, the restricted area of the channel downstream of the Merry Bridge and at the Merry Bridge. However, it is the hydraulic capacity of the channel in the vicinity of the bridge which controls the level of the lake when all the gates are open at the dam.

Through the application of reservoir routing techniques, a reasonably good correlation has been established between the flows on the Black River and the stage and discharge of the lake. This correlation should permit a more responsive procedure of operation of the control structure at the Dominion Textile Facilities within the natural constraints imposed by the outlet channel.

An analysis of the lake levels at the gages at Newport, Vermont and Magog, Quebec established an average difference in elevation of 0.17 feet or a gradient 0.0061 feet per mile when adjusted for the difference in datums. This gradient appeared to be constant for all flow conditions except during periods of high net inflow to the lake when an apparent surge effect was noted.

AUTHORITY

This report has been prepared for the State of Vermont under the provision for assistance by the Corps of Engineers in such investigations contained in Section 22 of the 1974 Water Resources Development Act (Public Law 93-251) which

states that:

"(a) The Secretary of the Army, acting through his Chief of Engineers, is authorized to cooperate with any State in the preparation of comprehensive plans for the development, utilization, and conservation of the water and related resources of drainage basins located within the boundaries of such State and to submit to Congress reports and recommendations with respect to appropriate Federal participation in carrying out such plans."

The report was prepared by Anderson-Nichols & Company, Inc. for the New York District of the Corps of Engineers.

ACKNOWLEDGEMENTS

Assistance in the investigation is gratefully acknowledged from the following:

1. Messrs. Stanley Maisel and Larry Petrosino, New York District, Corps of Engineers
2. Messrs. Charles Planzer and Normand Clement, Dominion Textile Limited
3. Mr. William F. Farrell, Newport, Vermont
4. Mr. Jean Bourassa, Hydro-Sherbrooke, City of Sherbrooke
5. Messrs. Yvan Carrier and Jacques Deziel, Department of National Resources, Government of Quebec
   Natural
6. Mr. Stewart Hopps, Canadian Department of Environment
7. Mr. David Clough, Department of Water Resources, Vermont Agency of Environmental Conservation

BACKGROUND

STUDY AREA

Lake Memphremagog is an international body of water, located in Northern Vermont on the border between the United States and Quebec, Canada. It has a total surface area of 40.0 square miles, of which 9.8 square miles are in Vermont (25 percent) and 30.2 square miles are in Quebec (75 percent). The lake has a maximum length of 27.7 miles and a maximum width of 3 miles with its major axis oriented in a north-south direction. It has a maximum depth of 351 feet which occurs in the Canadian portion of the lake. The lake's mean depth is 51 feet and volume is approximately 13,056,000 acre-feet. The outlet of Lake Memphremagog is the Magog River which flows in a north-easterly direction until it joins with the St. Francis River at Sherbrooke, Quebec.

The drainage area of the Lake Memphremagog basin, is 682 square miles, of which 484 square miles are in Vermont (71 percent) and 198 square miles are in Quebec (29 percent). The lake is fed principally by three streams which all enter the lake in the immediate vicinity of the City of Newport and constitute 65 percent of the total drainage area of the lake. They are the Black River, the Barton River and the Clyde River with drainage areas of 134, 174 and 142 square miles respectively. Lying in

a relatively low area east of the Green Mountains in the Vermont Piedmont areas, the Lake Memphremagog watershed can best be described as being hilly to mountainous. It has a somewhat regular fan-shaped appearance, focusing on Lake Memphremagog at the North end of the basin. Elevations range from 682 feet m.s.l. at the shoreline at Lake Memphremagog to 3,330 feet m.s.l. at Gore Mountain located at the eastern boundary of the watershed.

HISTORY

The level of Lake Memphremagog has been artificially regulated for more than 200 years dating back to a dam first built and used by the Indians for fishing to the present dam and hydroelectric facilities constructed by Dominion Textile Limited in 1920. For a more thorough discussion of the history of the structures at the outlet of Lake Memphremagog the reader is referred to the May 14, 1934, "Report upon the Levels at Which Lake Memphremagog Should be Maintained" prepared by the International Lake Memphremagog Board, and on file at the office of the New York District Corps of Engineers.

The above mentioned report was prepared in response to a complaint by the citizens of the City of Newport and vicinity in March, 1920 expressing concern that the Dominion Textile Company had raised the dam, causing higher lake levels and damages to their property and contemplated

further raising of the lake with the construction of the new control structure. The complaint also expressed concern that the company would enlarge the lake outlet for the purpose of drawing the lake down further during periods of extreme low-water.

A two-man engineering board was established in 1920 with one member each from the United States and Canada to study and make recommendations as to the level or levels at which the lake should be maintained. After considerable investigation of the structures and methods of regulation of the lake in the past the Board recommended in 1934:

(a) "That the levels of the lake shall continue to be regulated in accordance with the rights of regulation held and practiced by the Dominion Textile Company at the time of the signing of the Boundary Waters Treaty in 1909, i.e. the levels under conditions of normal flow to range between an upper elevation of 682.87 old datum or 682.70 Geodetic Survey of Canada 1923 Adjustment, and a lower limit of 678.85 old datum or 678.98 under the 1923 adjustment".[1]

[1]All elevations contained in this report, unless otherwise noted, are referenced to the Geodetic Survey of Canada datum, (GSCD) under the 1923 Adjustment. This datum is 0.3 feet lower than the datum of the USGS gage at Newport, Vermont.

(b) "That during times of flood the sluiceways of the dam shall be sufficiently opened to ensure that the overflow from the lake shall be unobstructed by the dam, the flood water drawn off, and the water level in the lake reduced to the normal regulated level of 682.70 as rapidly as possible".

These recommendations were subsequently agreed to by both governments in 1935.

Since completion of the report in 1934 the International Lake Memphremagog Board has continued to monitor the levels of the lake and address formal complaints to the Board. During the period between 1935 and 1964, there have been three major problems of concern brought to the attention of the Board and only one of these involved formal action by the Board.

(1) In 1957 when the Citizens Power Company began to construct a dam on the Clyde River, there was considerable concern over the effect that the dam would have on the land-locked salmon.

(2) Complaints regarding damage at Newport as a result of high lake levels were received by the Board in 1951, 1952 and 1959. These complaints led to the issuance of the second report of the Board in 1961.

(3) In early 1964, the City of Sherbrooke proposed to divert water from Lake Memphremagog for its water supply

and concern was expressed that the diversion would affect the lake levels.

Since 1964, there were no major actions by the Board. However, beginning in 1969, high lake levels have again brought concern and formal complaints from abutting land owners and the recreation interests on the lake.

PARTIES OF INTEREST

Lake Memphremagog represents a valuable natural resource to the area. It is used extensively for recreation, provides an excellent habitat for fish, waterfowl and other wildlife, furnishes water for hydropower and domestic and industrial water supplies and is used as the receiving waters for sewage effluent. While the lake is a major asset to the area, it also presents numerous concerns to its users. In addition to the fact that many of the uses represent competing demands, there are problems of erosion, flooding and water quality. Although it is beyond the scope of this report to examine these uses and problems in detail, the major parties of interest concerned with the water levels and related problems of Lake Memphremagog are outlined below.

Dominion Textile Limited owns and operates the dam and hydroelectric plant which regulate the levels of Lake Memphremagog. In addition to their use of these facilities to generate a portion of their electric demand, they also

obtain water from the lake for use in their manufacturing plant.

The city of Newport's principal interest in the levels of Lake Memphremagog is the influence of the water levels on their municipal and private recreation facilities and the erosion and flood damage effects of the high lake levels to private property primarily in the Bluff's area.

Public recreation facilities and beaches are also located at Perkin's Landing, Knowlton Landing, Bryant's Landing, Georgeville, Cederville, and the city of Magog.

In addition to the recreational interests of the city of Magog, the city obtains its water supply from the lake and has hydroelectric generating facilities on the Magog River.

Memphremagog Conservation Incorporated (MCI), representing more than 1000 members from both Canada and the United States, has as its principal objective the general protection of the environment in the drainage basin of Lake Memphremagog and is primarily concerned with the recreational use of the lake.

There are numerous downstream users which are also interested in recreation. Lake Magog, located downstream of the city of Magog, has considerable recreational development and the city of Sherbrooke has public beaches on the Magog River. These downstream recreational facilities are principally concerned with minimum flows from Lake

Memphremagog to maintain adequate water levels and provide sufficient dilution of the domestic waste water discharges into the Magog River. Conversely, too much flow reportedly creates downstream flooding problems.

The city of Sherbrooke is also interested in the releases from Lake Memphremagog because they own and operate four hydroelectric facilities on the Magog River. In addition, the city obtains its water supply from Lake Memphremagog.

OUTLET CONTROL

OUTLET CHANNEL DESCRIPTION

Lake Memphremagog discharges into the Magog River at the north end of the lake in the city of Magog. Located downstream from the mouth of the lake on the Magog River is the Dominion Textile Dam which regulates the levels of the lake. The outlet channel between the lake and the dam is approximately 5,000 feet long and has an average width of approximately 300 feet. The stream bed elevations in the channel vary from 660 feet at the dam to 677 feet near the lake. Located in this reach of the river are the visible remnants of the original dam, just upstream of the present dam, and the Merry Bridge further upstream near the mouth of the lake. A plan of the outlet channel is included as Figure 2.

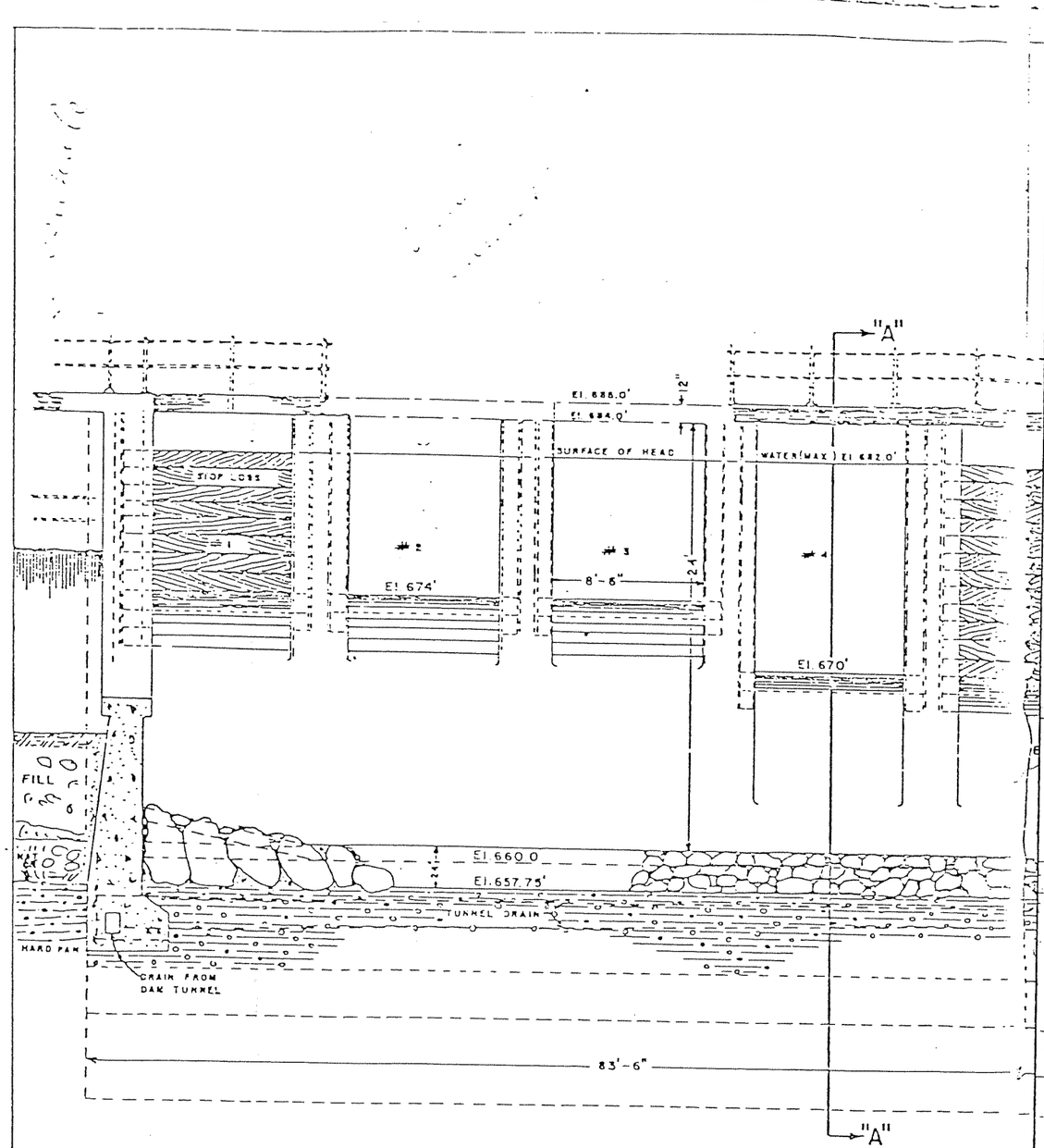
The outlet channel and the dam function as a system which provide the outlet control for the lake. To determine the extent and relationship of the control exercised by the outlet channel and the dam, the discharge capacity of the dam and the channel were computed.

DOMINION TEXTILE DAM

Description of the Dam

The present structure, built in 1920, to replace the original dam of 1882, consists of a combined power house and dam. The dam is situated at the south end of the power house. It is a concrete structure, composed of a total of seven sluices, connected to an earth embankment which extends upstream along the south bank of the river to the high ground. The sluices are each 8.5 feet wide. Numbering them from the power house southward, the first six are controlled by means of stop logs while the seventh is equipped with a manually operated sluice gate. Numbers 1, 2 and 3 have their sills at elevation 674.0, numbers 4, 5 and 6 at elevation 670.0 and number 7 at elevation 666.0. The dimensions and elevations of the dam were obtained from the detail drawings prepared for Dominion Textile Limited dated April 16, 1925. A sketch of the dam showing the general characteristics is attached as Figure 3.

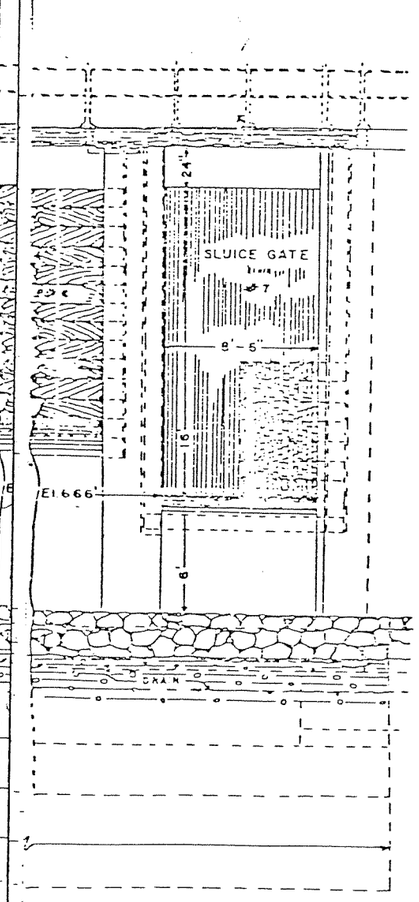
The generating facilities of the power house consists of two 51-inch William Hamilton vertical turbines of 1500 h.p. each, operating under an average head of 25 feet. Each

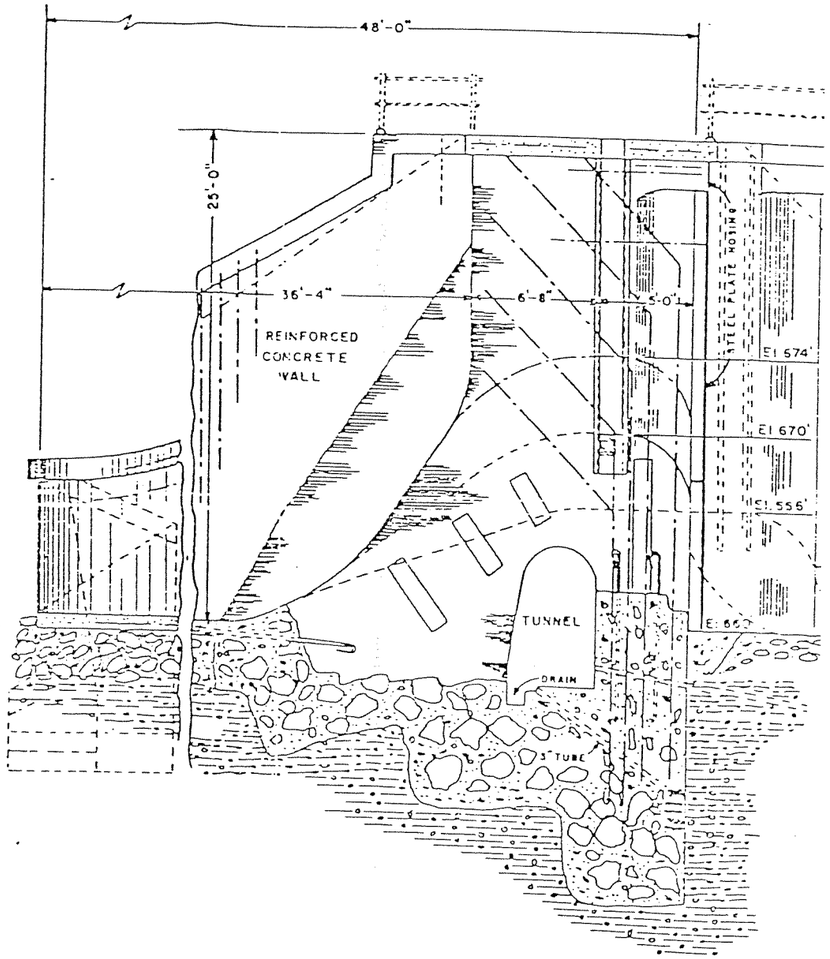


ELEVATION OF DAM

SCALE 0 4 8

1/8" = 1'-0"





SECTION "A"-"A"

SCALE 0 4 8

1/8" = 1'-0"

NOTE:
Prepared from Drawing No. 6/100 Dated April 16, 1925. Obtained from Dominion Textile Co., Limited.

DOMINION TEXTILE CO., LTD.
HYDRO-ELECTRIC DAM
JANUARY 1978

turbine is connected to a 1000 kilowatt Canadian General Electric A.C. generator.

METHOD OF OPERATION

Under normal flow conditions usually the only discharge from the lake is through the two turbines in the process of the generation of electricity. The combined maximum discharge capabilities of the two turbines is approximately 1300 cfs. Whenever the generation facilities are shut down, minimum flow releases are generally provided for by opening the sluice gate.

During anticipated periods of high flows, such as spring runoff, or high lake levels the gates are opened, as required, to pass the flows. The normal procedure for operation is to open the gates from right to left (descending order) by removing all the stop logs from a gate at the same time. Since the sluice gate at gate No. 7 permits more flexibility of operation than the stop logs, it is adjusted to provide for fine control of the discharges.

Records of the method of operation have been kept since 1963 by Dominion Textile Limited. These records include water levels at the dam and the lake, flow through each turbine, number of stop logs removed, flow through each sluice, and the total discharges through the control structure.

DISCHARGE ANALYSES

In 1963, discharge rating curves were prepared for

Dominion Textile by Waldo Faucher, hydraulic engineer. A separate set of discharge rating curves were prepared for sluices 1, 2 & 3, another set of curves for sluices 4, 5, & 6, and a third set for sluice gate No. 7. A fourth set of rating curves was also prepared for the generators. All the above mentioned rating curves are presented in Appendix I. These rating curves have been the basis for all the recorded discharges at the dam.

As the first step in the hydraulic analysis of the outlet control of the lake these rating curves were reviewed and evaluated as to their accuracy and reasonableness. Because it is the operating procedure of Dominion Textile to remove all stop logs from any given sluice at the same time and obtain finer control by varying the sluice gate at sluice No. 7, only the curves for the sluices wide open were analyzed for Gates 1 through 6. The rating curves for Gate No. 7 were examined for both weir flow and orifice flow operating conditions. The discharge analysis performed for this study was based on the assumption that the spillways conformed to the Standard Spillway Shapes developed by the U.S. Army Corps of Engineers Waterways Experiment Station (WES). The rating curves were prepared in accordance with the engineering and design data of Engineering Manual 1110-2-1603 (Hydraulic Design of Spillways).

The basic equation used to compute the discharge was:

$$Q=CLH^{\frac{3}{2}}$$

where Q= total discharge in cubic feet per second

C= discharge coefficient

L= effective length of the spillway in feet

H= head on the crest in feet

To compute the discharge for Gate No. 7 with the gate partially open the basic equation used was:

$$Q= C_d \sqrt{2g}\ L\ (H^{\frac{3}{2}} - H_T^{\frac{3}{2}})$$

where Q= discharge in cubic feet per second

C_d= coefficient of discharge

L= effective length of the weir in feet

H= total head on the bottom of the opening in feet

H_t= total head on top of the opening in feet

The effective length of the spillways was computed using a coefficient of contraction of 0.1 and 0.04 for end contraction and pier contraction respectively.

All assumptions and calculations are included as part of the back up information to this report. The resultant stage-discharge relationship for the dam is presented in Table I. Figure 4 presents the combined rating curve for the Dominion Textile Dam with all gates opened as computed by the procedure outlined above. Also included in Figure 4 is the combined rating curve as taken from the existing curves of Appendix I.

TABLE I

STAGE-DISCHARGE REALTIONSHIP

FOR

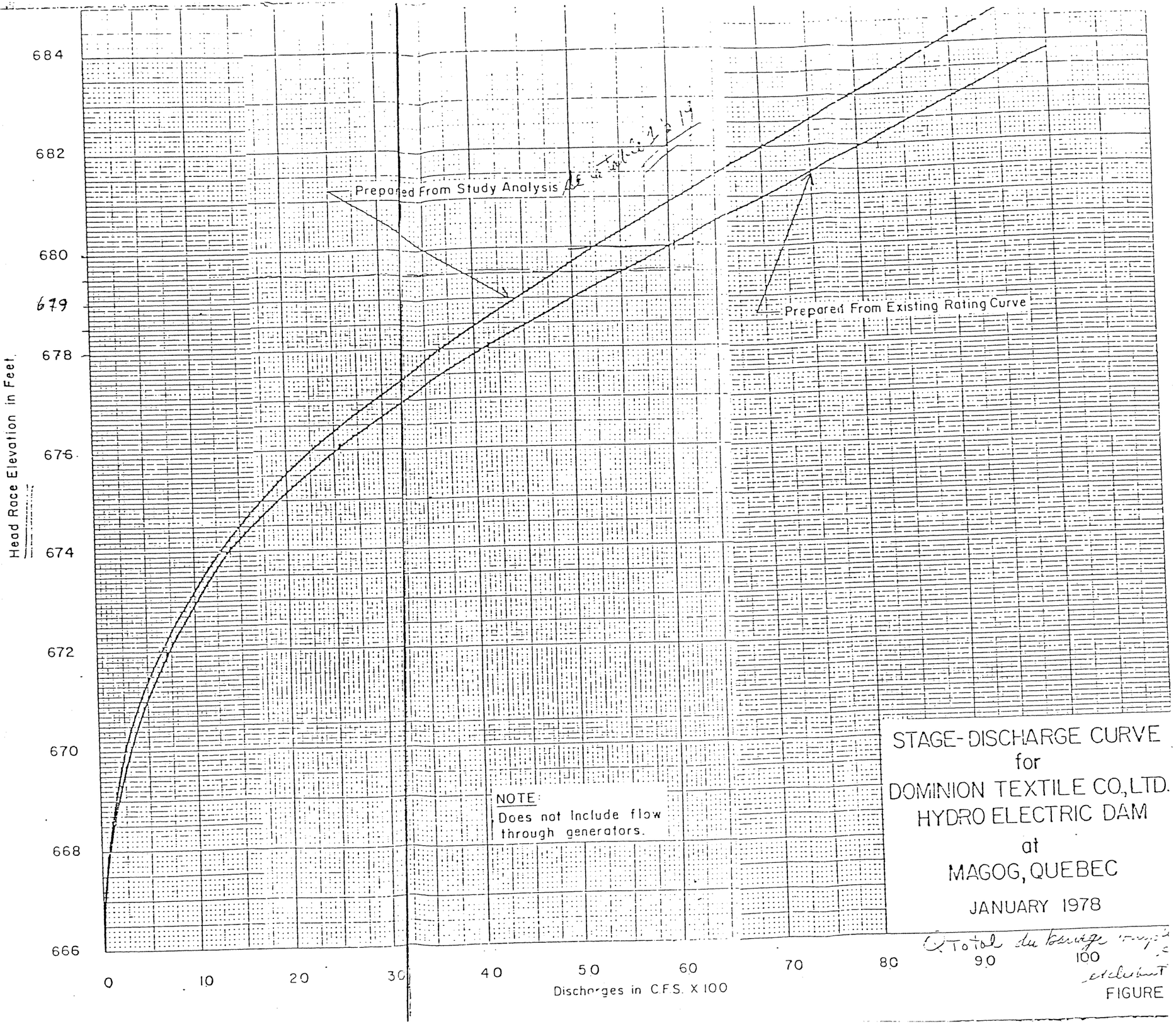
DOMINION TEXTILE CO., INC.

HYDRO ELECTRIC DAM

Elevation Feet, (GSCD)	1	2	3	4	5	6	7	Total[1]	Discharge[2] Through Generators
666	0	0	0	0	0	0	0	0	---
668	0	0	0	0	0	0	68	68	---
670	0	0	0	0	0	0	203	203	---
672	0	0	0	70	70	70	381	591	---
674	0	0	0	211	211	211	600	1233	---
676	69	70	70	403	403	403	822	2240	1040
678	207	213	213	644	644	644	1058	3623	1096
680	389	407	407	898	898	898	1292	5189	1144
682	610	649	649	1182	1182	1182	1526	6980	1196
684	837	908	908	1473	1473	1473	1758	8830	1248

[1]Total discharge does not include flow through generators

[2]Includes discharge through both generators.


Head Race Elevation in Feet.
684
682
680
679
678
676
674
672
670
668
666
0
10
20
30
40
50
60
70
80
90
100
Discharges in C.F.S. X 100
Prepared From Study Analysis
Prepared From Existing Rating Curve
NOTE:
Does not include flow through generators.
STAGE-DISCHARGE CURVE
for
DOMINION TEXTILE CO.,LTD.
HYDRO ELECTRIC DAM
at
MAGOG, QUEBEC
JANUARY 1978

FIGURE

A comparison of the two rating curves reveals a discrepancy of approximately 15% in the resultant discharges. From an investigation of the data it is apparent that the coefficients of discharge used in each analysis were very similar for each weir and that the difference in the results is primarily due to the assumptions made in calculating the effective lengths of the weirs. The existing rating curves apparently did not consider the effects of pier and end contraction. While this may have been, in part, due to the recognition that the status of operation of the adjacent gates would in fact alter the coefficients of contraction, the failure to consider these effects results in high discharges when using the existing rating curves.

OUTLET CHANNEL

Topographic Data

Two previous topographic surveys of the outlet channel of Lake Memphremagog between the lake proper and the Dominion Textile Dam were found to be available during the course of the study. An unknown party completed a survey in September 1921 probably in conjunction with the construction of the present dam. The survey information was obtained from the Dominion Textile Company. The other topographic survey, the one used for this study, was prepared by the Department of Natural Resources of Quebec, dated September 1976.

A comparison of the 1976 topographic survey to the one done in 1921 indicates that the river bottom has changed slightly over the years. Four sections located upstream of the Merry Bridge in the approximate same location were used to compare the surveys. The difference in stream bed elevations between the two surveys ranged from 0.8' to 1.2' higher now than in 1921. A section downstream of the Merry Bridge was also compared with the difference being minimal.

The significance of these differences in stream bed elevation is difficult to evaluate since partial attempts have been made to dredge the channel over the years.

Hydraulic Analyses

Analyses of the hydraulic characteristics of the outlet to Lake Memphremagog were carried out to develop the stage-discharge relationship for the combined effect of the outlet structure (Dominion Textile Dam) and the outlet channel and to determine the location of the hydraulic control sections during critical flow periods in the channel.

For the purpose of these analyses, the starting water surface elevations for the Magog River were taken from stage-discharge curves developed as a part of this study for the Dominion Textile Dam. The dimensions of the original dam immediately upstream were obtained from

survey information acquired during the construction period (1921 survey). The cross-section data for the Magog River upstream of Dominion Textile Dam was taken from the recent topographic survey done by the Department of Natural Resources. The elevations and structural geometry for the highway bridge crossing the Magog River were obtained from field survey.

Cross-sections for the backwater analyses of the Magog River were located at close intervals above and below the structures in order to compute the significant backwater effects of these structures. For the reaches between structures, appropriate valley cross-sections were used. Roughness coefficients (manning's "n") for the Magog River were estimated by field inspection at each cross-section. Further refinements to the coefficients selected were made based on a comparison of the results of the computed profiles with observed data. The coefficient used for the channel was 0.025.

Water surface elevations for selected flows were computed for the Magog River through the use of the Corps of Engineers HEC-2 step-backwater computer program. Profiles were developed showing computed water surface elevations and the energy gradient for the selected discharges.

The water surface elevations as shown on the profiles

are considered valid only if the hydraulic structures remain unobstructed. Water surface elevations in this region can be raised by ice jams or the accumulation of debris at the structures. As both of these occurrence are unpredictable, the hydraulic analyses for this study are based only on conditions of unobstructed flows.

Results of Analyses

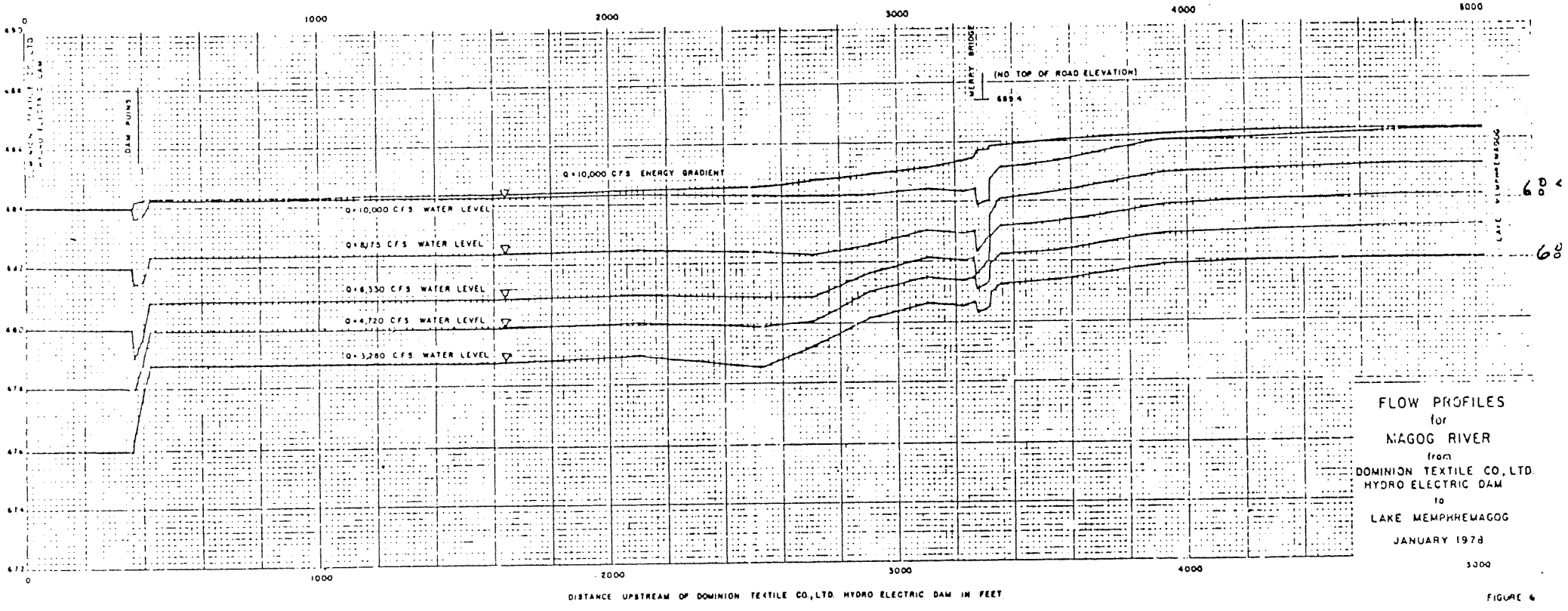
The hydraulic studies carried out for the lake outlet were used in establishing a stage-discharge relationship for Lake Memphremagog. In performing the backwater analyses the gates at the dam were assumed to be wide open thus establishing a natural unregulated condition based on existing conditions. Results of the computations were verified by using known water surface elevations at the dam when the gates were wide open and tying the backwater analyses to the lake stage elevations available from the lake level gage at Magog. Once concurrence was obtained with known data the backwater analysis was performed for a series of discharges thus establishing the lake level-discharge relationship. This stage-discharge relationship is presented graphically in Figure 5.

The studies on the outlet establish the presence of three hydraulic control sections between the lake and the dam. The first control section is located at the site of the 1914 coeffer-dam, the second is the restricted portion of the channel and immediately downstream of the Merry

Bridge while the third is the bridge itself. From the results of this analysis it is evident that control of the outflow from Lake Memphremagog is upstream from the dam during flood conditions. Thus, it is the discharge capacity of the channel and not the dam that determines the level of the lake when the sluice gates of the dam are entirely opened. Furthermore, the analysis indicated that the head losses at the site of the original dam do not have any visible effect on the level of the lake in light of the controls further upstream. Representative samples of the backwater profiles prepared during the course of the study are included in Figure 6.

The study also indicates that it may not be necessary to open all the gates during the periods of high flow and that the discharge and headwater elevations at the dam can be regulated to maximize the head without affecting the level of the lake.

As evidence of this effect, the starting water elevation (at the Dominion Textile Dam) was increased from 677.3 feet to 680 feet for a discharge of 4200 cfs without increasing the resultant level of the lake. However, elevations at which the water levels in the channel can be maintained at the dam without significantly affecting the levels of the lake are dependent upon the discharge in the channel.



FLOW PROFILES
for
MAGOG RIVER
from
DOMINION TEXTILE CO., LTD.
HYDRO ELECTRIC DAM
to
LAKE MEMPHREMAGOG
JANUARY 1978

FIGURE 6

LAKE HYDROLOGY

INFLOW ROUTING

As previously indicated, the drainage area of the Lake Memphremagog basin is concentrated at the southern end of the lake with the three major tributaries flowing into South Bay in Newport, Vermont. Together, the Black, Barton and Clyde Rivers have a total drainage area of 450 square miles which represents 65 percent of the drainage area to the lake.

Discharge records are maintained by the U.S. Geological Survey for two of these streams, the Black and the Clyde Rivers. Gaging stations are located on the Black River in Coventry and on the Clyde River in Newport. The location of these gages has been indicated in Figure 1. Table II provides a brief data summary of these and other gages in the basin.

TABLE II

Gaging Stations of the Lake Memphremagog Basin

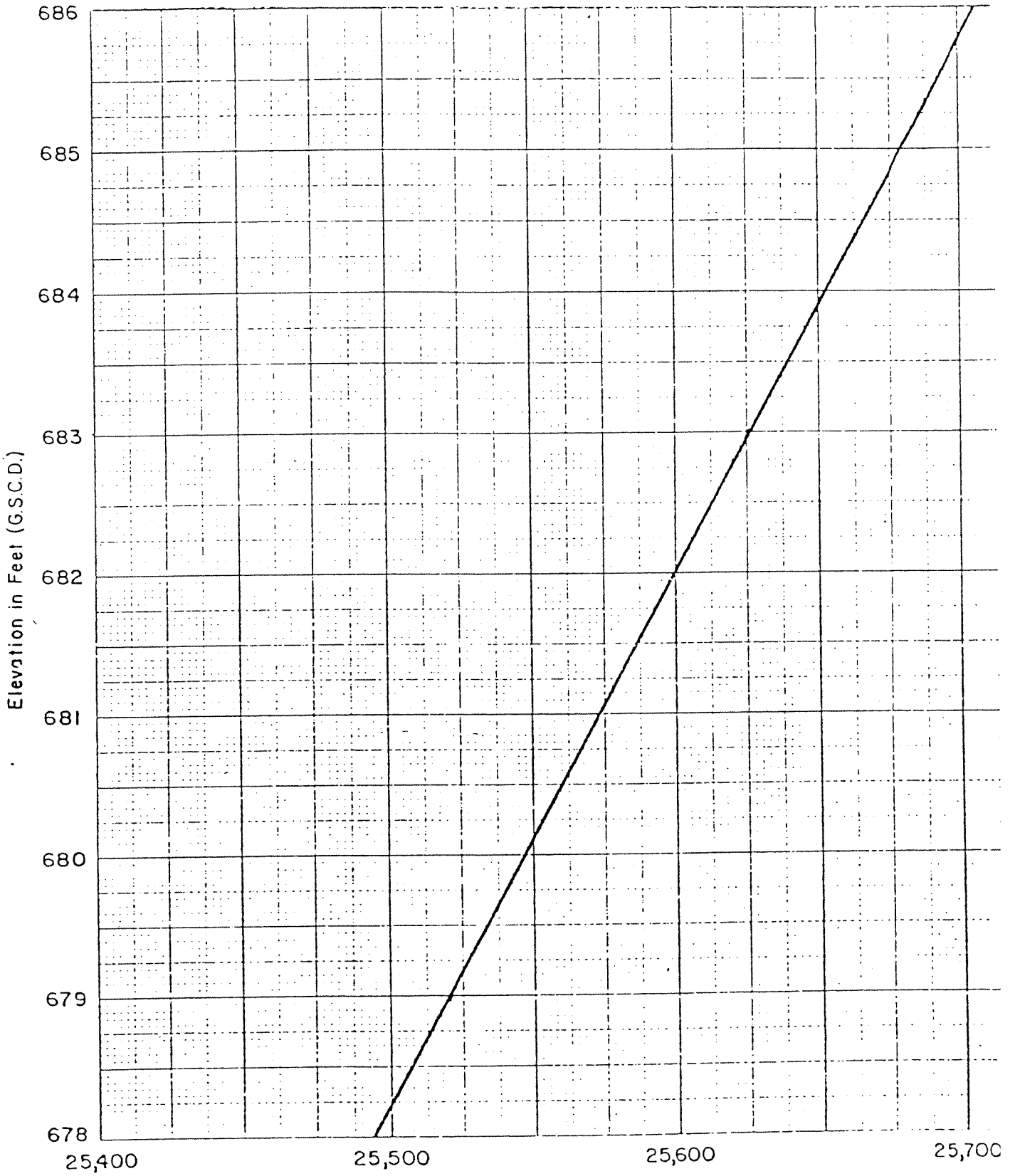
Gage and Location	Years of Record	Drainage Area square miles
Black River at Coventry, Vt.	1951-Present	122
Clyde River at Newport, Vt.	1909-1919 1920-1924 1928-Present	142
Brownington Br. near Evansville, Vt. (Barton River Basin)	1963-1973	2.15
Lake Memphremagog at Newport, Vt.	1931-Present	
Lake Memphremagog at Magog	1920-Present	
Magog River at Dominion Textile Dam	1963-Present	682

To define the hydrology of Lake Memphremagog, a reservoir routing method was used to develop an inflow hydrograph for the Lake for selected events.

To conduct the analysis, the fundamental equation Inflow=Outflow + Change in Storage was used. The outflow data used for this analysis were the daily discharges recorded at the Dominion Textile Dam as obtained from the Department of Natural Resources. Changes in storage were derived from the recorded mean lake levels at the gaging stations at Newport and Magog. Adjustment in lake level data were made for interception from precipitation records maintained by the weather station at Newport.

A stage-area curve for Lake Memphremagog was developed by planimetering the surface area of the lake from a Canadian Hydrographic Chart of Lake Memphremagog (Chart #1361). The additional area per increment of elevation was calculated by measuring the total length of the shoreline and dividing it into two categories, one with steep shoreline (slope 1:1) and one with shallow shoreline (slope 1:5).

At an elevation of 682 feet the area of the lake is 40.0 square miles and the total length of shoreline is 93.8 miles. Approximately 63 miles of this shoreline has a steep slope and the remaining 30.8 miles of the shoreline has a relatively flat slope. The resultant stage-area relationship computed in this manner is enclosed as Figure 7.



STAGE-AREA CURVE
for
LAKE MEMPHREMAGOG
JANUARY, 1978

FIGURE 7

PREDICTIVE MODEL

The inflow hydrographs provide a correlation between the inflow and the outflow and also serve as the bases for a comparison with the recorded flows on the Black and Clyde Rivers which permit the development of a predictive model to enable the regulation of the discharges from the lake and minimize the time the lake levels exceed the upper limit of the 1935 International Agreement.

Because the primary concern relates to the ability to regulate the level of the lake at high lake stages, the inflow study was conducted for periods of high runoff. Therefore, the flows for the spring runoff of 1972, 1973, 1974, 1976 and the July 1973 flood were selected for analysis.

All flows were routed through the lake using the reverse routing method previously described and a inflow hydrograph was developed for each runoff period selected. To establish the relationship of the computed inflow hydrograph with existing gaged tributary flows, the inflow hydrograph for each flow period was first compared graphically to the hydrographs of the Black River, the hydrograph from the Clyde River, and a combined hydrograph developed for the Black and Clyde Rivers. By visual inspection, the hydrographs of the routed inflow appeared more consistent with those from the Black River than either the Clyde River or the combination of the two. This is attributed to the fact that there is considerable modification of the flows on

the Clyde River resulting from its extensive use for hydropower production and the large amount of surface water storage area available in that basin.

To confirm the results of the visual inspection and establish the relationship and degree of correlation between the routed inflow and the flows of the Black River or the Clyde River, regression analyses were conducted for the selected discharges. In addition to computing the direct ratio between the tributary flows and the routed inflow, a linear regression and non-linear regression for the exponential, logarithmic and power curves were computed for each.

The application of the power curve regression to the Black River data provided the greatest degree of correlation with the resultant equation:

$$Q_I = 11.29Q_B^{0.9},$$

where Q_I is the average daily inflow in cfs and Q_B is the average daily discharge of the Black River in cfs for the same period of time.

The correlation coefficient established for this relationship is 0.89. This coeffecient indicates that there is good correlation between the data and that approximately 80 percent of the variance in the routed inflow valves is accounted for by the regression realtionship developed.

The relationships of the observed flows of the Black River to the routed inflows can have direct application in the regulation of the level of the lake. Given the flow at the Black River and the relationship of that flow to the routed inflow, and consequently the change in lake level and outflow, the outflow can be adjusted to achieve the desired lake level.

Stages at the Black River can be obtained from the gage on the Black River which is equipped with instrumentation and a telephone which automatically provides the stage of the river. The corresponding discharge can be determined from the rating curve for that gaging station shown in Figure 8.

Figure 9 provides a graphical representation of the relationship of the flow at the Black River with the change in the level of the lake and the discharge at the Dominion Textile Dam. The graph has been prepared using the equation derived for the total inflow. The curves for the change in lake level are based on the prescribed rate of flow for one day. Also shown on Figure 9 is the stage-discharge curve for the outlet channel since the channel capacity limits the maximum discharge possible.

While Figure 9 can provide a useful tool in the operation of the dam, several limitations and restraints on its use are noted. Since the graph is predicated on

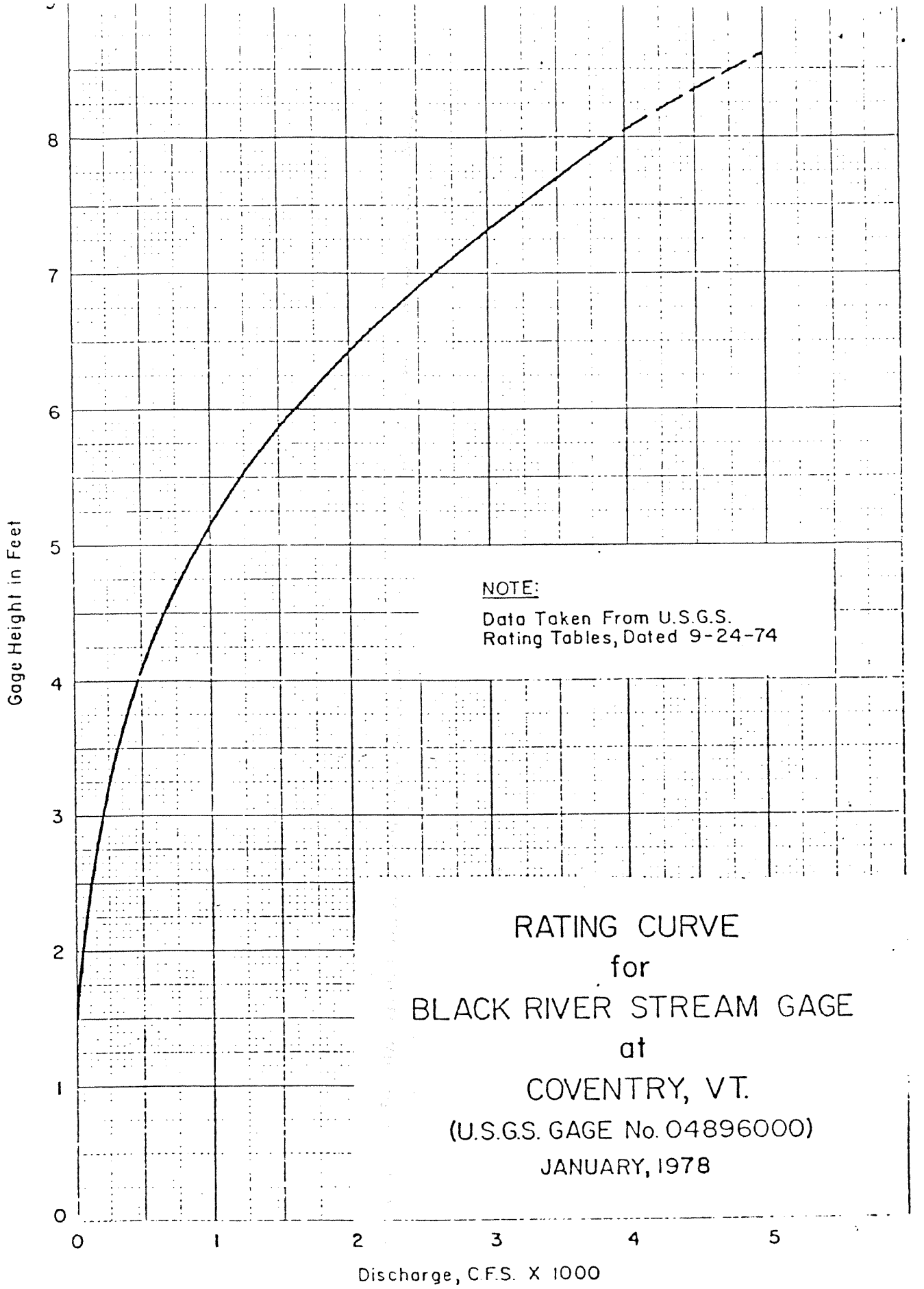

Gage Height in Feet
0
1
2
3
4
5
6
7
8
0
1
2
3
4
5
Discharge, C.F.S. X 1000
NOTE:
Data Taken From U.S.G.S.
Rating Tables, Dated 9-24-74
RATING CURVE
for
BLACK RIVER STREAM GAGE
at
COVENTRY, VT.
(U.S.G.S. GAGE No. 04896000)
JANUARY, 1978

FIGURE 8

Lake Memphremagog Water Level in Feet (G.S.C.D.)

676 678 680 682 684 686

Outlet Channel Rating Curve

Change in Storage in Feet

-0.6 -0.5 -0.4 -0.3 -0.2 -0.1 0.0 +0.1 +0.2 +0.3 +0.4 +0.5 +0.6 +0.7 +0.8 +0.9

Outflow at Dominion Textile Co., Ltd. Hydro-Electric Dam, C.F.S.-Days X 1000

0 1 2 3 4 5 6 7 8

Inflow at Black River Gage, C.F.S.-Days X 1000

0 1 2 3

ROUTING CURVE for LAKE MEMPHREMAGOG

JANUARY 1978

FIGU

a projection of the events of the Black River to the entire basin it is subject to error under condition of localized events, such as a storm located principally over the Black River Basin. Discrepancies of this nature have been noted during periods of very high flow on the Black River.

The use of the graph is also limited by the physical restraint of the discharge capacity of the outlet channel, which is dependent on the level of the lake. This limitation can be readily determined from the rating curve for the outlet channel superimposed on the graph of Figure 9.

Finally, as indicated earlier, the correlation between the Black River with the routed inflow was based on the discharge measurements at the Dominion Textile Dam as recorded in summary form by the Department of Natural Resources. These discharges were computed from the existing rating curves for the dam and consequently subject to the errors noted earlier. Since the Dominion Textile Limited records, indicating the headwater elevations and gate openings, were not available for inspection, it was not possible to adjust the discharges in accordance with the rating curves prepared during the course of this study. Therefore the results of the correlation established herein

will yield discharges consistent with the existing rating curves or approximately 15 percent too high.

LAKE GRADIENT

Data from the gaging station on Lake Memphremagog at Magog and Newport were analyzed to determine the gradient of the lake. The data used were selected to include a wide variety of lake level and flow situations, from high levels with rapid daily fluctuations to low levels with stable daily lake levels.

Numerous parameters were examined to determine the gradient of the lake and any variations thereto.

When corrected for the difference in datum, the average difference in the elevation of the lake between Newport and Magog was found to be 00.18 feet. From an inspection of the plotted data correlating the gradient of the lake to the discharge from the lake, the lake level and the change in lake level, the only relationship which could be observed was between the gradient and the rate of rise in the lake level. During periods when the lake level decreased or remained relatively constant (a rate of rise less than 0.1 feet per day) the gradient appeared to remain constant while during periods when the lake levels increased the gradient appeared to increase with the rate of rise in lake level.

When corrected for the difference in datum, the difference in the level of the lake for the periods when

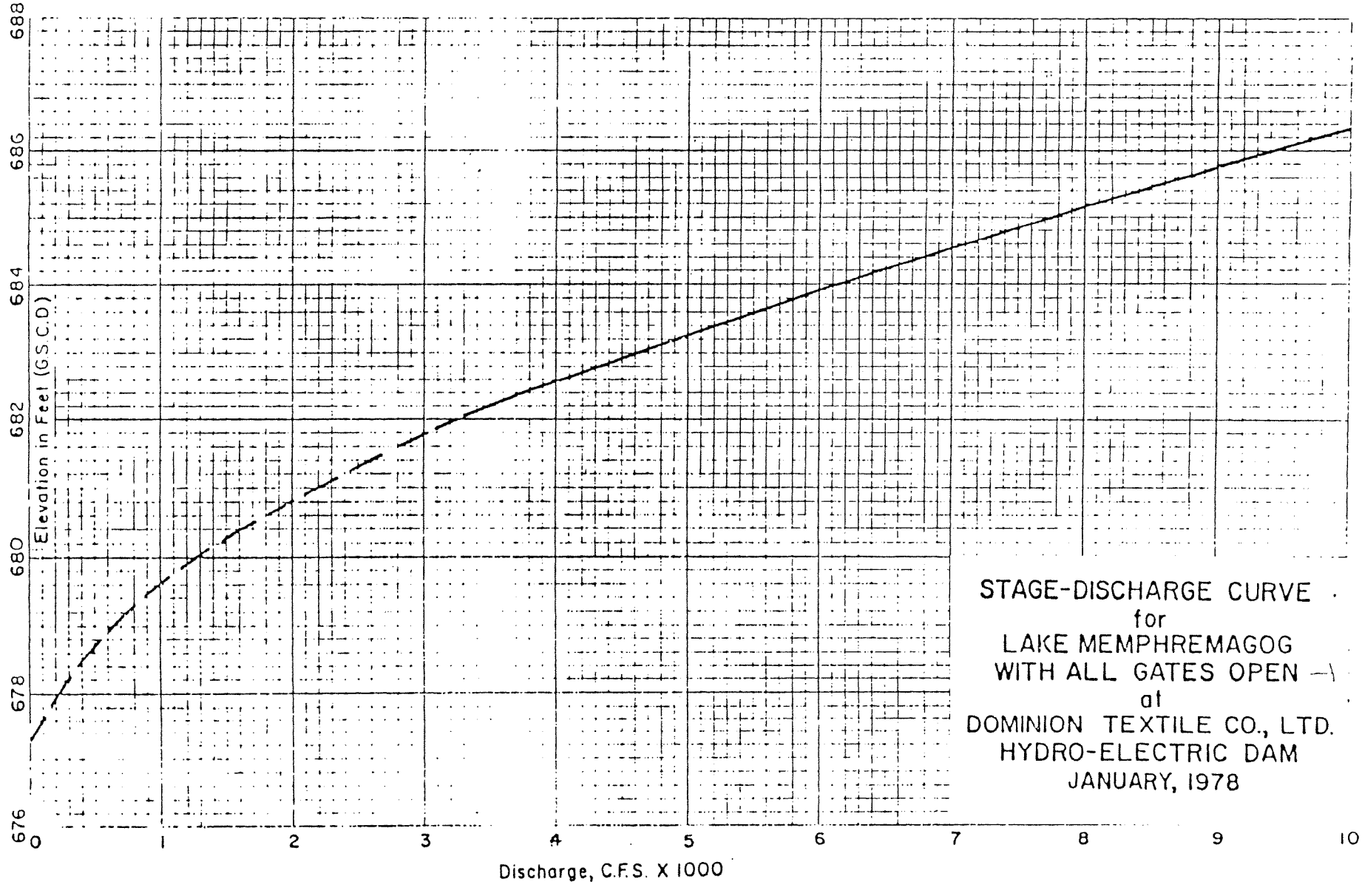

688
686
684
682
680
678
676
Elevation in Feet (G.S.C.D.)
0
1
2
3
4
5
6
7
8
9
10
Discharge, C.F.S. X 1000
STAGE-DISCHARGE CURVE
for
LAKE MEMPHREMAGOG
WITH ALL GATES OPEN
at
DOMINION TEXTILE CO., LTD.
HYDRO-ELECTRIC DAM
JANUARY, 1978

FIGURE 5

the lake level decreased or remained constant (low net inflow) was computed to average 0.17 feet between the two gages. This represents a gradient of 0.0061 feet For the periods when the lake level increased (high net inflow) a regression analyses was performed resulting in a linear relationship represented by the equation $Y=0.254X + .148$, where Y is the difference in elevation between the two stations in feet and X is the increase in lake level in feet per day. The correlation coefficient for this equation is 0.61.

The results of the analysis establishes a natural lake difference of 0.17 feet between gages,increasing during periods of high net inflow. Based on the analysis and the low correlation coefficient, the effect of the increase, however, appears to be more the result of a surge effect rather than an increase in lake gradient. Furthermore, a surge effect at the Newport Gage appears to be reasonable in light of the concentration of inflow in that area caused by the Barton, Black, and Clyde Rivers) and the shallow depth of Lake Memphremagog on the Vermont side (maximum depth 39 feet, average depth 21 feet.)

It is interesting to note that when the lake gradient was computed for periods of low summer flow the difference in elevation between the two gaging stations was also 0.17 feet.

CONCLUSIONS

This study was intended primarily to determine the discharge capacity of the outlet of Lake Memphremagog and to correlate the inflow to the lake with the discharges from the lake.

An evaluation of the rating curves currently being used to compute the discharge for the Dominion Textile Dam was made, resulting in the preparation of a stage-discharge relationship which yields lower flows than the previous curves. The primary difference between the rating curves prepared during the course of this study and the existing rating curves is that the existing curves did not appear to consider the effect of pier and end contractions of the sluices and dam. The lower flows obtained from the stage-discharge relationship prepared during the course of this study were further supported by the backwater analyses of the outlet channel and the comparison of the inflows to the lake with the recorded discharges. Because a stage-discharge relationship was only prepared for the condition where all gates are open, it is recommended that a complete set of curves be prepared which incorporate the effects of pier and end contractions for the different operating conditions and used to record flows at the Dominion Textile Dam.

The analysis of the outlet channel yielded several interesting results and conclusions. Essentially, it was

determined that when all the gates are open at the dam the outlet channel controls the level of the lake. Head losses in the channel occur primarily at the site of the old dam, the restricted portion of the channel downstream of the Merry Bridge and at the Merry Bridge. However, it is the capacity of the channel in the vicinity of the bridge which regulates the level of the lake during high flows when the gates of the dam are all open. From the stage-discharge curve prepared for the outlet channel it is apparent that the maximum discharge capacity of the channel at the upper limit of the International Agreement (682.7 feet) is only 4200 cfs.

The results of this analysis indicate that the reduction of the lake levels when the outflow exceeds 4200 cfs, can only be accomplished by increasing the hydraulic capacity of the outlet channel in the vicinity of the Merry Bridge.

However, the frequency of occurrence and the period of time that the lake levels exceed the upper limit of the International Agreement can be reduced with a knowledge of the inflow to the lake which would permit the improved regulation of the discharges at the dam. An analysis of the gaged tributary flows indicated that a good correlation could be established between the flows on the Black River

and the stage and discharge of the lake. By projecting the flows of the Black River to the rest of the basin the discharges from the dam can be adjusted to regulate the level of the lake within the limitation imposed by the discharge capacity of the outlet channel.

This correlation permits the responsive operation of the control structure as the event is occurring.

It is possible that even more control could be exercised over the high lake levels by forecasting the major runoff events. Using indicators, such as precipitation and the water content of the snow, it may be possible to predict the volume of runoff from the basin in sufficient time to provide for additional storage by drawing down the level of the lake in anticipation of the projected runoff.

It should be noted that no attempt has been made during the course of this study to determine the desired levels of operation of the lake or the environmental and economic impacts of altering the lake levels. The study attempted only to promote a better understanding of the hydrologic and hydraulic considerations with regard to the lake levels. Alterations of the hydraulic capacity of the outlet channel or the lake level regime, could have a significant effect on the lake. Such alterations should not be undertaken without investigation of the economic

and environmental impacts as they affect the lake and the Magog River.

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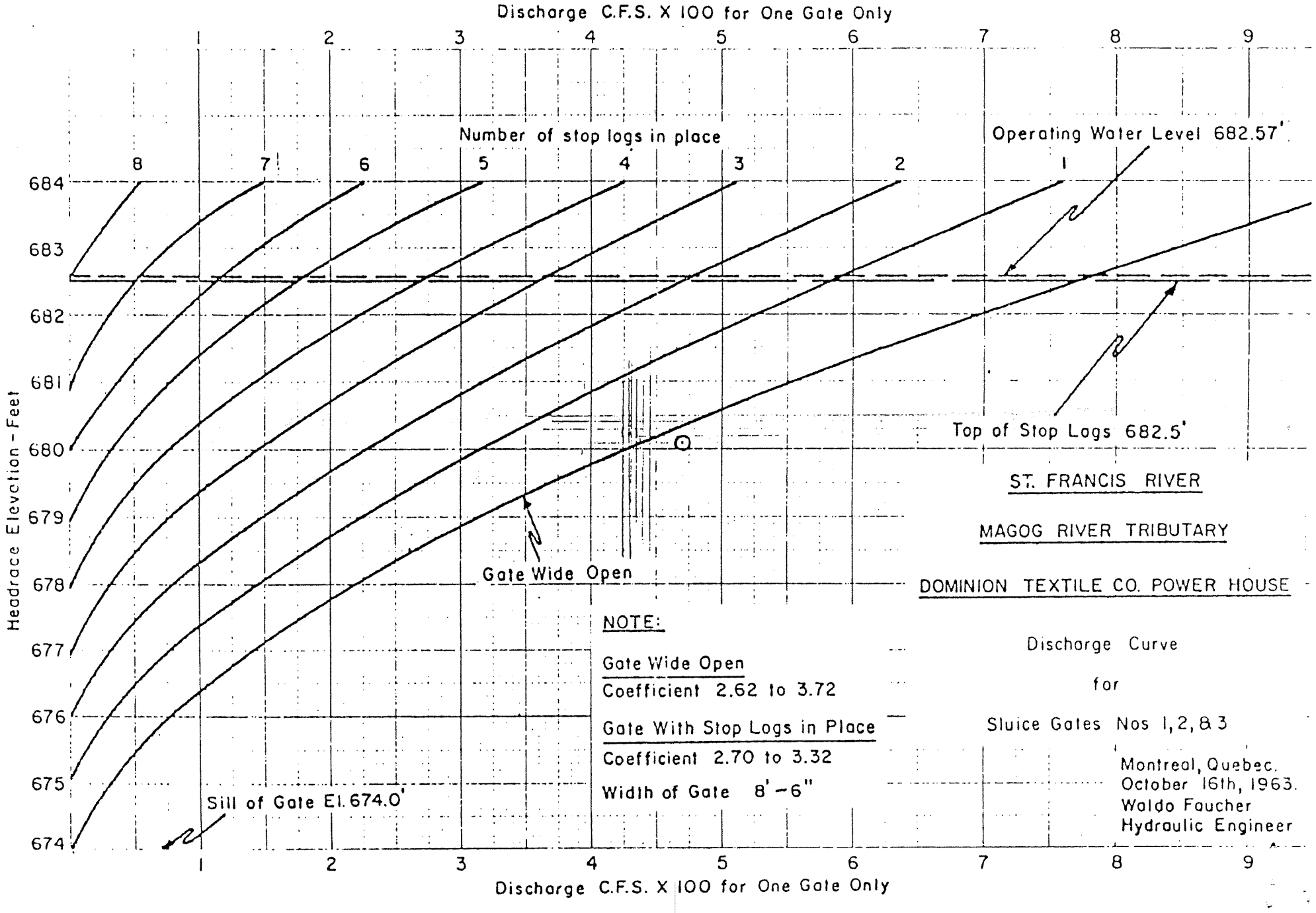
APPENDIX I

Individual Sluice Gate Rating Curves

Obtained from Dominion Textile Ltd.


Discharge C.F.S. X 100 for One Gate Only
1 2 3 4 5 6 7 8 9
Number of stop logs in place
8 7 6 5 4 3 2 1
Operating Water Level 682.57'
684
683
682
681
680
679
678
677
676
675
674
Headrace Elevation - Feet
Top of Stop Logs 682.5'
Gate Wide Open
Sill of Gate El. 674.0'
ST. FRANCIS RIVER
MAGOG RIVER TRIBUTARY
DOMINION TEXTILE CO. POWER HOUSE
Discharge Curve
for
Sluice Gates Nos 1, 2, & 3
NOTE:
Gate Wide Open
Coefficient 2.62 to 3.72
Gate With Stop Logs in Place
Coefficient 2.70 to 3.32
Width of Gate 8'-6"
Montreal, Quebec.
October 16th, 1963.
Waldo Foucher
Hydraulic Engineer
1 2 3 4 5 6 7 8 9
Discharge C.F.S. X 100 for One Gate Only

Discharge C.F.S. X 100 for one gate only

Number of stop logs in place

Operating Water Level 682.57

Top of stop logs 682.5'

Gate Wide Open

Sill of Gate El. 670.0'

Headrace Elevation - Feet

NOTE:

Gate Wide Open

Coefficient 2.62 to 3.80

Gate with stop logs in place

Coefficient 2.70 to 3.32

Width of Gate 8'-6"

ST. FRANCIS RIVER

MAGOG RIVER TRIBUTARY

DOMINION TEXTILE CO. POWER H

Discharge Curve

for

Sluice Gates Nos. 4,5,& 6

Montreal, Qu

October 16th

Waldo Fauch

Hydraulic En

DISCHARGE C.F.S. X 100 for sluice gate No. 7 only

1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26

Gate Opening 1' 2' 3' 4' 5' 6' 7' 8' 9' 10' 11' 12'

Operating Water Level 68

Gate Wide Open

Sill of Gate El. 666.0'

Headrace Elevation - Feet

684 683 682 681 680 679 678 677 676 675 674 673 672 671 670 669 668 667 666

NOTE:

Gate Wide Open

Coefficient 2.82 to 3.88

Gate Partly Open

Coefficient 0.74 to 0.78

Width of Gate 8'-6"

ST. FRANCIS RIVER

MAGOG RIVER TRIBUTAR

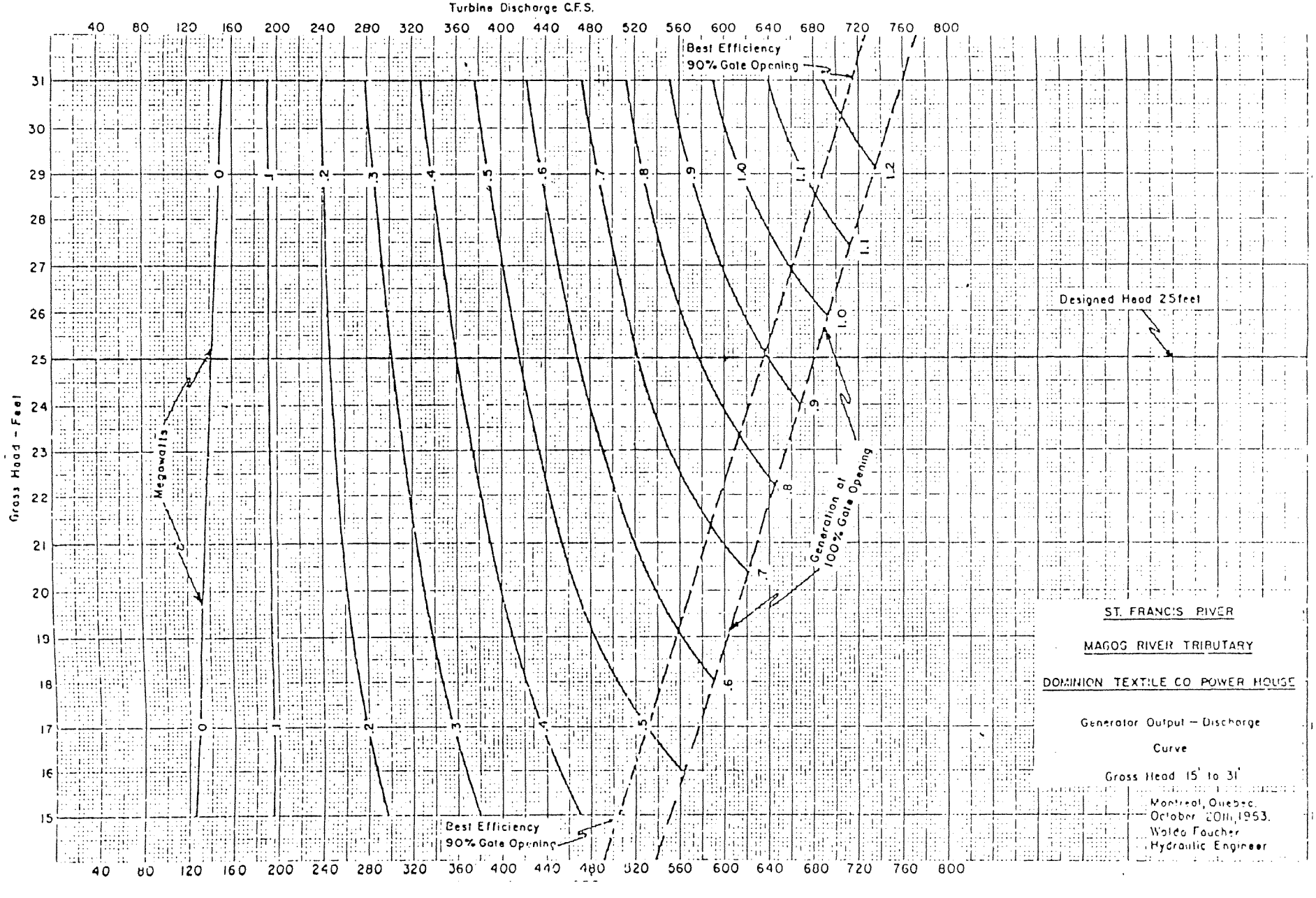
DOMINION TEXTILE CO. POWER

Discharge Curve

for

Sluice Gate No. 7

Montreal,
October
Waldo Fo
Hydraulic

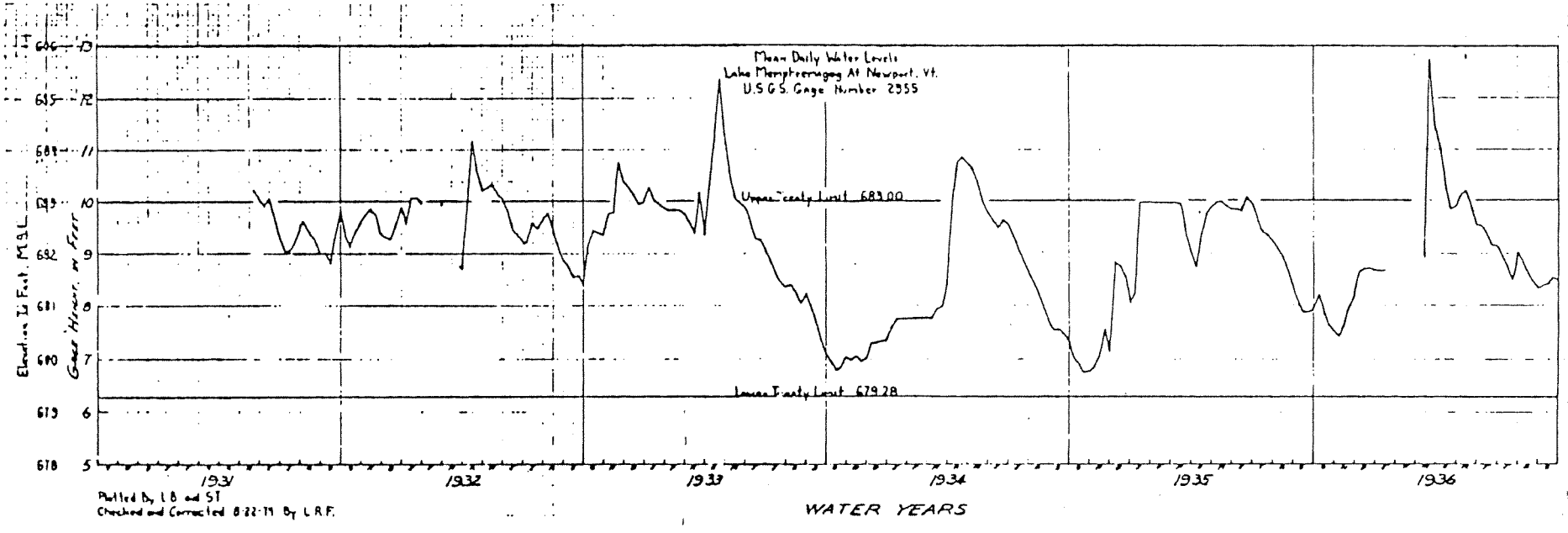

Turbine Discharge C.F.S.
40 80 120 160 200 240 280 320 360 400 440 480 520 560 600 640 680 720 760 800
Gross Head - Feet
31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15
Best Efficiency
90% Gate Opening
Megawatts
Generation at
100% Gate Opening
Designed Head 25 feet
Best Efficiency
90% Gate Opening
ST. FRANCIS RIVER
MAGOG RIVER TRIBUTARY
DOMINION TEXTILE CO POWER HOUSE
Generator Output — Discharge
Curve
Gross Head 15' to 31'
Montreal, Quebec.
October 20th, 1953.
Waldo Foucher
Hydraulic Engineer

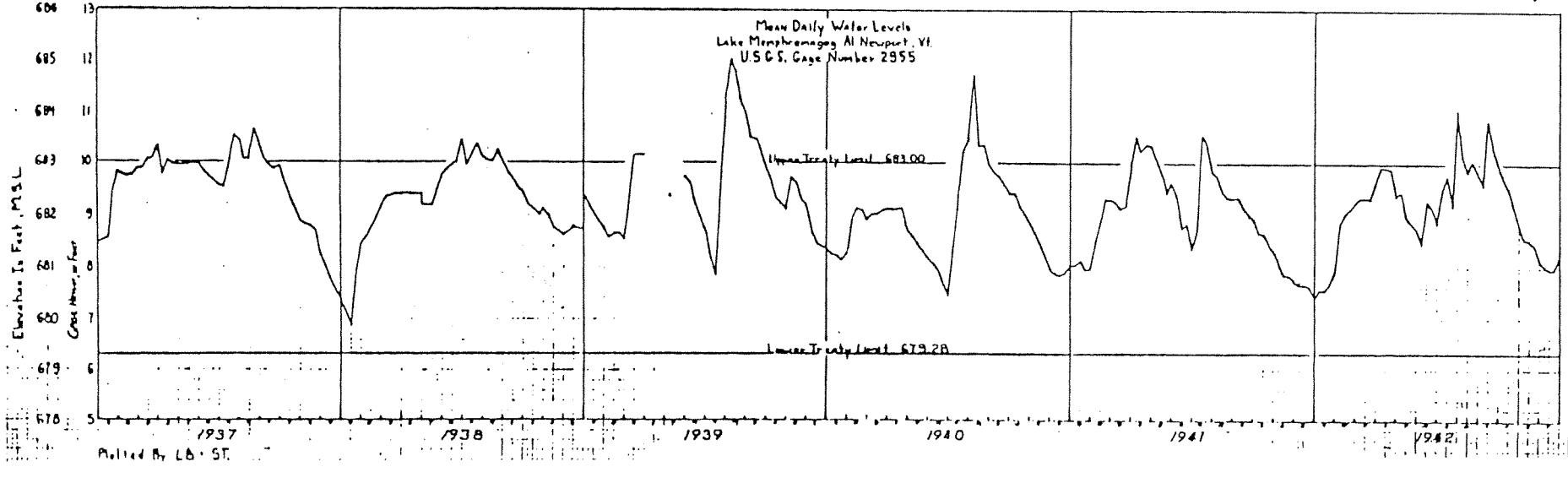
APPENDIX II

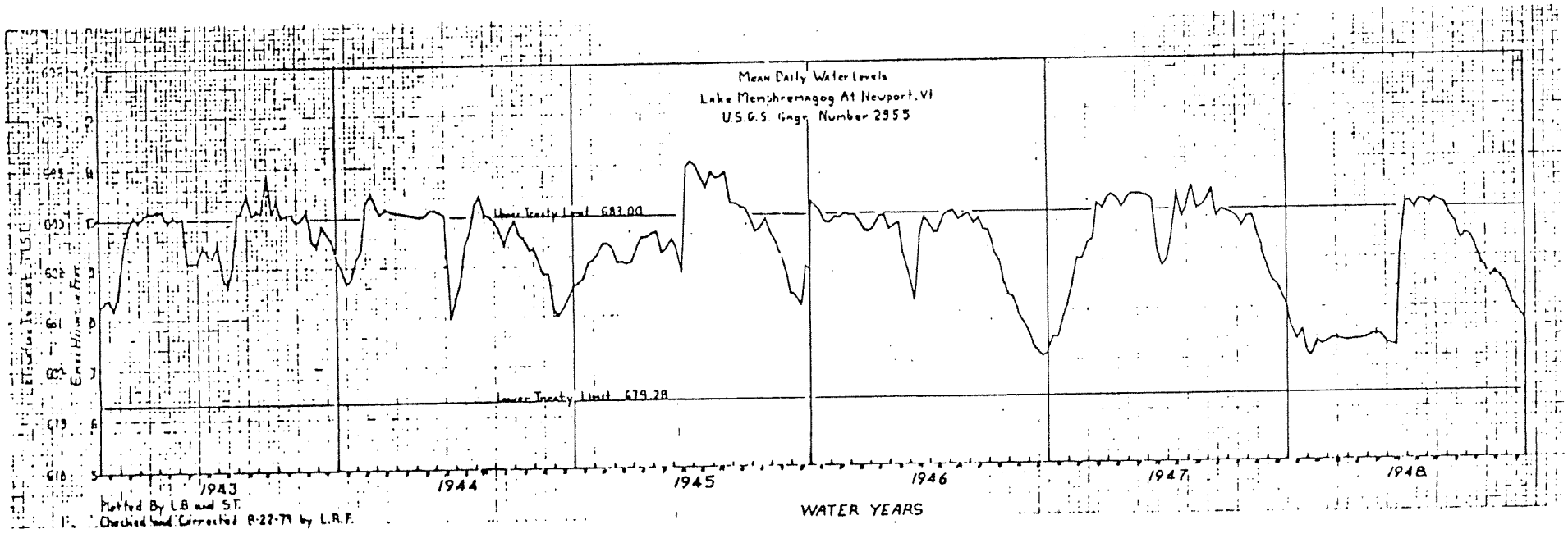
Mean Daily Water Levels

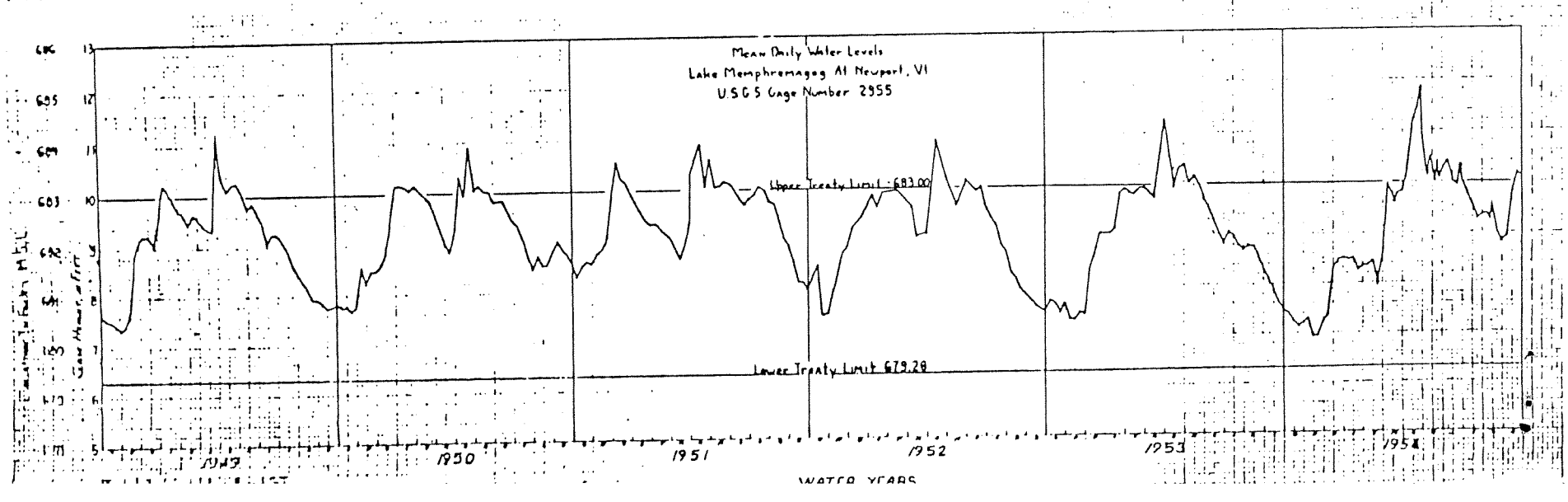
Lake Memphremagog at Newport, Vermont

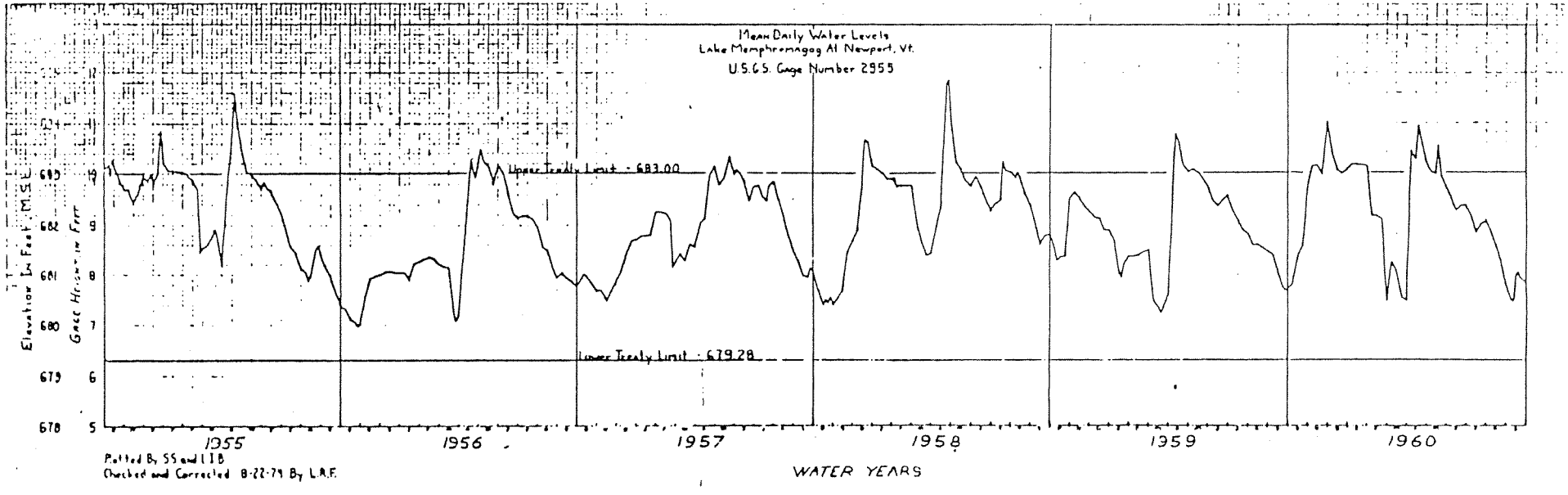
1931 - 1977

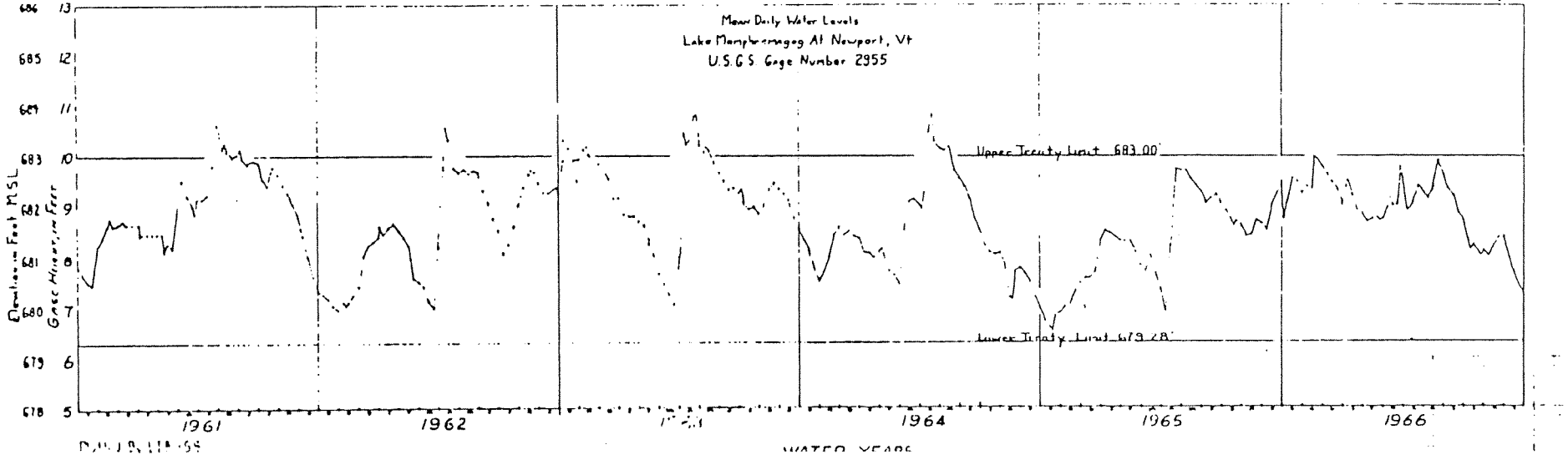

Mean Daily Water Levels
Lake Memphremagog At Newport, Vt.
U.S.G.S. Gage Number 2955
Upper Treaty Limit 683.00
Lower Treaty Limit 679.28
Elevation In Feet, M.S.L.
Gage Height, in Feet
606
685
684
683
682
681
680
679
678
13
12
11
10
9
8
7
6
5
1931
1932
1933
1934
1935
1936
WATER YEARS
Plotted By L.B. and S.T.
Checked and Corrected 8-22-11 By L.R.F.

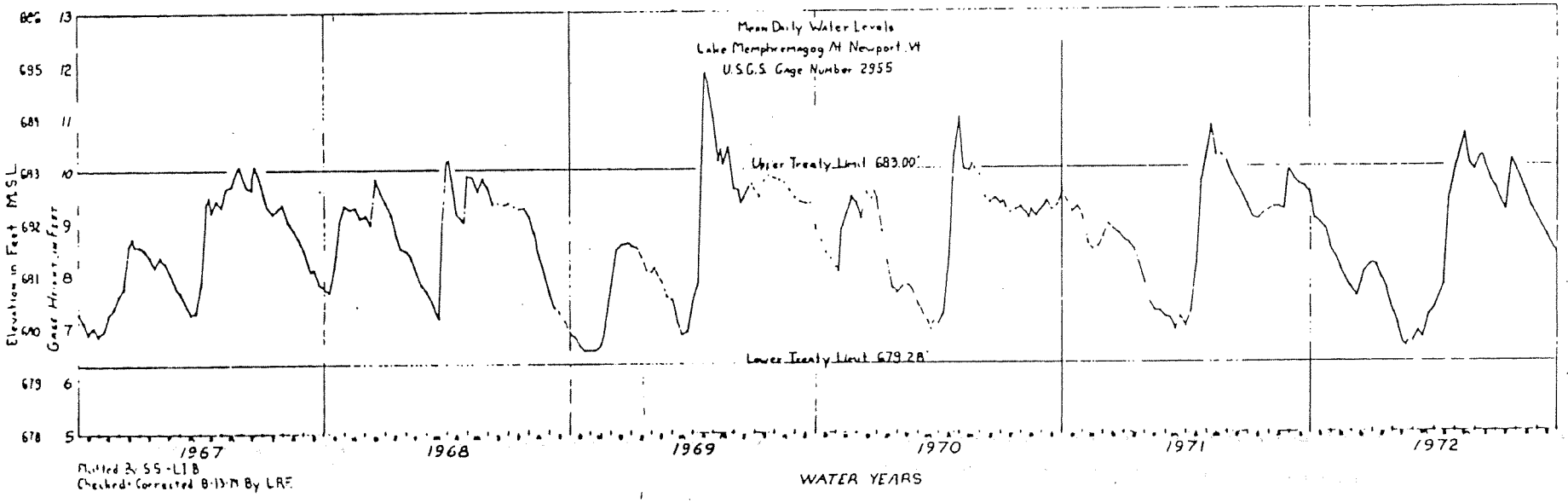

Mean Daily Water Levels
Lake Memphremagog At Newport, Vt.
U.S.G.S. Gage Number 2955
Upper Treaty Limit 683.00
Lower Treaty Limit 679.28
Elevation In Feet, M.S.L.
Gage Height, in Feet
606
685
684
683
682
681
680
679
678
13
12
11
10
9
8
7
6
5
1937
1938
1939
1940
1941
1942
Plotted By L.B. · S.T.


Mean Daily Water Levels
Lake Memphremagog At Newport, VT
U.S.G.S. Gage Number 2955
Upper Treaty Limit 683.00
Lower Treaty Limit 679.28
1943
1944
1945
1946
1947
1948
WATER YEARS
Plotted By L.B. and S.T.
Checked and Corrected 8-22-79 by L.R.F.

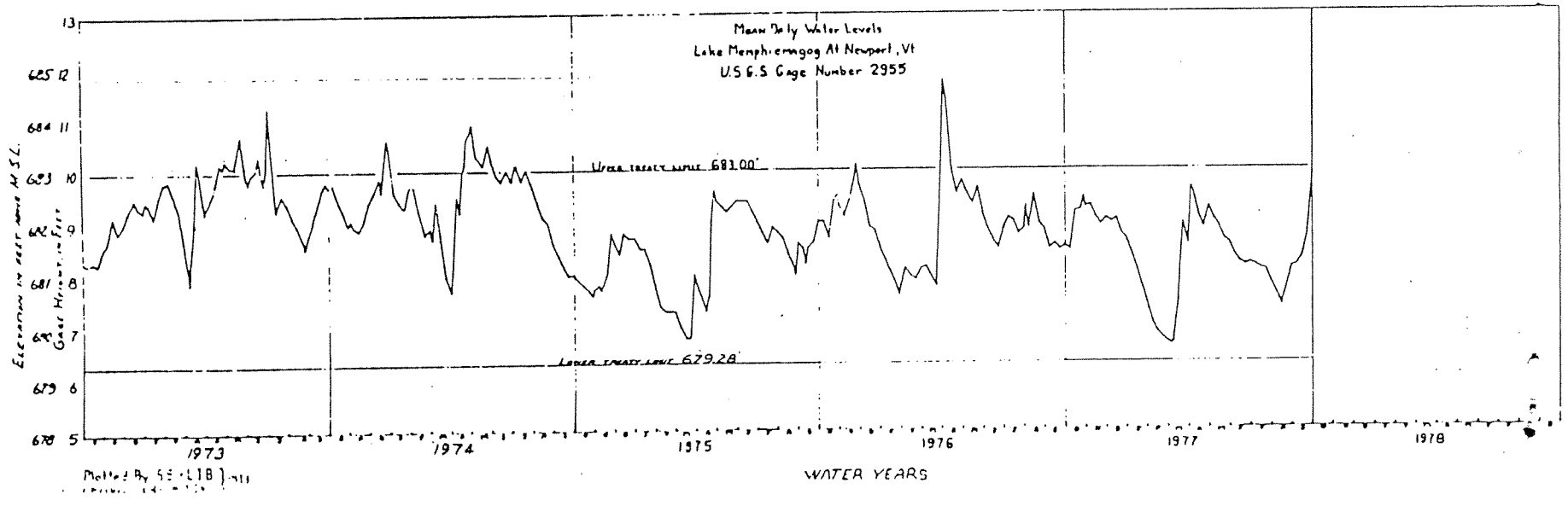

Mean Daily Water Levels
Lake Memphremagog At Newport, VT
U.S.G.S. Gage Number 2955
Upper Treaty Limit 683.00
Lower Treaty Limit 679.28
1949
1950
1951
1952
1953
1954
WATER YEARS


Mean Daily Water Levels
Lake Memphremagog At Newport, Vt.
U.S.G.S. Gage Number 2955
Upper Treaty Limit - 683.00
Lower Treaty Limit - 679.28
Elevation In Feet M.S.L.
Gage Height In Feet
1955
1956
1957
1958
1959
1960
WATER YEARS
Plotted By SS and LTB
Checked and Corrected 8-22-79 By L.R.F.


Mean Daily Water Levels
Lake Memphremagog At Newport, Vt
U.S.G.S. Gage Number 2955
Upper Treaty Limit 683.00
Lower Treaty Limit 679.28
Elevation Feet MSL
Gage Height In Feet
1961
1962
1964
1965
1966
WATER YEARS

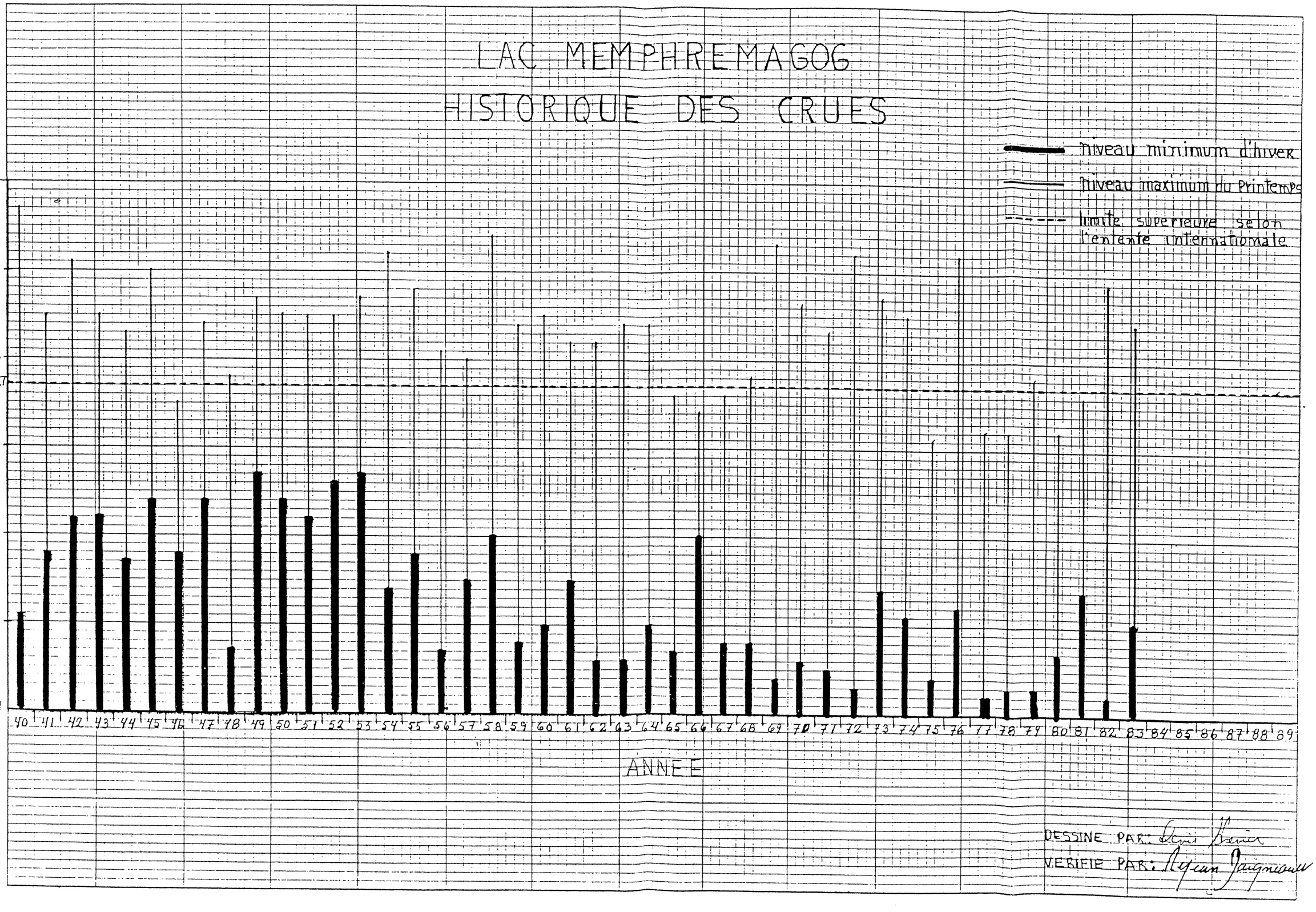


Plotted By SS-LIB
Checked-Corrected 8-13-71 By LRF



Plotted By SS-LIB

LAC MEMPHREMAGOG
HISTORIQUE DES CRUES



DESSINE PAR: Denis Bernier

VERIFIE PAR: Réjean Jaigniaux

1983

JANUARY FEBRUARY MARCH APRIL MAY JUNE JULY AUGUST SEPTEMBER OCTOBER NOVEMBER DECEMBER

7000 6000 5000 4000 3000 2000 1000 CFS

684 683 682 681 680 679

Passe Entrée

47 2810 1 YEAR BY DAYS