ANALYSIS OF LAKE LEVELS AT VOYAGEURS NATIONAL PARK

WR REPORT NO. 86-5

WATER RESOURCES DIVISION
NATIONAL PARK SERVICE
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO 80523

This report presents the results of a study conducted by the National Park Service Water Resources Division. It is intended primarily for use by the particular Park Service area or areas that are addressed in the report but may be of interest to other persons working in water resources management. Requests for copies of this report should be addressed to:

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Marshall Flug

April 1986

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INTRODUCTION

Voyageurs National Park, located along the Minnesota-Canadian border encompasses about 85,000 acres of water, consisting of more than 30 lakes of which five large ones comprise 96 percent of the water area; some 40 percent of the total park area. Figure 1 shows the complex network of lakes, rivers, portages, and dams in this northern Minnesota area. In 1971 an act by the United States Congress (16 U.S.C. 160) created Voyageurs National Park which was then established in 1975 to preserve the natural environment, and native plant and animal life, for the benefit of future generations. These management functions of the National Park Service are harmonious with directives of the Organic Act (16 U.S.C. 1) which established the National Park Service. The international boundary, between the United States and Canada, follows the eighteenth century fur traders route between Lake Superior and Lake of the Woods; Voyageurs National Park adjoins a 56 mile (90 km) stretch of that Voyageurs Highway. Lakes in this area fill glacier carved rock basins and extend into bogs, marshes, and beaver ponds up to nearby rocky knobs. From a hydrologic basin perspective, the four major sub-basins of interest are quantitatively described in Table 1. Namakan and Rainy Lakes together contribute about two thirds of the total inflow to Lake of the Woods. Both Namakan and Rainy Lakes are partially contained within Voyageurs National Park and are both international bodies of water; i.e., the international boundary lies within these lakes.

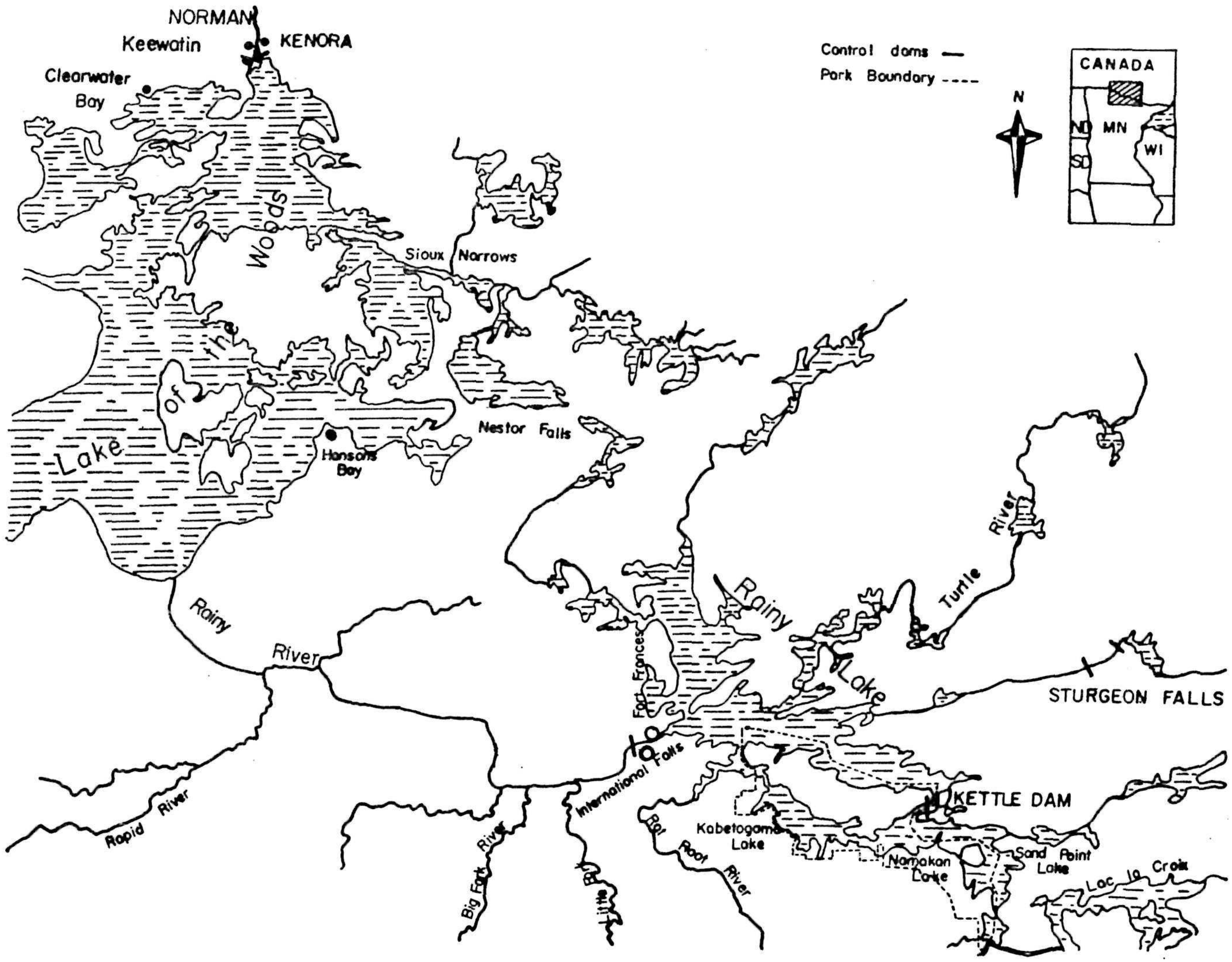

Figure 1. Hydrologic Drainage of Voyageurs National Park

Table 1. Hydrologic Subbasins

Subbasins	Active Depth ft	Lake Area mi^2	Drainage Basin Area mi^2
Namakan Lake	11	100	7440
Rainy Lake	4	345	7460
Rainy River			6570
Lake of the Woods	6	1485	5700

Lake of the Woods Control Board, 1982.

Why is there interest in studying the regulation of lake levels in this drainage basin? The hope is that through better management and operation of the existing regulated reservoir system, a larger variety of interests will be accommodated. The mission of the National Park Service, as detailed in the Organic Act (16 U.S.C. 1), clearly mandates that management policies regulate use to preserve natural objects and wildlife. Although both Namakan and Rainy Lakes existed as natural water bodies, the present day reservoirs are larger and regulated to satisfy specific desires of many group and individual concerns. A comprise between desirable lake levels and outflows is the primary objective with various interests each having different preferences throughout the year. Around the lake shores interest groups are primarily concerned with lake levels and include resort owners, tourist outfitters, wild river harvesters (including native people), paper companies, municipal water suppliers, commercial and sport fishermen, and commercial and recreation navigators. However, apparent conflicts exist because some interests prefer higher lake levels when others desire lower lake levels, particularly during the spring and summer months. Downstream interests, which include resorts, hydroelectric power producers, and developed communities, are primarily concerned with reservoir outflows. The National Park Service is most interested in restoring "natural conditions" (i.e., to comply with the Organic Act) whereas the dams in this system were constructed with the main objective of producing hydropower. Mutual present day interests are grouped into those wishing to restore and preserve the natural environment which includes wild rice, native fish, birds and mammals, and associated recreation uses; whereas other mutual interests include a corporation for producing forest products (which owns and operates the dams), local and state governments concerned about continued industry employment and a viable local economy, and individuals employed by industry. Additional concerns include navigation and pollution abatement which are more flow dependent.

As early as 1905 construction began on the International Falls Hydroelectric Project at Koochiching Falls at the outlet of Rainy Lake. This dam, as well as the two upstream parallel dams at the outlet of Namakan Lake (i.e., Kettle Falls Dam and its sister the Canadian Dam) are presently owned and operated by Boise Cascade (i.e., a private corporation) and previously by the corporate predecessor. The purpose of these dams historically have been to provide storage of water for the Corporation's powerhouses at International Falls for processing in their pulp and paper mills. The International Falls Hydroelectric Project was completed in 1909 and spans the Rainy River from International Falls, Minnesota to Fort Frances, Canada. The international boundary crosses through the middle of a rock and masonry overflow section of this dam. Kettle Falls Dams were completed in 1914 with one dam on each side of the international boundary; both are stop log dams which require manual operation for removal and insertion of logs for controlling reservoir releases. Turbines at International Falls and Fort Frances were installed initially in 1909 and then replaced in 1921 with further additions in 1924, later in 1978 grinding stones which were coupled to the first turbines for the purpose of grinding logs into pulp were removed and presently a new upgrading of turbines is planned.

Authority granted by an Act of Congress and of the Canadian Federal Parliament permitted construction of the dam and powerhouse on the Rainy River between 1905-1909. This action paved the way for development of forest products mills which in turn created communities at International Falls, Minnesota and Fort Frances, Ontario; a transition from furtrading posts to small urban communities. This geographic area is well suited to the production of wood and for recreation use with an economic base highly dependent upon the continued operation of the forest product mills. Other interests in the region include numerous resorts, flying services, campgrounds, summer houses, restaurants and hotels. Rainy Lake also supplies domestic water as well as high grade process water for the industrial mills. A water treatment facility owned and operated by Boise Cascade Corporation, owners of the dam, is the source of domestic water for the city of International Falls.

HISTORICAL LAKE LEVELS AND REGULATION

In 1909 the Boundary Waters Treaty between the United States and Canada was created and established the International Joint Commission (IJC), to prevent disputes regarding use of boundary waters and to provide for adjustments and settlements of questions regarding common surface waters, and to provide a framework for cooperation on questions relating to air and water pollution, as well as the regulation of water levels and flows. The IJC appoints International Boards of Control which perform in both a technical capacity and ensures compliance with IJC orders.

COMPUTED NATURAL LAKE LEVELS

Natural flows and lake levels are a thing of the past in most of the Rainy Lake Watershed. Artificially regulated levels have existed on Rainy Lake since March, 1909 and on Namakan Lake since March, 1914. The lower lines of Figures 2 and 3 represent the computed natural long-term mean lake levels, respectively, for Namakan and Rainy Lakes. These lines are derived by converting actual recorded lake level data for each reservoir to natural (i.e., undammed) lake levels; a computation performed by the U.S. Army Corps of Engineers as part of their assignment as members of the Rainy Lake Board of Control. Monthly values for the periods 1941 to 1980 and 1931 to 1980, respectively, for Namakan and Rainy Lakes are used in the long-term averages shown in Figures 2 and 3. Of course, there is considerable variability, from year to year and month to month, about these long-term average lines, with variations as much as seven feet. The point to emphasize is that naturally occurring lake levels and discharges (i.e., river flows) are quite variable with time in an uncontrolled system as compared to a highly regulated system. This difference has strong implications on the conservation of scenery, natural objects, and wildlife and preservation in an unimpaired state for future generations.

Some statistical analysis of the computed natural lake levels are provided by the data presented in Figures 4 and 5, respectively, for Namakan and Rainy Lakes. The lines plotted in each of these two figures are the median elevations for the end of each month, based on data as

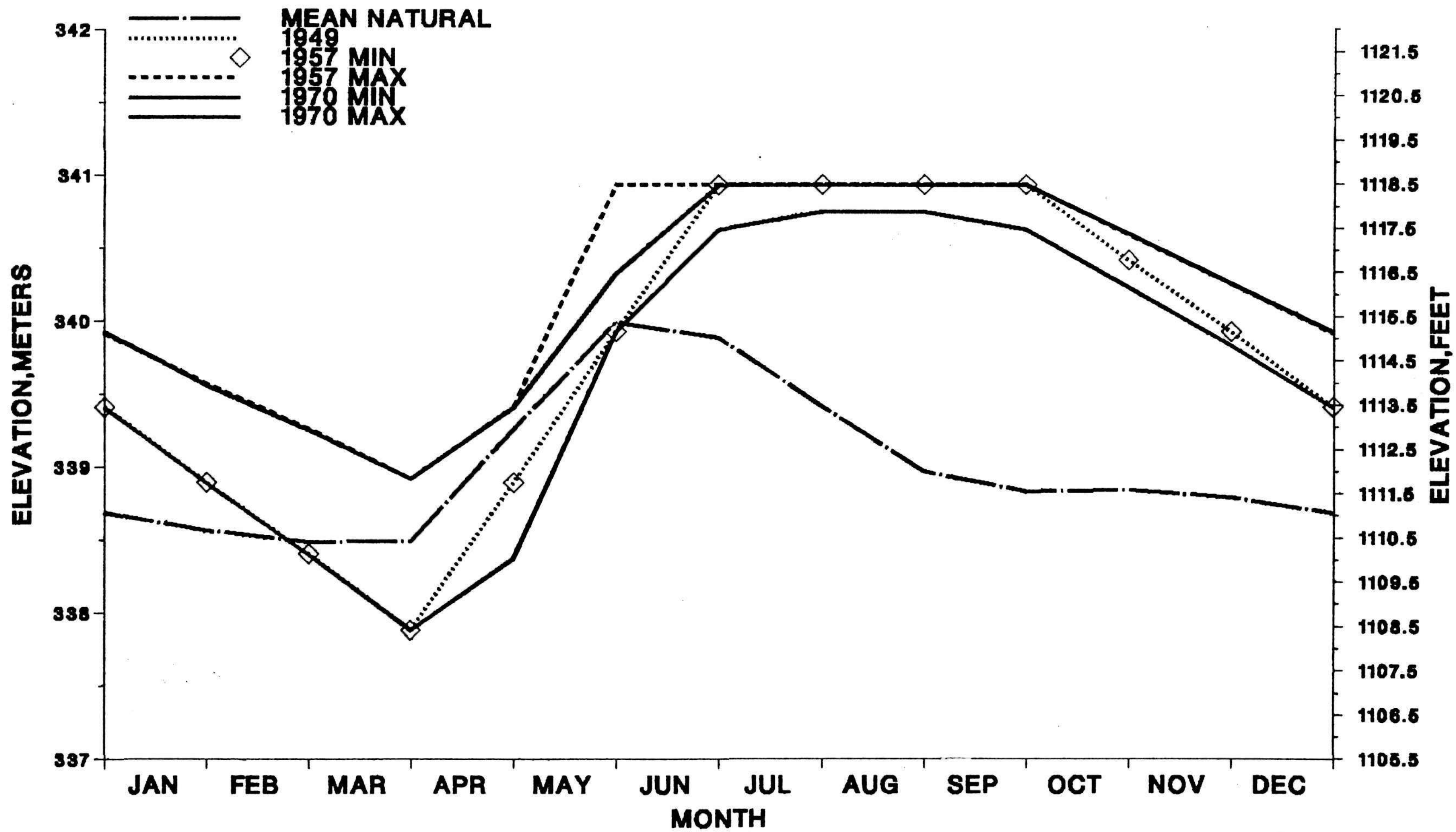

Figure 2. Rule Curves -- Namakan Lake

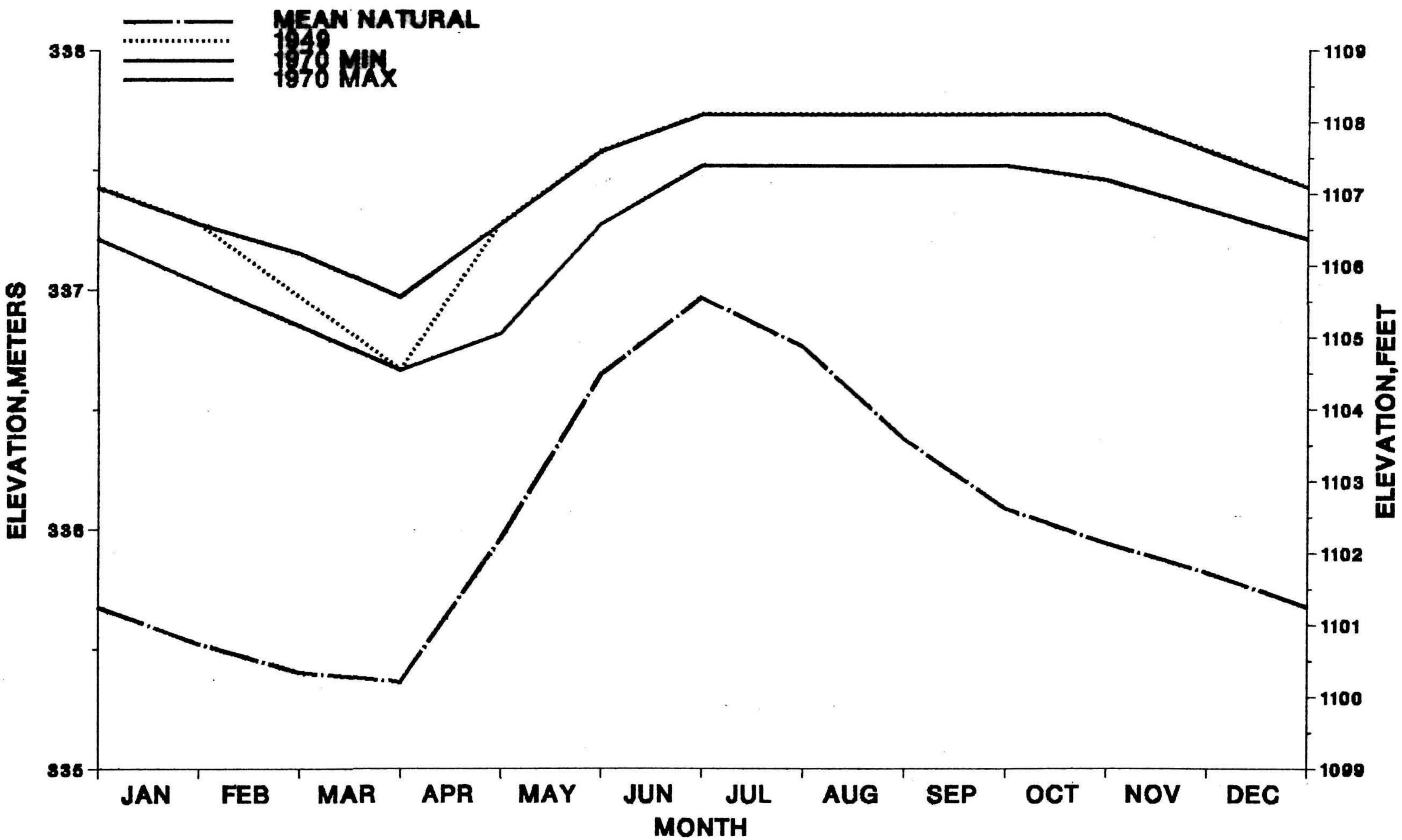

Figure 3. Rule Curves -- Rainy Lake

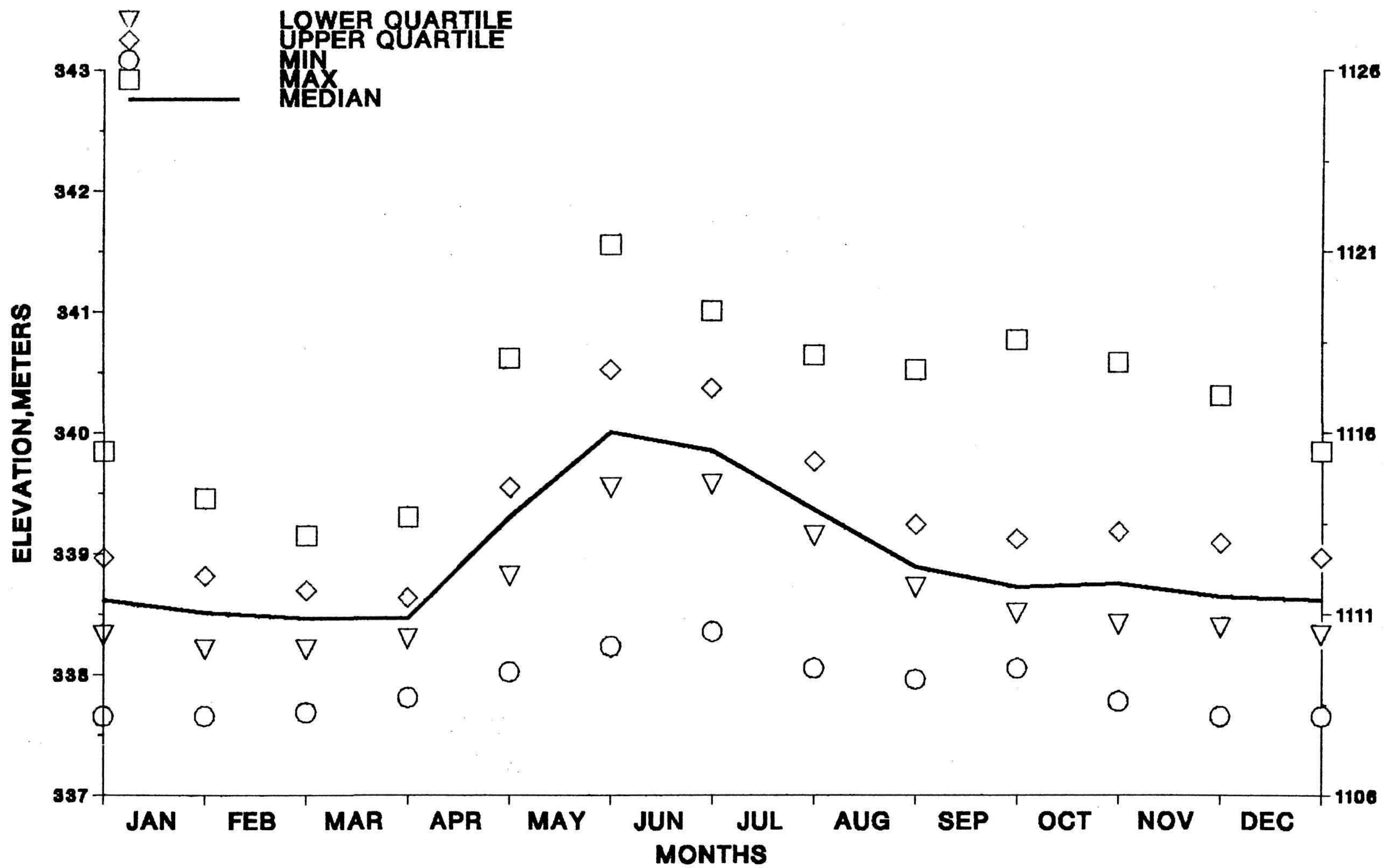

Figure 4. 40 Years Computed Natural Data -- Namakan Lake

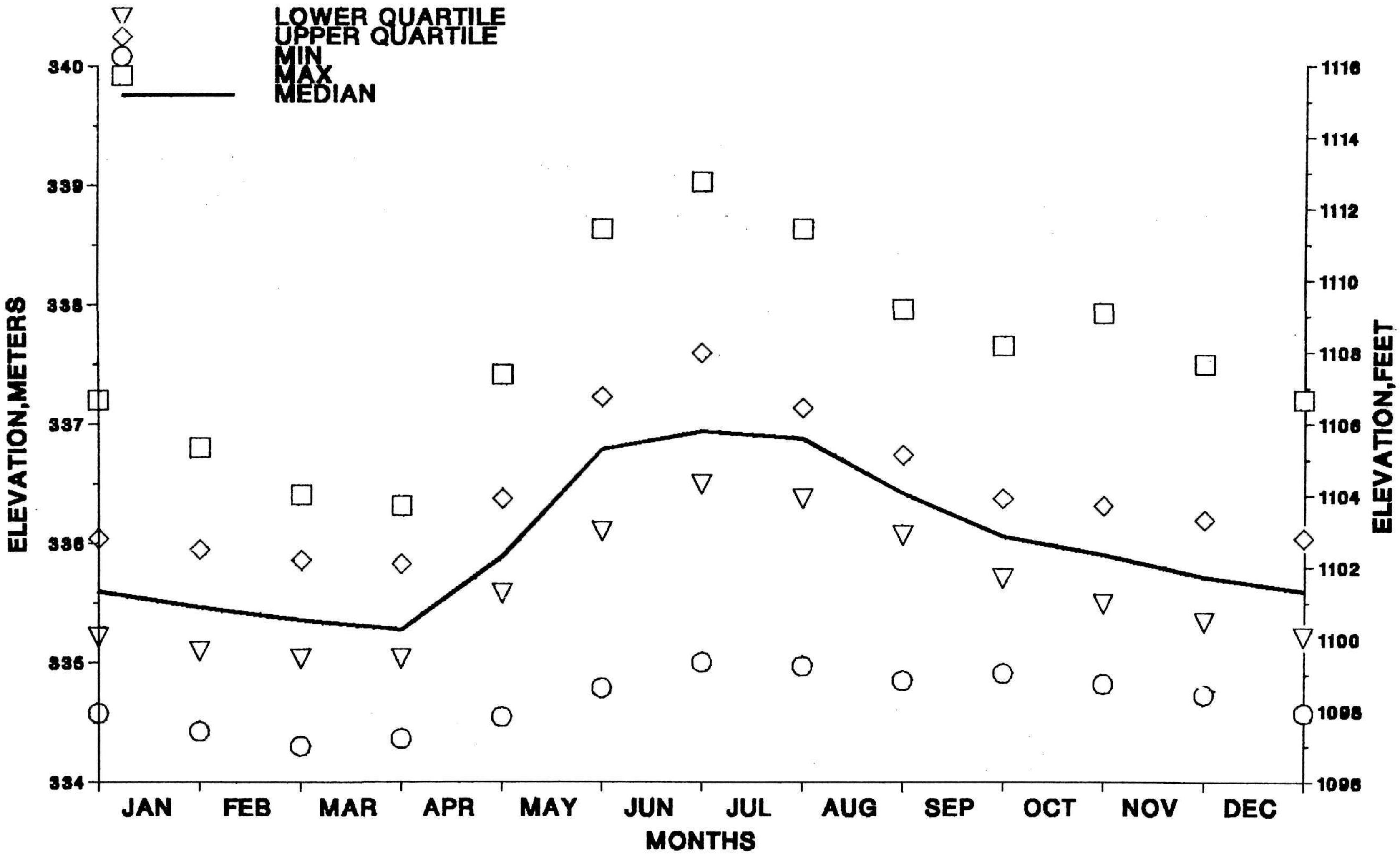

Figure 5. 50 Years Computed Natural Data -- Rainy Lake

reported by the U.S. Army Corps of Engineers. A similar graph is provided in Figure 6 for Lac La Croix, an uncontrolled lake just upstream from the Namakan Lake chain. However, the data for Lac La Croix are not "computed natural" but rather actual historic lake level measurements. Also shown in Figures 4, 5, and 6 are the maximum and minimum reported end of month lake levels, as well as the levels occurring at least 25 and 75 percent of the time (i.e., the lower and upper quartile). Values for the minimum and maximum indicate the range and timing of water inflows experienced by the Lake of the Woods drainage basin due to naturally occurring hydrologic variability from year to year. The upper and lower quartile are very uniformly distributed about the median, however, the maximum and minimum lake levels indicate some skew which is most pronounced in the fall months. These statistical summaries and particularly the median lines provide useful information relating to the timing and variation between naturally occurring lake levels, as well as the rate of rise and fall of these lake levels. The data presented in Figures 4, 5, and 6 clearly indicates that the peak lake levels under uncontrolled conditions occurs between June and July on Rainy Lake, a month later than that indicated for upstream Namakan Lake or Lac La Croix.

LAKE REGULATION

In 1938 a convention between both Canada and the U.S. was initiated and duly ratified in 1940 by His Majesty and the President which empowers IJC to determine when emergency conditions exist in the Rainy Lake Watershed. Furthermore, this convention empowered IJC to adopt definite practical measures of control or rules of regulation deemed proper with respect to existing and future dams or control works.

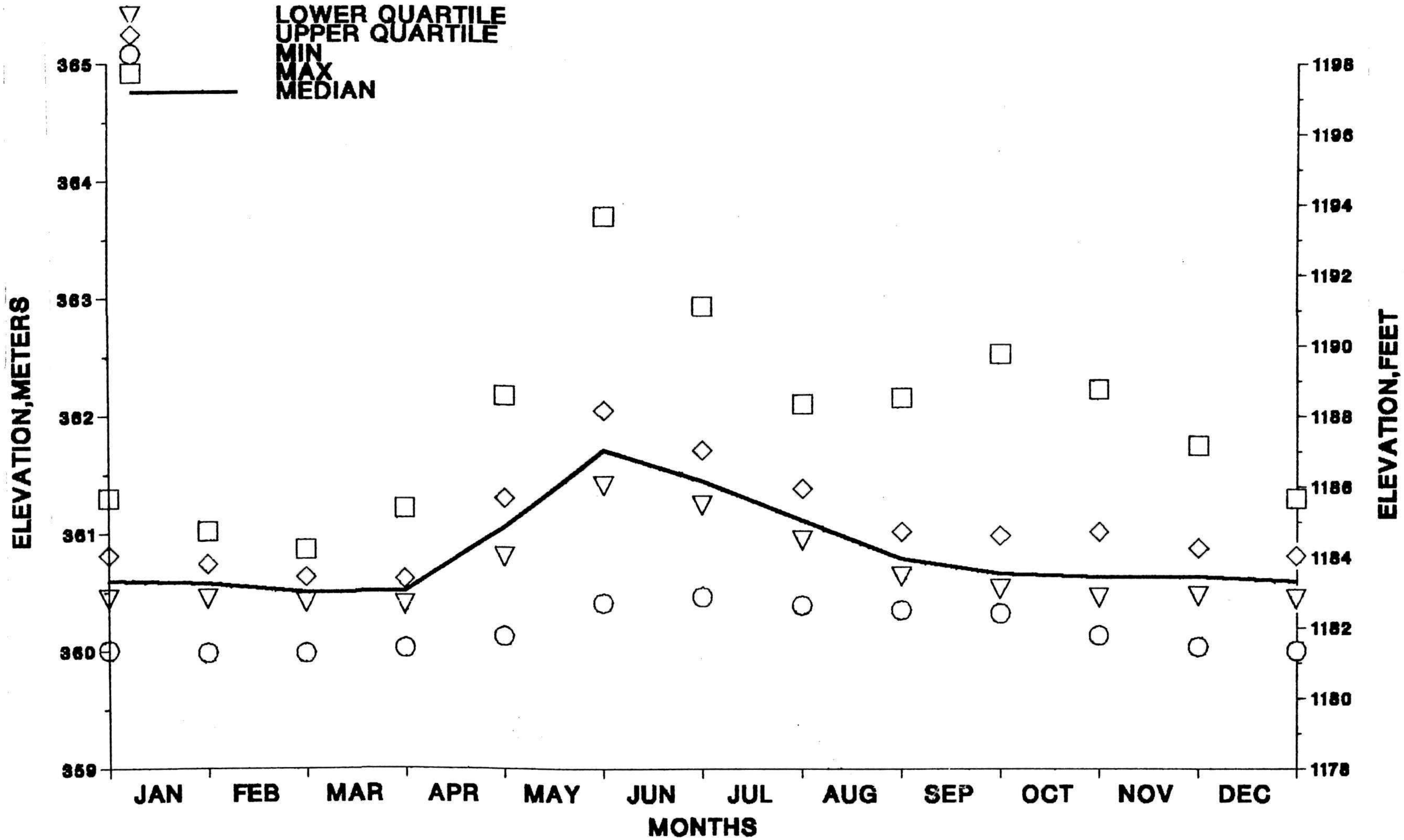

Figure 6. Natural Levels -- Lac La Croix

A primary objective was to secure most advantageous use of waters for combined purposes of navigation, sanitation, domestic water supply, power production, recreation, and other beneficial purposes. Noteworthy actions resulting from this convention included: 1) a careful field investigation and technical studies of the hydrology of the watershed by the International Rainy Lake Board of Control; 2) identification on the north rim of Namakan Lake of a natural high-level outlet called Bear Portage, which was at least partially obstructed by a crudely built timber and rock-fill barrier apparently constructed by owners of the dam without authorization from IJC; and 3) the holding of public hearings to allow all interested parties to be heard and present evidence addressing questions raised by the Convention. These actions eventually led to the IJC Order of 1949 which established criteria for flow releases and desirable surface water levels at both Namakan and Rainy Lakes on a monthly basis. This order specifically recognized the interests of the pulp and paper mills which owned and operated the dam and powerhouses at International Falls and Fort Frances. In addition, impacts of regulated lake levels on riparian lands, shore properties, erosion of banks, flooding, creation of unsightly and unsanitary conditions, recreational use, and damaging high flow discharges were recognized concerns of individuals and the general public in both the U.S. and Canada.

The following subsections provide a detailed description of each action taken by the IJC. Figures 2 and 3 portray as best as possible the tabular values presented by the IJC. The graphs in these figures use only one value for the beginning of each month and do not include any intermediate dates within any month. A brief summary of the IJC actions described below is presented in Table 2 toward the end of this section.

1949 ORDER

The International Joint Commission Order of 1949 attempted to prevent emergency conditions (defined below) and identified the need to anticipate high and low watershed inflows so that regulation of reservoir outflows would preclude the occurrence of emergency conditions. Emergency conditions were defined as follows:

EMERGENCY CONDITIONS - IJC 1949 ORDER

	Elevation, feet above Mean Sea Level	
	Maximum	Minimum
Namakan Lake	1118.61	1108.61
Rainy Lake	1108.11	1104.61

The longest records of data available at that time indicated that the maximum level for Namakan Lake need not be exceeded by as much as 0.5 feet, and that only on rare occasions the maximum and minimum levels on Rainy Lake would be violated, due in past to the prescribed method of regulation. Other primary stipulations of the 1949 Order are represented by the reservoir rule curve shown for Namakan Lake in Figure 2 and for Rainy Lake in Figure 3. These curves graphically portray a tabular set of lake evelvations which Namakan Lake was to be at on the first of each month and Rainy Lake was not to exceed. Additional conditions set maximum discharge restrictions at International Falls Dam (i.e., from Rainy Lake) at an average of 6,000 cfs whenever the lake elevation is below the prescribed level for that date; and furthermore, that discharge be reduced to 4,000 cfs when on July 1 the lake level falls below 1108.11 feet and the average inflow rate is less than 10,000 cfs, or whenever the level of Rainy Lake is more than two (2) feet below the level indicated by the 1949 rule curve of Figure 3 and the inflow on the first of the month is below 10,000 cfs.

1957 ORDER (AMENDMENTS)

As a result of complaints lodged with the International Joint Commission surrounding operation of the flow control works under the 1949 Order and in view of the floods of 1950 and 1954, the Commission directed the International Rainy Lake Board of Control to prepare a report on the operation of reservoir control works and method of regulating levels of the boundary waters. Specific questions the Board and its subsequent report were directed to address were: 1) in what particulars has the 1949 Order proved unsatisfactory; 2) in what instance, if any, have requirements of the Order not been complied with and why; 3) considering the various interests in both Canada and the U.S. concerning lake levels, what changes in the method of regulation is desirable; and 4) what changes to existing control works or operation of such is necessary for improved regulation, if any, and at what cost? Further directions to the Board included consideration of legal rights of all interests and that any suggested change in regulation have no adverse effects on riparian interests along the shores of Lake of the Woods, or appreciable interference with Lake of the Woods hydropower generation. Additionally, any revision of the method of regulation should consider snowpack in the basin and forecasting of such to allow the drawdown of lake levels in advance of peak inflows.

The resulting report, completed in July 1956, concluded that: 1) the 1949 Order is generally satisfactory; 2) the terms of the Order have been satisfactorily met during the seven year period except for two extreme high water years in 1950 and 1954; 3) no change be made in operation for Rainy Lake; 4) Namakan Lake be allowed to vary between the 1949 levels and a proposed maximum set of levels for the period October 1 to June 1; and 5) the existing control works need not be modified as long as the company maintains the condition such that outflow adjustments can be made promptly. Following this reporting of the International Rainy Lake Board of Control to the International Joint Commission, a public hearing was held with the recommendations explained and all interested parties offered an opportunity to be heard. As a result, all of the report recommendations were included in an amendment to the 1949 Order; including, under the direction of the Board the lowering of Namakan Lake in anticipation of spring runoff but not below the 1108.61 feet minimum level. Figure 2 includes a graphical representation of the maximum rule curve for Namakan Lake established by this 1957 Amendment. Besides providing greater flexibility to operation of the system, the maximum rule curve provides for the extension of full reservoir level in Namakan Lake on June 1 as opposed to July 1, to accommodate resort interests, and furthermore provided a maximum level of 1112 feet during the period April 1-21 to improve fish spawning activity. This amendment was implemented for a five year period with an opportunity for interested parties to be heard prior to modifying or continuing the enactment of the 1949 Order with these 1957 Amendments.

1970 AMENDMENTS

The Commission extended the above described Order and Amendments twice; however, in the summer of 1968 requested the Board to further examine the method of regulating levels of Namakan and Rainy Lakes. This examination came in response to heavy rainfalls which occurred since 1957 and particularly throughout the summer of 1968 which resulted in water levels considerably above full pool elevations as specified in the 1949 Order and 1957 Amendments for both Namakan and Rainy Lakes. Additionally, various occurrences of low water levels since 1957 have resulted in both Namakan and Rainy Lakes to fall below the prescribed minimum elevations. Therefore, the periodic high and low flow occurrences, combined with the desire to better qualify "emergency conditions," and the operational difficulty in achieving desired lake levels on specified dates indicated a need to reevaluate the method of regulating this system.

One year later, in 1969, a report was completed, presented, distributed, and public hearings held at which all interested persons were given the opportunity to present testimony. Later, in April 1970, the Commission was informed, by the International Rainy River Water Pollution Board, that unsightly fibrous sludge deposits are exposed and become increasingly offensive when Rainy Lake outflow is less than 4,000 cfs; and that at a flow less than 3,300 cfs the dissolved oxygen (DO) level falls below the objective of 5 mg/ℓ.

As a result of the above actions occurring between 1968 and 1970, the Commission further amended the then existing 1949 Order and 1957 Amendments. The first item of change surrounds a complete redefining of "emergency conditions" in and along the shores of the Namakan Chain of Lakes and Rainy Lake. For Namakan Lake, emergency conditions exist when the water level is higher than 1118.6 feet above mean sea level and the inflow at that time is in excess of the total outflow capacity of the Kettle Falls structures. Likewise, emergency conditions exist when the water level is lower than 1108.6 and outflow has been reduced to 1,000 cfs. In addition, an allowance of a 0.5 feet flood reserve is permitted when flood inflows are greater than the outflow capacity; at this time (i.e., elevation 1119.1 feet) all gates and fishways in Kettle Falls Dams shall be fully open to ensure the most rapid return to maximum levels as specified by the new maximum rule shown in Figure 2. At the lower levels, when Namakan Lake falls below the minimum rule shown in Figure 2, the total outflow from Kettle Falls Dams shall be reduced to 1,000 cfs until the level returns to the specified minimum for that date. This 1,000 cfs minimum outflow was established because it approximates what would occur in a state of nature, and is intended for pollution abatement and to appease property owners at the outlet.

For Rainy Lake a minimum rule curve was added and is shown in Figure 3 along with a slightly modified rule curve of the 1949 Order which now serves as a maximum. Furthermore, whenever Rainy Lake exceeds 1108.6 feet above Mean Sea Level and flood inflows are in excess of the outflow capacity of the dam at International Falls-Fort Frances, all gates shall be fully open to ensure rapid return to the prescribed maximum elevation for that date. Similarly, whenever the level falls below the minimum for that date, outflow is reduced to a minimum instantaneous 4,000 cfs between sunrise and sunset from May through October, and 3,300 cfs otherwise. The Commission recognized the importance of the Natural high-level Bear Portage outlet from Namakan Lake and specifically ordered that it remain natural and that the deterioration which has occurred to the man-made obstruction should continue to erode and no repairs or other modifications are permissible without prior Commission authorization. To further maintain system flexibility, the Board after obtaining approval from the Commission, can authorize temporarily that Namakan and/or Rainy Lake be raised or lowered in violation of the 1970

Ordered rule bands of Figures 2 and 3 in anticipation of extremely high or low inflows.

EMERGENCY REGULATION AMENDMENTS, 1976 AND 1977

In October 1976 the Commission was informed that operational difficulties at the Fort Frances, Ontario hydropower plant had arisen and a request to exceed outflow restrictions would assist the Company in overcoming these difficulties. The Commission therefore responded by amending the Order to allow a maximum daily average discharge of 4,900 cfs during the period October 13-31, 1976, provided that the instantaneous minimum flow of said Order is not violated. Once again, in November 1976, the Commission was notified that, due to maintenance requirements, additional flows up to an instantaneous flow of 6,300 cfs would be required for short periods to maintain plant operation during a one day period. This temporarily increased flow release, however, would result in an average daily flow of less than 3,600 cfs. The Commission responded positively to these needs by formalizing an Amendment to the existing Order.

In April 1977, the Commission was informed that due to low runoff the minimum prescribed outflows of the 1970 Amendments were continuing to be implemented and that both Namakan and Rainy Lakes were expected to fall below the minimum specified levels. The Board, therefore, recommended and the Commission directed the implementation of a reduced outflow regime for the period May 5 to June 15, 1977. Daily mean discharges were reduced to 2,500 and 500 cfs, respectively, for Rainy and Namakan Lakes; with the Board given discretion to increase discharges if the situation requires. Later, on June 14, 1977, this Amendment was further extended to August 15, 1977 with the added stipulation that the

Board could temporarily direct increases in either or both discharges to prevent the dissolved oxygen level in the Rainy River from falling below 4 mg/ℓ.

At the other extreme, heavy rainfall, occurring in the summer of 1968, created a situation in which Namakan Lake rose to 1121.1 feet on July 6 and Rainy Lake reached an elevation of 1110.2 feet on July 18. Previous high level events occurred on Namakan Lake on May 23, 1916, reaching a level of 1122.9 feet and Rainy Lake rose to 1112.5 feet on June 8, 1916. The lowest recorded levels occurred on Rainy Lake on April 11, 1909 at 1098.9 feet, and on April 13, 1923 for Namakan Lake at 1106.2 feet. Violations to rules specified in the existing Order continually recur during periods of extreme hydrologic events. In addition, various interests change with time and apply pressure to alter specific stipulations of the governing rules (i.e., Order). However, without perfect knowledge as to future hydrologic events, some flexibility and therefore, temporary infractions to the strict rules and orders of the Commission must be expected.

SUMMARY OF OPERATING RULES AND AMENDMENTS

Table 2 briefly portrays the significant lake level and outflow rules that historically have been placed in effect. These Orders, Amendments, and rules of regulation were established by the International Joint Commission in response to natural hydrologic events that overtaxed the system of operation in place at the time and due to resulting outcries from various interests along the lake shores. The objective in these rules of regulation were to secure most advantageous use of waters for several combined purposes including power production, recreation, sanitation, navigation, and other beneficial public

Table 2. Historic Reservoir Rules of Operation Summary

COMMISSION ACTION	Namakan Lake[1]	Rainy Lake[2]
1949 Order	Established elevations that the Lake is to be at on the first of each month. "Emergency conditions" exist above 1118.61 ft and below 1108.61 ft.	Established elevations that the Lake is not to exceed on the first of each month. "Emergency conditions" exist above 1108.11 ft and below 1104.61 ft. Set discharge maximum when lake falls below established levels.
1957 Amendments	Established a maximum set of elevations for the period October 1 to June 1. Full reservoir level achieved on June 1, instead of July 1. Maximum elevation of 1112 ft between April 1-21, to improve fish spawning.	No change
1970 Amendments	Redefined both the maximum and minimum of the rule band. Delayed full reservoir level to June 21. Provide for a 0.5 ft flood reserve; i.e., maximum elevation of 1119.1 ft. Redefine "emergency conditions"; when level is above 1118.6 ft and inflow greater than outflow capacity, or below 1108.6 ft and outflow is reduced to 1,000 cfs (i.e., approximates natural state).	Established a minimum set of elevations and modified the existing set to now serve as a maximum; thus creating a rule band. Established minimum discharges of 4,000 cfs and 3,300 cfs for pollution abatement. Provide for a 0.5 ft flood reserve; i.e., maximum elevation of 1108.6 ft. Redefine "emergency conditions;" when level is above 1108.1 and inflow greater than outflow, or lake is below the prescribed minimum.
1976 Amendments	Temporarily allowed for modified daily averages and instantaneous flow releases.	
1977 Amendments	In response to drought conditions, reservoir releases were temporarily reduced to: 500 cfs	2,500 cfs

[1]Established lake elevations are shown in Figure 2.
[2]Established lake elevations are shown in Figure 3.

purposes. Various studies and reports, based on analysis of data from historic extreme hydrologic events (i.e., floods and droughts), have been completed along with public meetings to obtain input from all concerned citizens in both the U.S. and Canada.

MODELING THE LAKE SYSTEM

Given that violations of the established rules of operation are a natural phenomena which have occurred in the past, and considering the multitude of wants from various lake shore interest groups which change with time, the National Park Service became interested in evaluating alternative rules of operation. A mathematical simulation model of the multi-lake watershed seemed an obvious approach to permit management to evaluate if slight modifications of the regulated rules of operation could reduce adverse effects on Park aquatic and riparian life without conflicting with other authorized uses of water.

A conceptual schematic which identifies the major components of the modeling approach is given in Figure 7. Each of these components is described in greater detail in a separate subsection. In brief, the hydrologic/hydraulic system of concern is isolated and the flow path of water through the rivers and lakes identified. The model employs a series of mathematical equations to represent the system as described. The resulting mathematical system of equations are then solved for the input data given (i.e., hydrologic inflows and other rules of operation). In reality, there is little difference between some input data, operating rules, and elements of the system description. They are separated out primarily because of ways in which they are used in analyzing alternative reservoir management operating policies in this particular study. Except for the upstream inflow data, all other inputs

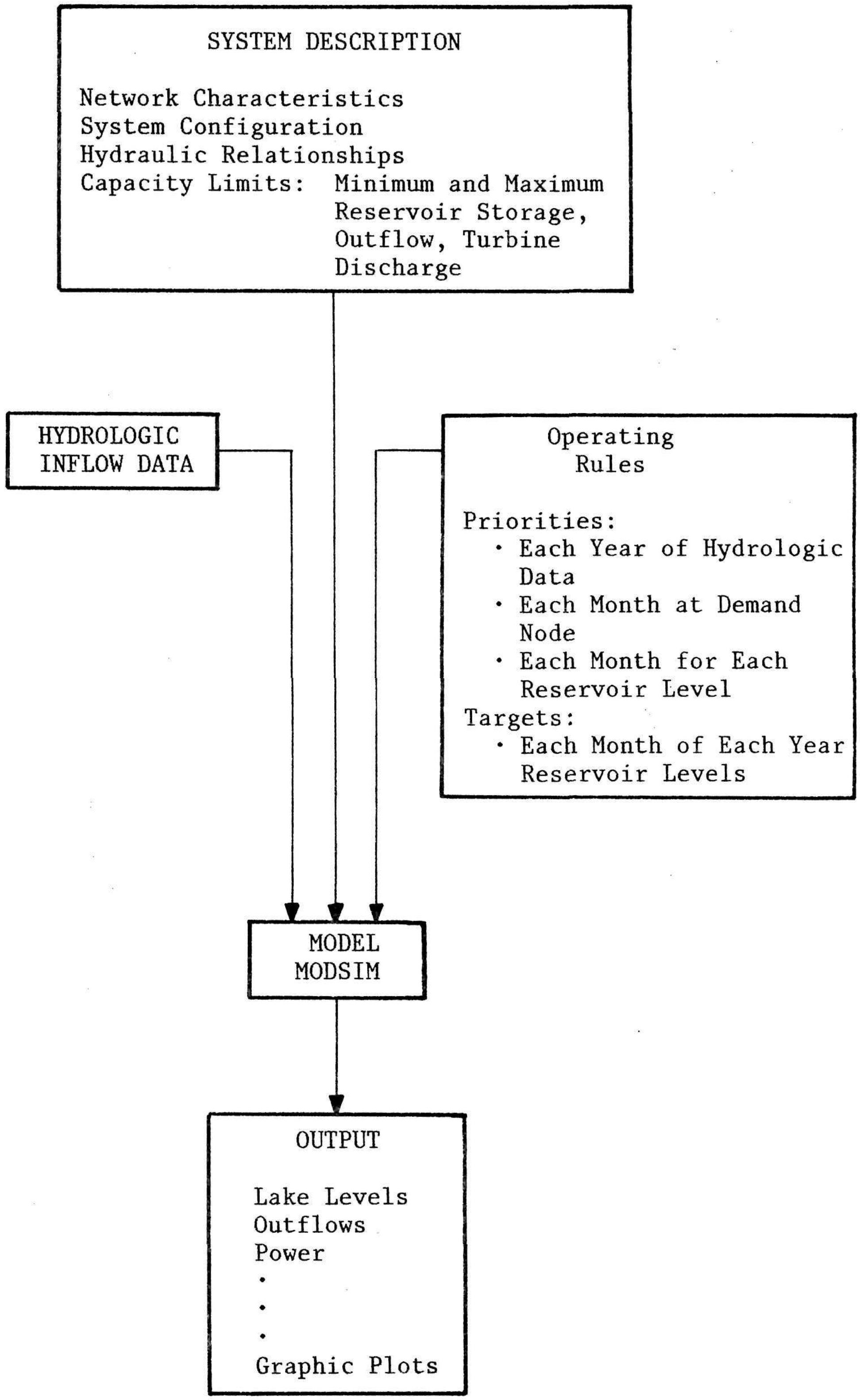

Figure 7. Conceptual Model Overview

could be considered a part of the system description for any given model solution.

A mathematical simulation model was desired for this study that could rapidly and easily evaluate many alternative management schemes. For example, to preserve higher lake elevations in one reservoir as opposed to another (e.g., Namakan Lake instead of Rainy Lake); or to maintain a larger minimum outflow from a particular dam (e.g., International Falls-Fort Frances outflows). The simulation model selected, MODSIM(2), represents the real river basin system as a circulating network. Priorities (or costs) are assigned to each link of the network on a monthly basis and an out-of-kilter optimization algorithm is used to minimize a weighted objective function. By assigning a different set of priorities, the simulation behaves in an alternative fashion while maintaining continuity. The assignment of priorities changes the weights of the objective function and thereby forces the optimum simulation to operate in the desired alternate mode; for example, increased discharges or higher lake elevations can be given higher priorities. In addition to continuity, various constraints are included in the model which represent physical or legal limitations of the reservoir system. These constraints include maximum outflows through existing outlet works, minimum flow requirements for water pollution, both maximum and minimum lake levels, and others as appropriate. As used in this study, the model routes mean monthly inflows through the system; and is not intended for daily operation of the reservoir in real time.

SYSTEM DESCRIPTION

Figure 8 portrays the hydrologic/hydraulic system for that portion of the Lake of the Woods Basin of Figure 1 in a flow chart format. For

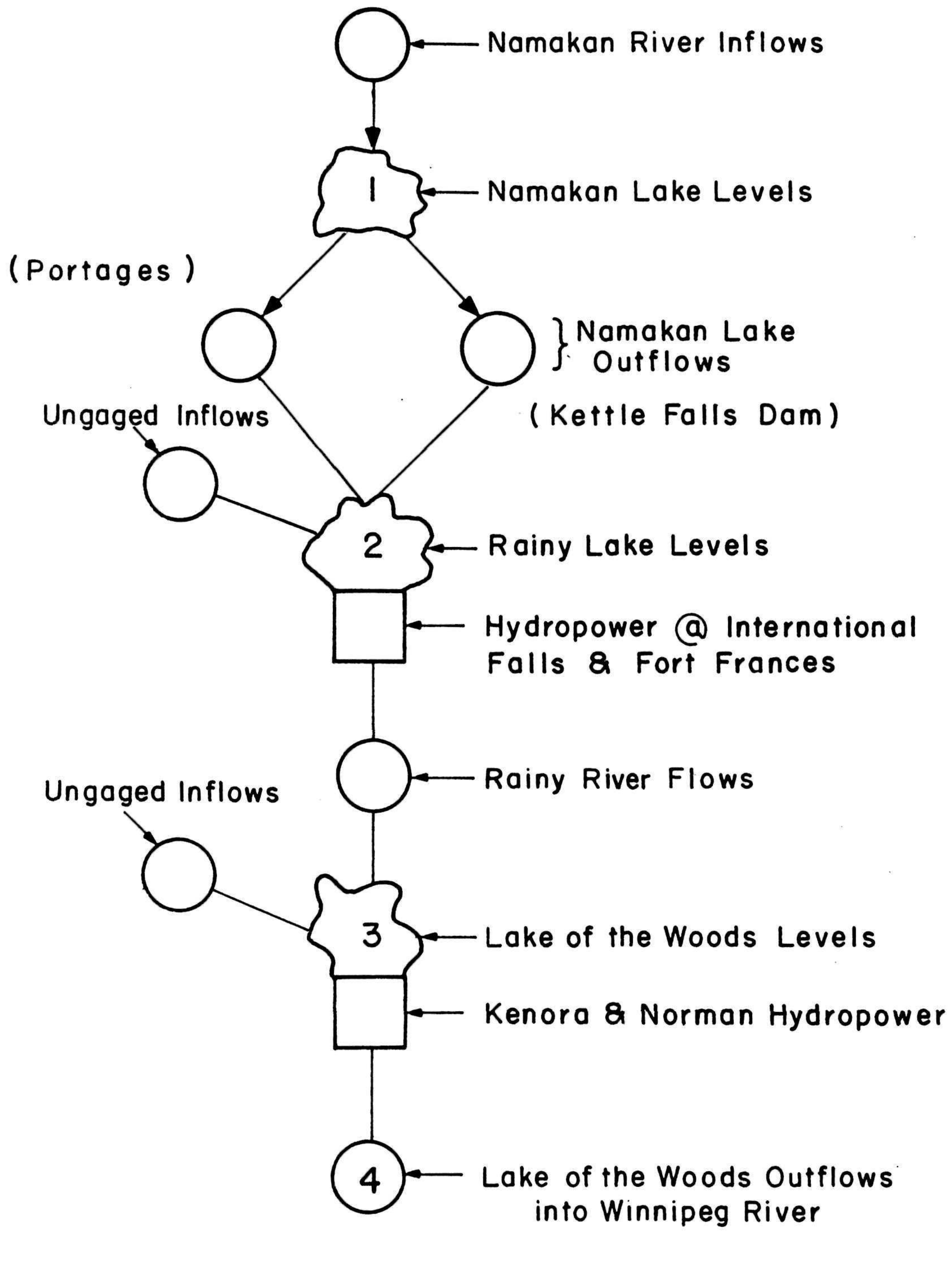

Figure 8. Flow Chart of Water Flows through the Three Reservoir System

the problem at hand the network system begins at the upstream end of the watershed with inflows to the Namakan Lake chain and proceeds through the lake with outflows via Kettle Falls Dams and portages. These outflows then enter Rainy Lake along with other unmeasured inflows. Flows out of Rainy Lake are all through the dam at International Falls/Fort Frances and generate hydropower up to a maximum turbine discharge and based on a turbine efficiency which is a function of the head (i.e., Rainy Lake level). These Rainy River flows then become input to Lake of the Woods along with other ungaged inflows. Discharges from Lake of the Woods are through the hydrpower facilities at Norman and Kenora.

The flow chart of the drainage basin network shown in Figure 8 is interpreted as a series of <u>nodes</u> and <u>links</u> which operate by defined mathematical relationships. A mass balance model simulates the lake system by maintaining continuity between reservoirs in the system such that:

Inflow = Outflows + Change in Storage

where, Inflows serve as the input data (i.e., the independent variable); Outflows are computed at each node (i.e., dam outlet); and the Change in Storage is computed for each reservoir.

Hydrologic inflow data are used as input and consists of series of ungaged inflows and monthly Namakan River flows which correspond to historic data. These values are referred to as the independent variables, a further discussion of these input data is given in a subsection to follow. The maximum and minimum capacity limits for volumes of water stored in each node (i.e., reservoir) and for flows through each link are given in Table 3. The level of each reservoir is maintained between the respective corresponding maximum and minimum capacity.

Table 3. Input Capacities for Reservoirs and Links

	Capacity		Maximum Turbine Discharge
	Minimum	Maximum	
Reservoir	Million M^3		
Namakan	0	1234	
Rainy	0	4342	
Lake of the Woods	0	13000	
Links	Million M^3/month		Million M^3/month
Kettle Falls	74	1406	NA
Portages	0	1934	NA
Rainy Lake Outflow into Rainy River	186	3563	758
Lake of the Woods Outflow into Winnipeg River	0	8000	1051

Table 4 provides, in tabular form, the corresponding hydraulic relationship of reservoir elevation, capacity, area, and power factors. Namakan Lake accepts the Namakan River inflow volumes of water and routes them through the lake as regulated outflows via both dams at Kettle Falls, (which are treated as one controlled outlet) and via high level portages. Outflow from Namakan Lake is first routed through Kettle Falls Dams until the maximum capacity is reached. Any additional outflows are then routed through the high level portage links up to their maximum capacity. These outflows from either link then become gaged inflows to Rainy Lake.

Inputs to Rainy Lake consist of the Namakan Lake outflows plus the ungaged hydrologic inflows, computed as a part of the historic input

Table 4. Reservoir Physical Data

Reservoir	Elevation Meters	Storage	Power Factor Meters	Turbine Elevation Meters
Namakan Lake	337.1	0		NA
	338.3	271		
	339.2	469		
	339.9	617		
	340.8	845		
	341.4	1011		
	342.0	1141		
	342.2	1234		
Rainy Lake	334.4	62	5.4	329.
	335.9	1061	6.9	
	336.5	1517	7.5	
	337.3	2159	8.3	
	338.0	2825	9.0	
	338.6	3454	9.6	
	339.5	4342	10.5	
Lake of the Woods	321.0	0	5.0	316.
	324.0	13000	8.4	

data series. The level of Rainy Lake is maintained between the corresponding maximum and minimum capacity (see Tables 3 and 4). Rainy Lake outflows are all through the dam at International Falls/Fort Frances. These flows generate hydropower according to the corresponding power factors given in Table 4, which are related to the Rainy Lake level. The "head" for power generation is taken as the difference between the lake level for the average volume of water stored in a given month and the turbine elevation, as specified by values given in Table 4. Intermediary values relating to items defined in Table 4 are computed within the model by linearly interpolating between the appropriate two defined data pairs. Flows through the dam are limited to values given in Table 3.

Hydropower is generated in proportion to the Rainy outflow up to the maximum turbine discharge listed in Table 3. Power is normally computed according to the following formula:

$$KW = \frac{\gamma \times H \times Q \times E}{1000}$$

where:

KW = power, kilowatts;

γ = specific weight of water, 9810 N/M^3;

H = head, M;

Q = discharge, M^3/s;

E = efficiency.

The hydropower formula used in modeling the Lake of the Woods basin is modified to accommodate the monthly data and time period used in analysis. The altered equation is computationally equal to that given above and is as follows:

$$KWH = H \times D \times C$$

where:

KWH = average daily energy output for a given month, kilowatt-hours per day;

H = power factor or head, M;

D = monthly turbine outflow volume, M^3/month;

C = conversion factors, specific weight of water, efficiency;

such that:

$$C = \frac{9810}{1000} \frac{N}{M^3} \frac{12 \text{ month}}{\text{year}} \frac{\text{year}}{365 \text{ day}} \frac{\text{hour}}{3600 \text{ second}} \times E$$

and when: $E = 0.65$

$$C = 58.23 \times 10^{-6} \frac{N}{M^3} \frac{\text{month}}{\text{second}} \frac{\text{hour}}{\text{day}}$$

so that the month/second units convert the outflow D to M^3/s which is equivalent to Q. The remaining units of hour/day are used to compute the energy, KWH, in units of kilowatt-hours/day.

Rainy Lake outflows enter the Rainy River and become input to Lake of the Woods along with some other ungaged hydrologic inflows, also computed as part of the historic input data series. Lake of the Woods levels are maintained between the limits as specified in Tables 3 and 4. Outflows are all through the dams at Kenora and Norman. These flow releases are maintained within the limits specified in Table 3 with corresponding hydropower generated according to the power factors given in Table 4. The monthly outflow from Lake of the Woods is compared to model input data assigned to the "demand node" on the Winnipeg River. By adjusting the priority (i.e., weight) of this modeling component, Lake of the Woods outflows can be forced to match the data assigned to the "demand node", that is, the actual historic releases.

OPERATING RULES

The "operating rules" provide attributes by which the model is instructed to allocate and route water through the system. Of most importance are the monthly target lake levels which are a set of values similar to the historic operating rules previously shown in Figures 2 and 3, respectively, for Namakan and Rainy Lakes. Lake of the Woods is given a set of lake levels which correspond to actual historic levels that belong to the data input and time period modeled. In addition to the desired lake levels each month, a priority is assigned to each reservoir for each month. These priorities instruct the model as to the relative importance of maintaining lake levels as specified by the operating rules. In routing historic inflows through the system, some time periods present situations in which lake levels can not be maintained exactly as specified while adhering to the continuity relationships and constraints for flow limits in each link. Using the specified priorities the model determines the order reservoirs will be allowed to deviate from the desired operating rule levels. In an analogous fashion, a demand node, outflows from Lake of the Woods into the Winnipeg River, is given a set of priorities. This demand node and the corresponding priority determine the relative importance of computed outflows from the overall system equalling the historic outflows given as a part of the input data set. For the problem at hand, this demand node is given the highest priority so that no violations from the desired outflows will occur. In this way, a portion of the Lake of the Woods Basin of interest to Voyageurs NP is modeled with no resulting external influences further downstream in the basin.

As mentioned previously, many of the system constraints described as a part of the System Description can be considered variable, and therefore can be treated as operating rules. The variable constraints and operating rules include: maximum and minimum limits in each flow link; maximum turbine discharge; overall turbine efficiency as included in the power factors for each respective lake level; monthly desired lake levels for each reservoir (i.e., operating rules); priorities for each reservoir node and the demand node; and the order of spilling (i.e., wasting) water from each reservoir. Spilling water is required only if the continuity relationships can not be adhered to given all the other specified input data and constraint limits. Values given in Table 4 for the power factor correspond to the respective lake elevation value and the model linearly interpolates for intermediary values. In an analogous fashion, calculations for the head on each turbine is computed within the model.

To properly analyze this multi-lake system and evaluate alternative management options, several operating rules and constraints need to be set at different values. In this way, the model will route flows through the system and thereby simulate reservoir operation according to the alternative management option corresponding to the defined operating rules and limits. One set of alternative operating rules for Namakan and Rainy Lakes are given, respectively, in Figures 9 and 10. These target lake levels, labeled ALT F are only one example of an alternative set of operating rules. Specific values shown in Figures 9 and 10 for the beginning of each month are selected by attempting to follow the pattern and aspects of the naturally occurring lake levels. The natural levels from Figures 4 and 5 are also shown as the mean in Figures 9 and 10. Adjustments were made to these natural occurring flows to accommodate the higher lake levels created by the dams at Kettle Falls and at International Falls/Fort Frances. Also shown in Figures 9 and 10 are the maximum and minimum rule curves corresponding to the 1970 IJC amendments.

HYDROLOGIC INFLOW DATA

The desired data for evaluating this lake system consist of long-term records of lake levels, outflows, and most importantly river inflows. Ideally, inflows, outflows, and lake levels are known and then continuity relationships are used to compute losses or other ungaged fluxes to the system. A lack of inflow data exists, however, both upstream and tributary to the Rainy River. To overcome these data deficiencies and keeping in perspective the initial intention of this

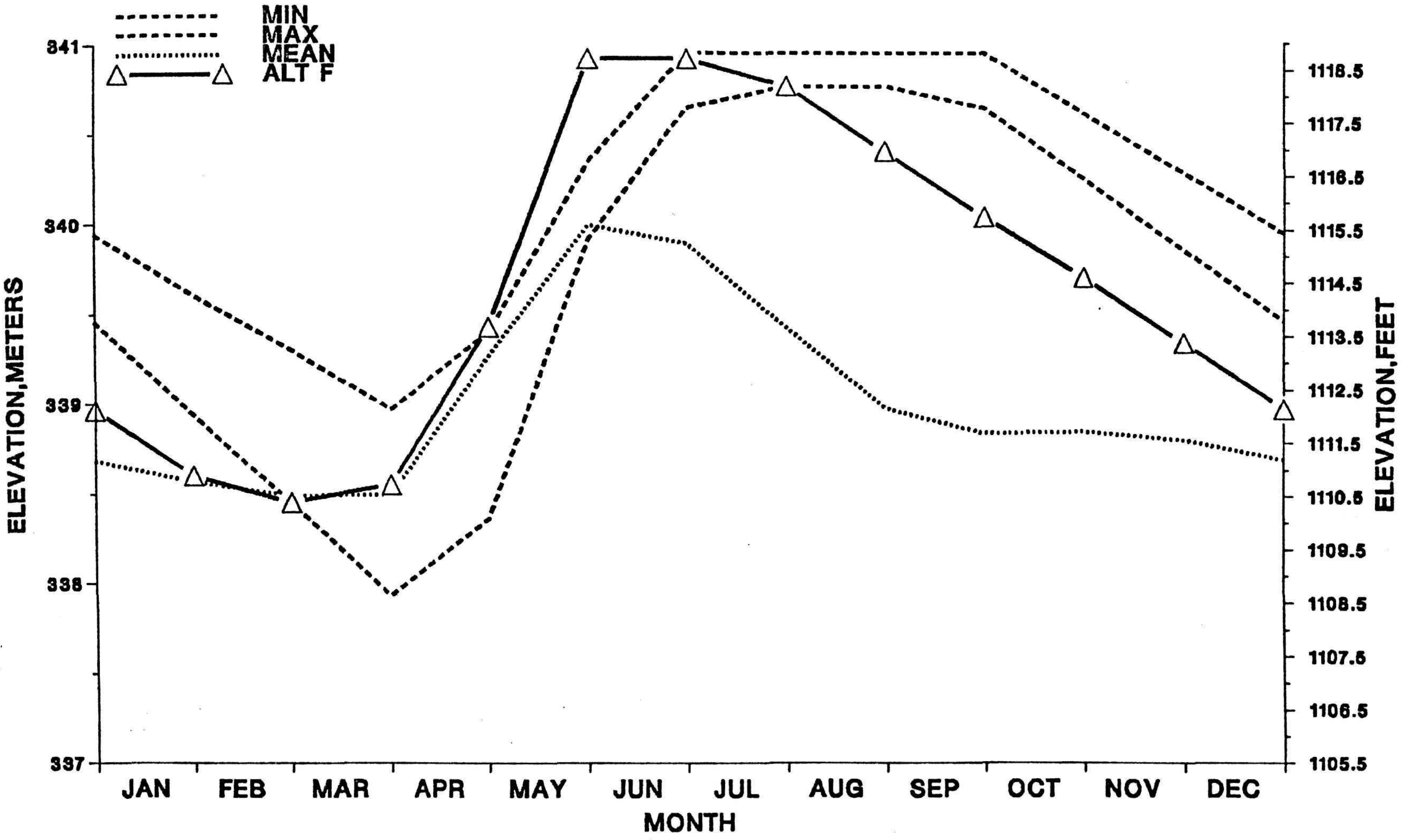

Figure 9. Namakan Lake Target Levels

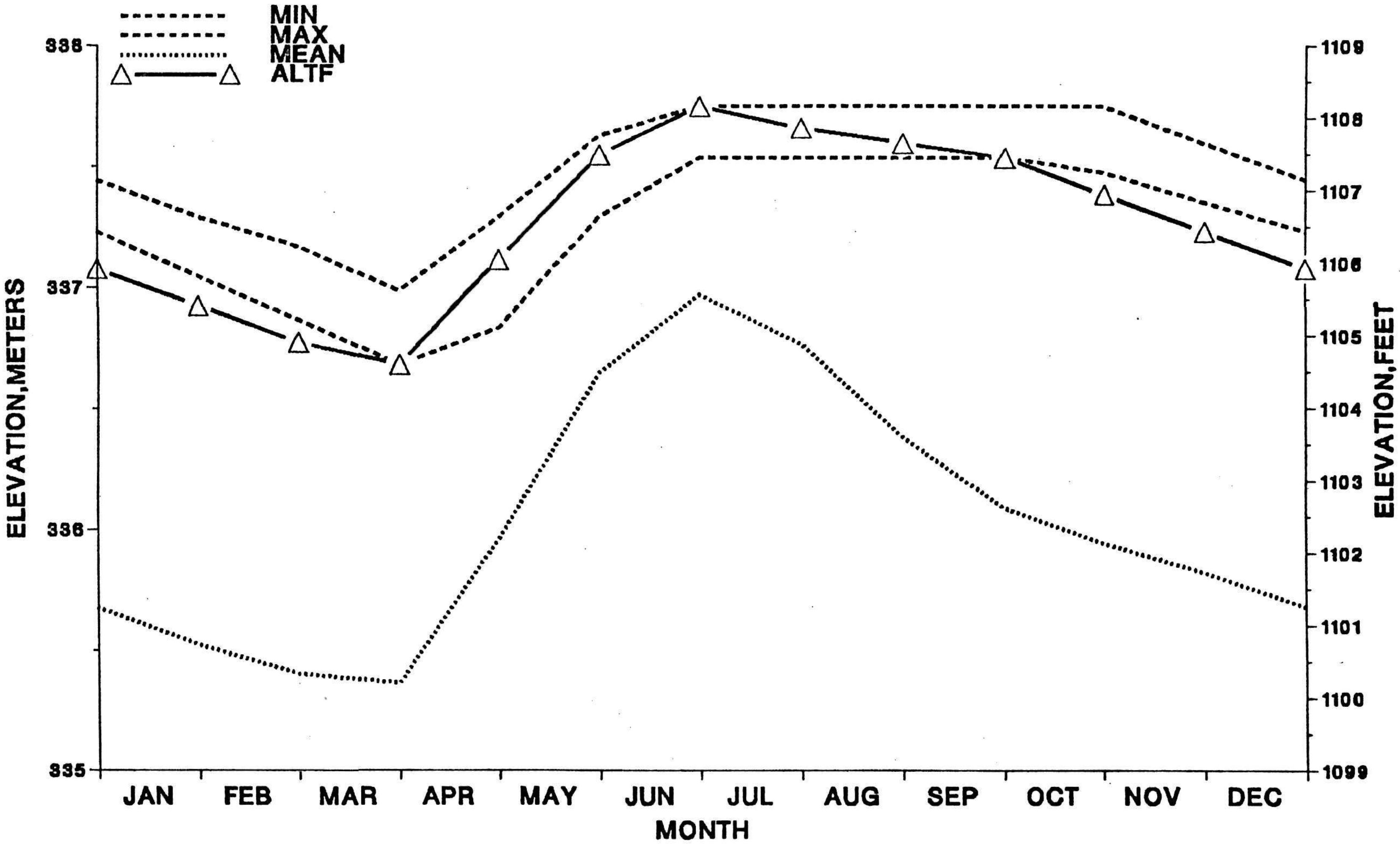

Figure 10. Rainy Lake Target Levels

study, daily measured lake levels and outflows (i.e., discharges) are used as independent variables. A "back calculation," to determine inflows, is performed using the continuity relationship and working upstream from Lake of the Woods outflow. Additionally, end of month lake levels are used in the calculation of lake (i.e., reservoir) storage and mean monthly discharges to represent outflows. The end of month lake levels are actually computed by averaging levels from the last two days of one month with that for the first day of the following month. This procedure provides a more stable estimate of end of month elevations. The back calculation procedure is performed in a routine called Program REVERSE, as outlined in Figure 11, prior to data input to MODSIM for modeling. Output from Program REVERSE is a generated representative sequence of inflows that accurately portray the naturally occurring hydrologic time series of net inflows for the historic period of record. In this way, the same set of inflows, that the real reservoir system operated in response to, are used in model simulations for analyzing modified rules of operation.

A summary of the available long-term daily records of lake levels, outflows, and inflows used in Program REVERSE are given in Table 5. Any period of inflows generated from the available data shown in Table 5 can be used for simulation using the system model, MODSIM. Typically, however, any one ten-year sequence is used because of the needed computer memory and computation requirements. The 1972-1981 time period is most often used because this period contains both high and low water years.

As outlined in Figure 11, Program REVERSE converts daily lake level and outflow data into a series of monthly inflow values. In addition, a simple transformation is performed within REVERSE to convert lake

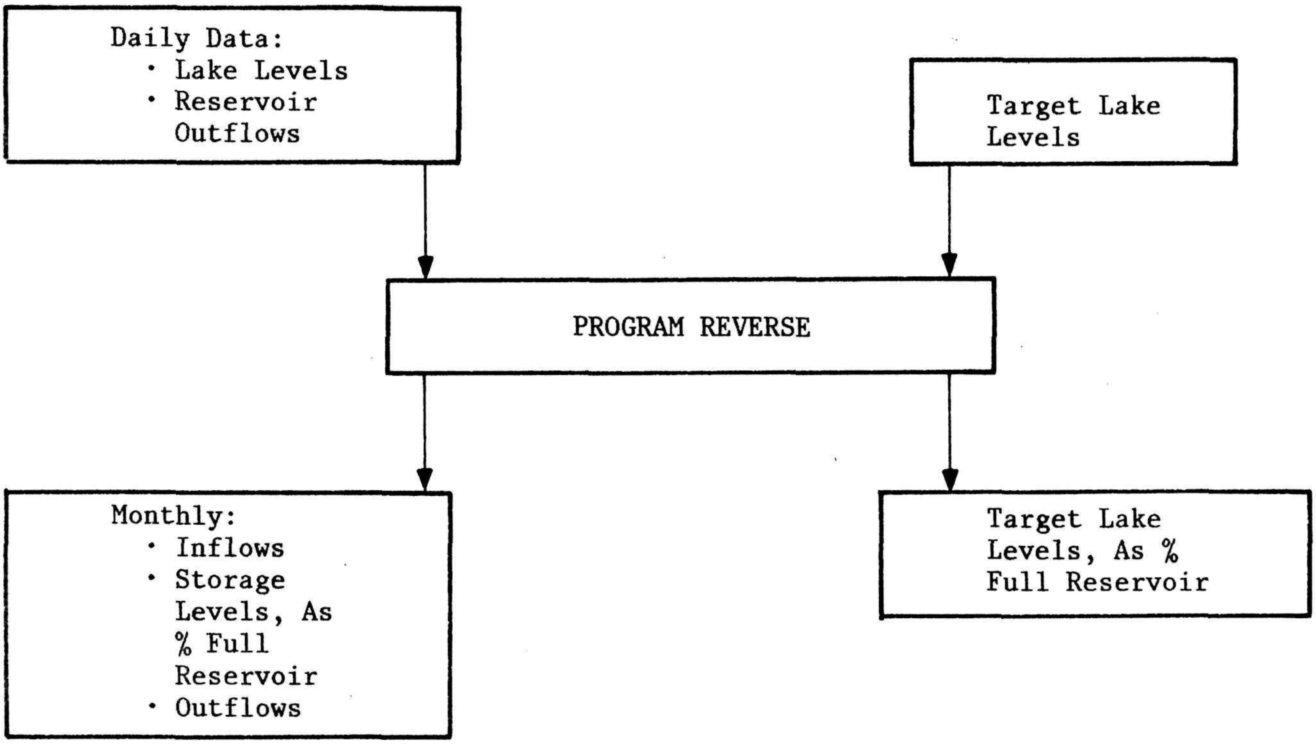

Figure 11. Flow Chart of Program REVERSE for Formatting Data

Table 5. Historical Data Available for the Voyageurs NP Lake System Model

Type of Data	Period of Measurement	Comments
LAKE LEVELS		
Namakan Lake	1912-Present	
Rainy Lake	1911-Present	
Lake of the Woods	1913-Present	
OUTFLOWS		
International Falls-Fort Frances Dam	1905-Present	Computed from head-capacity relationships.
Kettle Falls Dam	1914-Present	Computed from head-discharge relations.
Lake of the Woods	1892-Present	Two outlet channels are Kenora and Norman, Ontario.
INFLOWS		
Namakan River	1921-Present	Upstream at Lac La Croix Lake.

levels into units of "percent full reservoir". These are relative values based upon the storage volumes and corresponding reservoir elevations as given in Table 4. This transformation is needed to provide MODSIM with the correct units for lake level related data. As shown in Figure 11, the target lake levels, which are the operating rules, are also converted to percent full reservoir as required by the network optimization model, MODSIM. These conversions are simply a numeric interpolation using data as given in Table 4 and considering the last data pair of elevation and storage capacity as full reservoir.

Although relatively long periods of data are available regarding lake levels and outflows, there is some concern as to the consistency and accuracy of these data. Lake level measurements are subjected to wave action (i.e., surface water waves) which can influence the level (i.e., elevation) recorded at each lake's gage. This is a relatively minor problem and is further compensated for, in this modeling effort, by representing the end of month lake levels by a convoluted average from several days about this time. An additional complication surrounding lake level data relates to use of the same in computing the "head" on hydropower units at International Falls, Minnesota and Fort Frances, Ontario, as well as at the outlets from Lake of the Woods (i.e., Norman and Kenora). Due to the configuration (i.e., layout) of the powerhouse relative to lake level gaging locations, there is some "headloss" which is related to natural conditions (i.e., elevation drops) and outflow rates (i.e., velocity head). Estimates of such headlosses can be accounted for mathematically in simulation modeling if detailed information (i.e., rating and tailwater curves) are available for the physical system. Tailwater effects can also create problems by directly influencing the total head available to the power units. The elimination of lake-level data related problems is achievable by proper gage location and measurement. All in all, these are minor problems which are applicable to all simulations, and therefore, result in minimal impact on power calculations and comparisons of total power generated under alternative reservoir operating regimes.

Other more serious data reliability questions surround outflow data from Namakan and Rainy Lakes, as well as from Lake of the Woods. Outflows from Namakan Lake involve two dams at Kettle Falls plus Bear and Gold Portage; i.e., two unregulated and ungaged natural high water outlets. Leakage between stop logs in Kettle Falls Dams is unmeasured and at times has been reported as extensive. This leakage is a real problem that is not subject to correction as far as the historical outflow record at the dams. Another serious problem with recorded Kettle Falls outflows is that a rehabilitation of the dams took place in the 1960's, however, all reported outflows are based on the original rating curve for these sluiceways. Additionally, some discrepancies exist between monthly outflow data obtained from different government agencies although, presumably they are derived from a single source. The origin of the early years of data are uncertain and are available only as "provisional" by the cooperating agency.

Outflows from Rainly Lake are computed from theoretical rating curves derived from preconstruction specifications, not from measured releases. Furthermore, a somewhat arbitrary change in the discharge coefficient, from 0.68 to 0.60, was made and is used in computation of the historic record of outflow data. Additional flow related data problems include the rebuilding of powerhouses and elimination of grinders originally coupled to some power units, both of which impact computed outflow but are not now quantifiable. Some additional "head-loss" occurs between the point of lake level measurement and the entrance to the turbines, due to convergence as flow enters the intake structure. Although some of these shortcomings could be quantified by an extensive and elaborate field investigation, many of the above described problems will never be quantified and adjustments made to past data records. Once again, these data are used in all simulations and therefore should have minimal, if any, impact upon the analysis of results from alternative reservoir operating schemes.

Hydropower computations are also effected by the uncertainty surrouding lake levels, outflows, and each power unit's operating characteristics. Unit performance is influenced by wear and tear which alters efficiency for power generation and by periodic replacement or repair. The removal of grinders, initially attached to some units, influenced power output but to a degree that will ever remain unquantified.

All of the above cited shortcomings represent minor problems for the intended study at hand and subsequent system analysis. Rarely, if ever, does perfect data exist, and for this lake system under study the period of record available is longer than most. Any specific problems are dwarfed by the length of record and by the intended use. A skew in any direction influences each simulation in the same manner. Analysis of model results based on the same input data preserves the relative differences between outcomes (e.g., power outputs, discharges, or lake levels). The magnitude of these differences may not be exact, but then again the application of this study is to indicate management options and directions for change (e.g., when to allow various lake levels). In the final analysis, the alternative is to do nothing if one will not accept the record of data, which is the best it can be unless a new data collection effort is implemented.

MODEL OUTPUT

As shown in the conceptual model overview of Figure 7, the network model provides various outputs relating to management of water in this three reservoir system. After simulating the operation of this system for the hydrologic input data and subject to the hydraulic constraints and prioritized operating rules, the resulting lake levels, reservoir outflows, and hydropower generated each month of the simulation are output. These data results are then analyzed by comparison with results from simulations with other target operating rules or to historic reservoir regulation. Numerous graphic and tabular options are available to compare results from one simulation to another. For example, monthly lake levels for Rainy Lake can be plotted along with the monthly target lake levels and with historic levels for the corresponding input data. Examples of output are included in the Results section of this paper.

SIMULATION RESULTS

The first simulation performed is considered a model calibration. In this simulation, as in all simulations, historic inflow data (i.e., computed from Program REVERSE) are used however, for the operating rules the historic lake levels are input for all three reservoirs. These historic lake levels then serve as the target levels. At this time the monthly priorities are assigned for meeting target lake levels and the Winnipeg River demand node, as well as for the priority of spilling water from reservoirs. This procedure hopefully reproduces the historical outflows and thus tests the model to simulate the real lake system. By properly adjusting all of the priorities, the simulation model is forced to operate in the desired fashion (i.e., according to past practices).

Figure 12 shows the results of a "calibration" run for the 1972-1981 time period for Rainy Lake. A similar plot is presented in Figure 13 for Namakan Lake. Also superimposed on Figures 12 and 13 are the 1970 Amendments to the IJC Order (i.e., reservoir rule curves) and the actual historic lake levels. As shown on these figures, there are occasions when lake levels are not contained within the prespecified rule curves. The simulated levels shown fall significantly below the minimum rule curve during late summer and fall of 1976, spring and summer of 1977, and the summer of 1980, a phenomena that actually occurred on both Namakan and Rainy Lakes as evidenced by the historic levels. In fact, all the simulated results correspond almost identically to the historically observed lake levels, which indicates the reliability of this simulation model. These graphic plots demonstrate that under extreme hydrologic events (e.g., droughts and floods) the reservoir system cannot maintain strict compliance with the current rules of regulation (i.e., IJC Order). This difficulty is due in part to a lack of meteorological and hydrologic forecasting which would provide information useful to anticipate runoff and inflows. Forecasting of expected inflows provides earlier reservoir regulation in anticipation of either high or low inputs, and thus dampens the impact of extreme hydrologic phenomena. Violations of the expected lake levels (i.e., rule curves) as shown in Figures 12 and 13, continuously raise voices and concerns of various interest groups on and near the lake

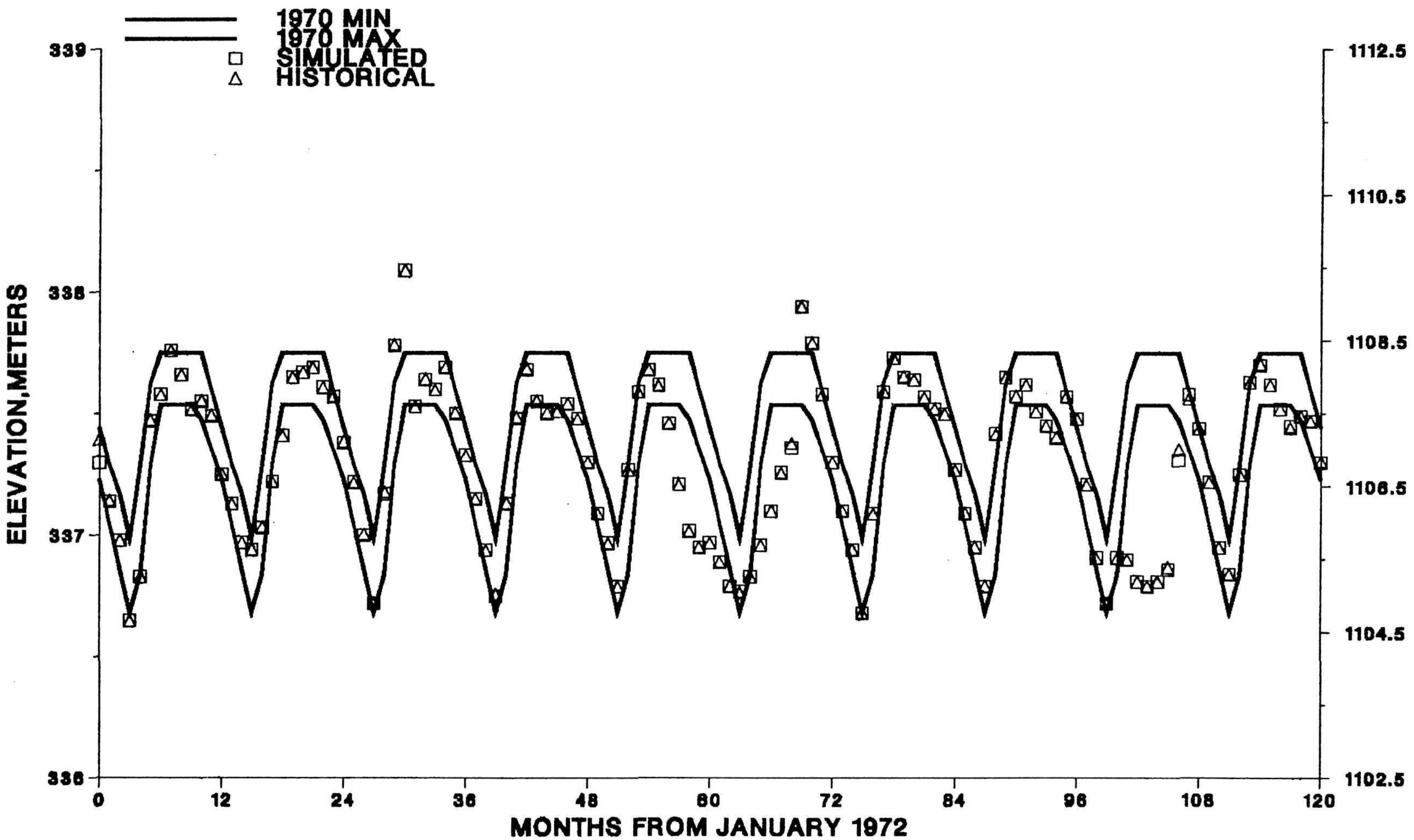

Figure 12. Ten Year Calibration-Simulation for Rainy Lake

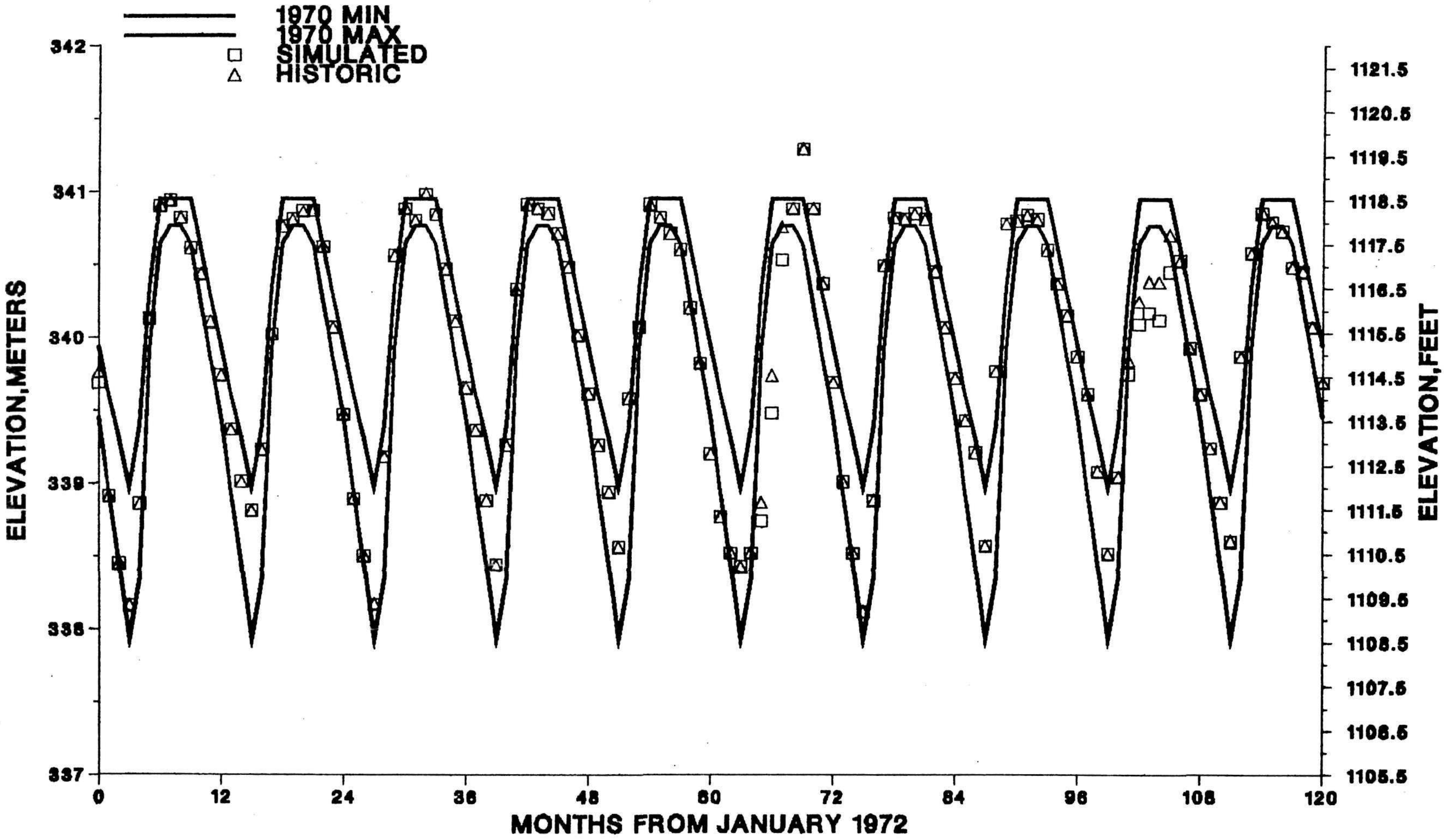

Figure 13. Ten Year Calibration-Simulation for Namakan Lake

shores. As a result, new calls for alternative rule curves and regulation policies are asked for and from time to time implemented.

Figure 14 shows the deviation of simulation results and historic levels at Lake of the Woods for the calibration analysis. Although levels in this lake are given the lowest priority, deviations from actual levels are very small. The close agreement of simulation and historic levels is a result of two phenomena. Of primary influence is the assignment of the highest priority to outflows at the demand node, into the Winnipeg River. Secondly, the relatively large size of Lake of the Woods in comparison to Namakan and Rainy Lakes permits a large volume of water to be stored or releaed for a correspondingly small change in Lake of the Woods level. Output results from the model for the demand node are identical to the historic outflows which are input to the model, and as mentioned given the highest priority.

ALTERNATE TARGET SIMULATIONS

The intent of this modeling approach described herein is to assist with the evaluation of alternative management options for water storage in Namakan and Rainy Lakes. Figures 9 and 10, which are discussed under Operating Rules, present an alternate set of target lake levels for Namakan and Rainy Lakes. These target levels are used within the simulation model to determine the feasibility of regulating the reservoir system under these alternate set of management rules. Figures 15 and 16, respectively, show both the alternate targets and the simulation results for Namakan and Rainy Lakes for a five year period, 1976-1980. Only this five year period is presented because it more vividly depicts deviations. As described elsewhere in this paper, "back calculated" monthly inflows for this period are used as model inputs. The

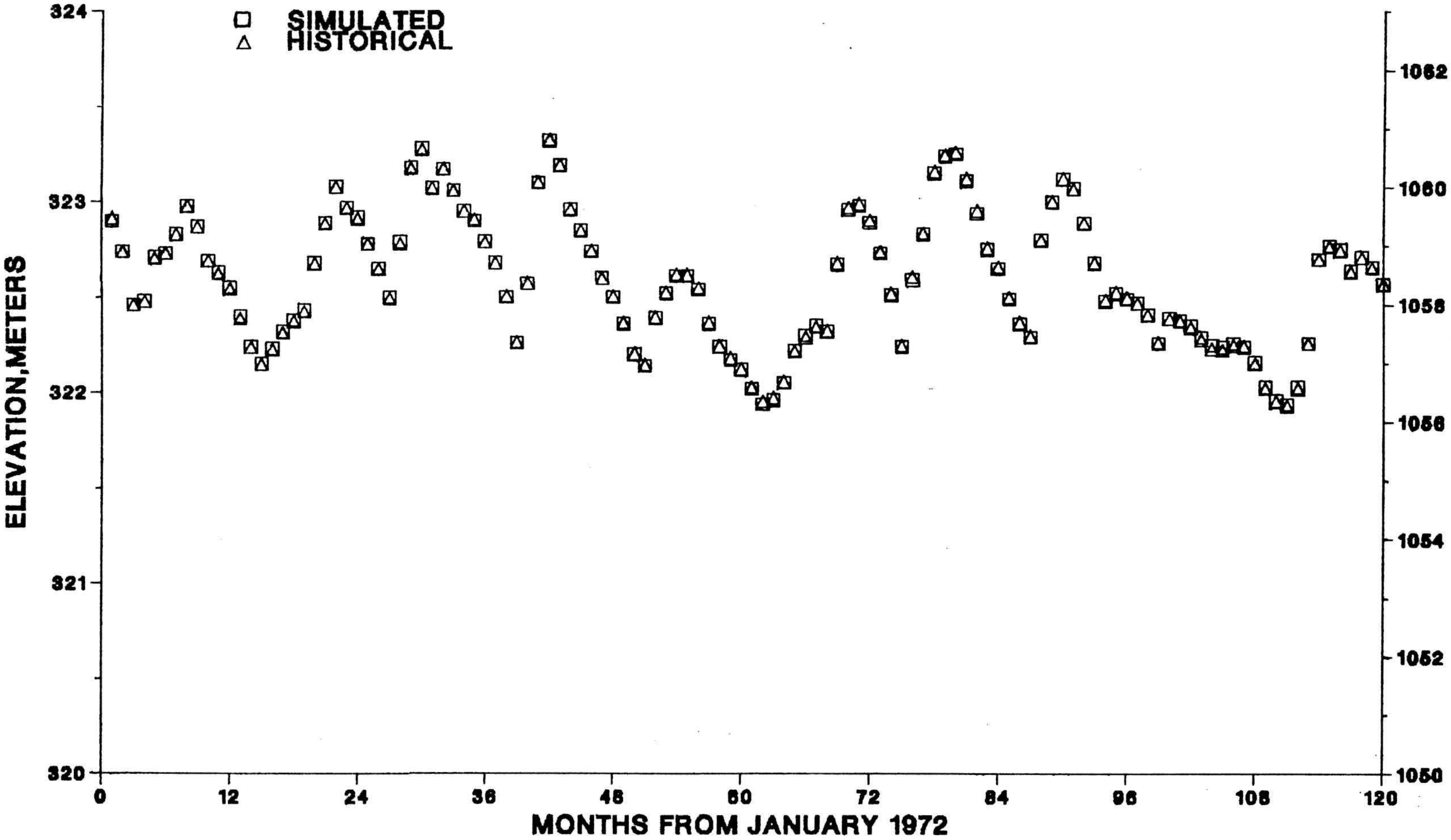

Figure 14. Ten Year Calibration-Simulation for Lake of the Woods

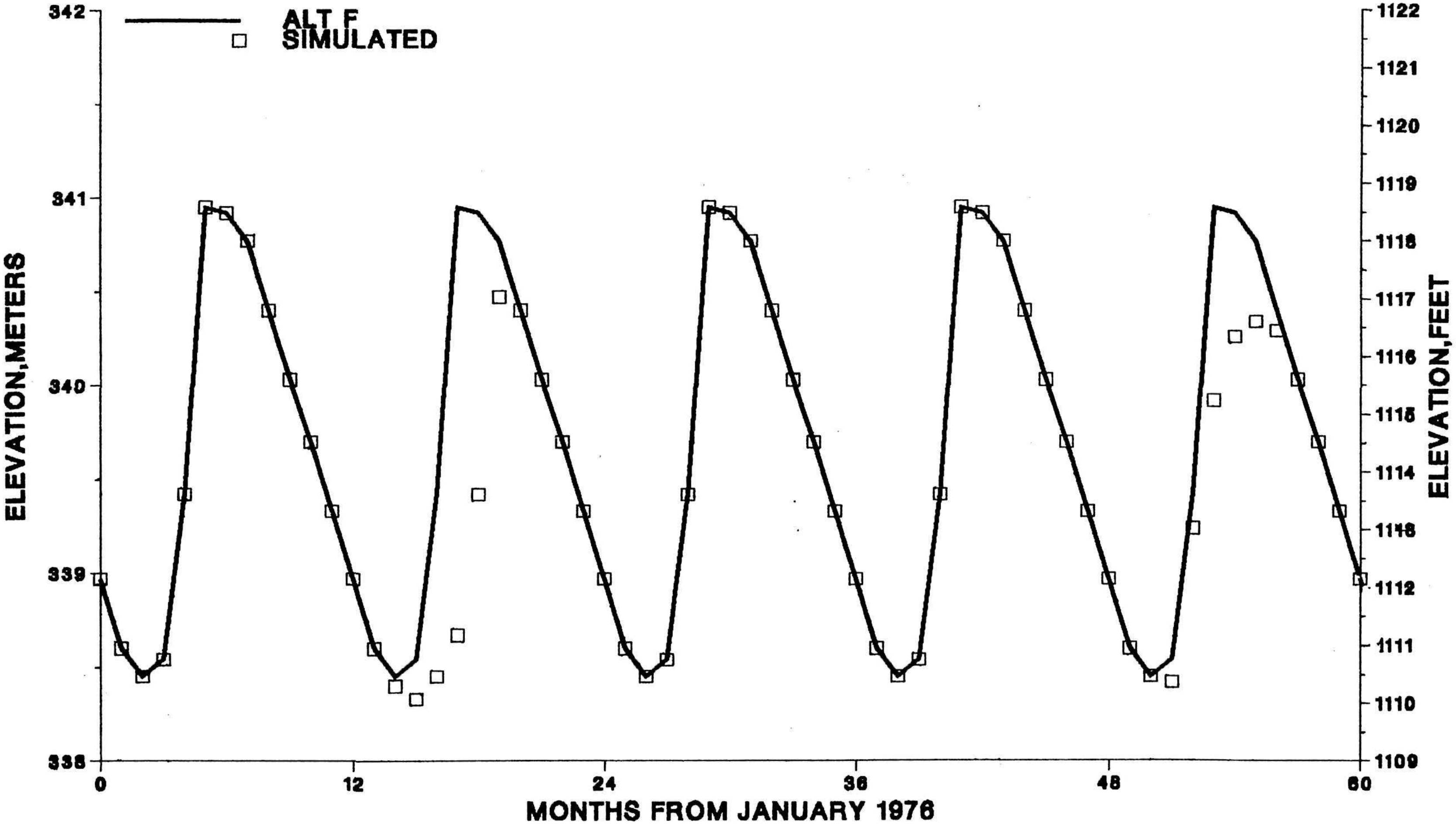

Figure 15. Namakan Lake Simulated Results - 1976 to 1980

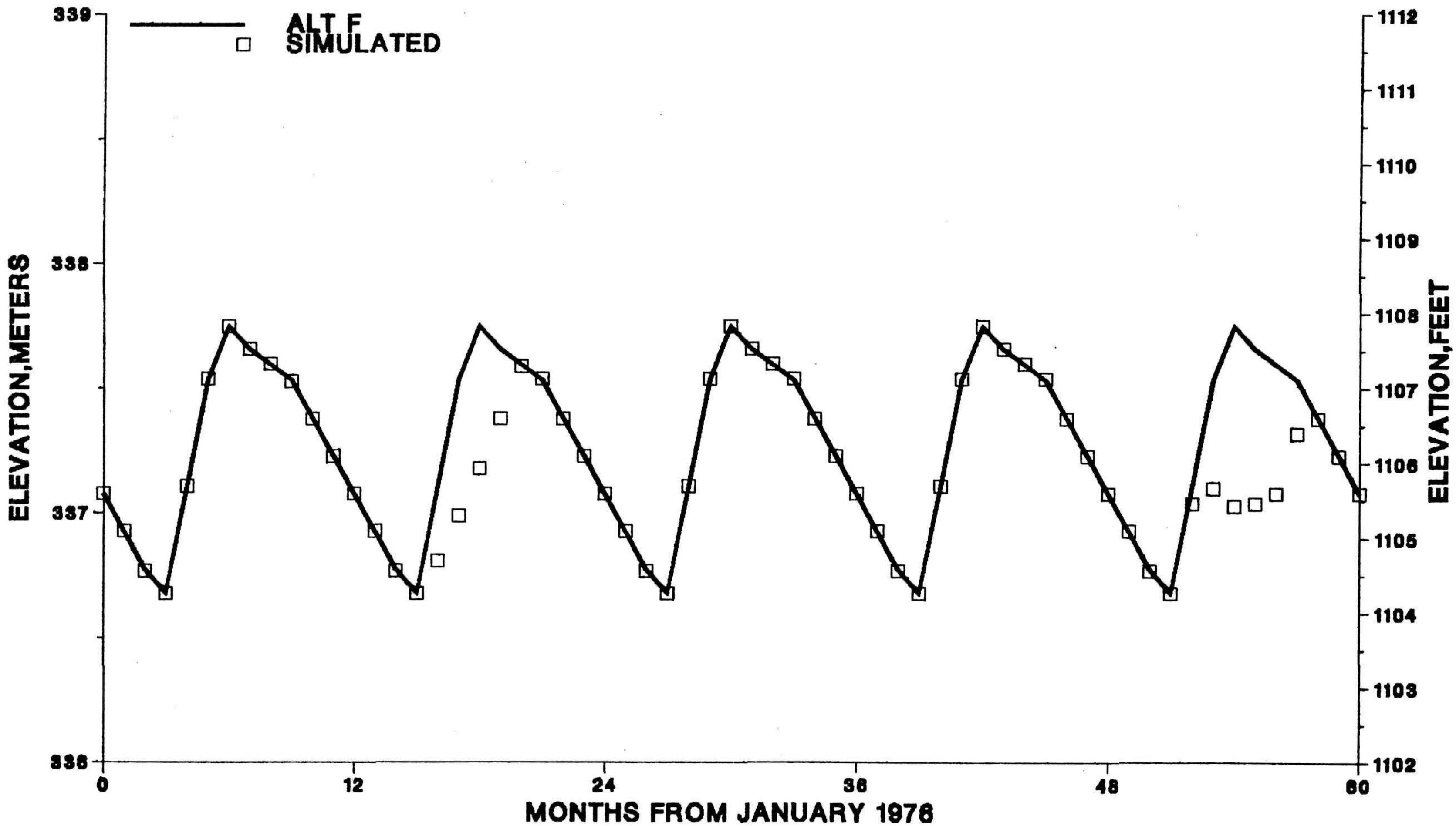

Figure 16. Rainy Lake Simulated Results - 1976 to 1980

simulation then attempts to satisfy prespecified target lake levels while maintaining mass balance relationships between inflows, outflows, and lake storages. As shown by the close fit of the simulated elevations with alternate target rules in Figures 15 and 16, the reservoir system can accommodate modified operating schemes under normal hydrologic events. Close observation of Figures 15 and 16 indicate two time periods in which the simulated conditions (i.e., levels) deviate from target elevations, the 1977 and 1980 low spring runoff years. In addition, a single summer storm in 1977 actually resulted in the one high lake level shown for the simulated Rainy Lake levels in Figure 16. These violations (i.e., levels different from the target) shown for the simulated lake elevations are also experienced under the current operating rules (i.e., IJC Order) and were really observed in 1977 and 1980. Lake elevations as observed under historic conditions were shown previously and are plotted in Figures 12 and 13. These violations point to the inability of the physical reservoir system to respond to every natural hydrologic series of events, particularly without forecasting inflows. Emergency regulations were implemented in 1976 and 1977 to permit reduced flow releases from the reservoirs in a last minute attempt to alleviate some of the consequences of the drought. Similar deviations from the rule curves have occurred at other times in response to both high and low water inputs (i.e., runoff). Without good predictions of meteorologic conditions, little can be done to lake storages in anticipation of runoff inputs, particularly runoff resulting from thunderstorm activity and not snowmelt.

The simulated lake levels shown in Figures 15 and 16 are only slightly different than the historically observed elevations. However, these simulated levels are more responsive to additional aquatic and riparian interests and yet have little, if any, negative impact on other beneficial uses of water including hydropower. Analysis of the hydropower produced from Rainy Lake and Lake of the Woods shows some differences in the timing of hydropower produced. For example, power produced at the outlet of Rainy Lake on a given month is often different in the simulated scenario as compared to that historically observed. This is due in part to the priorities of the simulation and the use of an alternate target policy. The net change in power produced for the ten-year period, 1972-1981, is shown in Table 6. For Rainy Lake an increase of about 3 percent is realized, and the net change for Rainy Lake and Lake of the Woods combined is about a 1.5 percent increase. Much of the reason that no significant differences are found in hydropower generation for example, is because the alternative target elevations are no more than 3 feet (0.9 m) different than current operating policy. Therefore, the "head" available for power production is similar to historic levels. Additionally, the outflows at the downstream end of the system (i.e., Lake of the Woods outflow) are prioritized the highest so as to match the actual historic releases, and this also strongly influences the discharges at International Falls and Fort Frances (i.e., from Rainy Lake).

As discussed for the calibration simulation and shown in Figure 14, the levels of Lake of the Woods are maintained very close to the historic levels even under simulation with alternate targets. This result is supported by the discussion above indicating that the alternate target levels for both Rainy and Namakan Lakes are only slightly different from the IJC operating policies. In addition, the demand node on the Winnipeg River matches the historic outflows exactly.

Table 6. Hydropower: 1972-1981 Simulation

	Mean Daily, 10^3 kwh		
	Actual	Alternate	Δ
Rainy Lake	265.3	272.9	+ 7.6
Lake of the Woods	325.7	327.5	+ 1.8
			9.4
Total Ten-Year Change: 34.3×10^6 kwh			

SUMMARY

Dams constructed in the early 1900's are regulated for the primary purpose of hydropower generation. Reservoir operating rules, which primarily specify desired lake elevations but also define limited discharge constraints, evolved over the years with changes periodically implemented in response to various lake shore interests and due to difficulties in operating the physical system in adherence to the existing rules of regulation. Interest groups continue to voice their concerns for more natural lake level fluctuations, different timing of peak and low lake elevations, increased flood storage reserve, navigation, and improved water levels for fish (e.g., walleye pike), wild rice, nesting birds, and other aquatic and riparian life, as well as individuals and resort owners with vested lake shore interests. Of late, the National Park Service (circa 1975) was given the responsibility to conserve natural objects and wildlife, and to leave them unimpaired for future generations. This alone is a formidable task for a system that was regulated for over half a century. However, Voyageurs NP is actively pursuing and cooperating with other groups to quantify aquatic and riparian biotic needs as evidenced by this modeling study of the lake system. The Park Service is interested in management options for regulating lake levels and reservoir outflows to accommodate all beneficial uses of these waters. An optimizing simulation model is used to help assess the impact of alternate reservoir operating rules on various lake shore interests. An analysis of impacts on specific beneficial uses of these waters is quantifiable by simulation modeling. Such an effort supplies sound information for evaluating management options. As new data become available, from ongoing aquatic and riparian studies, alternative reservoir target elevations can be modeled. The results provide valuable information for fruitful discussions and negotiations between Federal, State, international, and private interests, and hopefully can lead to mutually agreeable solutions for continued beneficial use of water. Use of a simulation model and the associated output provides concrete indications as to what changes are possible and goes a step beyond idle rhetoric of what are and are not realistic management options.

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