COMPUTER SIMULATION AS A WORKING TOOL IN WATER MANAGEMENT OF A MAJOR HYDROELECTRIC DEVELOPMENT

by

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ABSTRACT

Simulation models designed to study the short, medium and long term hydraulic operation of a major hydroelectric system are described. The system analyzed is the hydroelectric generating facilities of the Aluminum Company of Canada in the Lake St. John region of northern Quebec which consists of three major storage reservoirs and six (6) powerhouses collectively producing an average yearly generation of approximately 2,000 MWS. Mathematical modelling techniques are discussed and examples are given of how high speed computers can be used to optimize the utilization of available water resources where the production of hydroelectric energy is the major objective.

Introduction

Engineers, scientists and economists are often charged with the task of assuring a rational utilization of the nation's natural resources. Water resources management techniques have rapidly changed during the last decade. Computer simulation of man controlled and natural processes are but one of the many modern tools which are being used to accomplish this important task of extracting the maximum benefits from available resources.

The Aluminum Company of Canada, Limited (ALCAN) has, over the past four years, developed a group of computer programs for use in the magement of it's hydroelectric generating facilities, in the Saguenay - Lake St. John Region of Northern Quebec. This article describes the ALCAN power system, modelling and simulation techniques, and presents several examples of the utilization of simulators for establishing short, medium, and long term operating policies.

Alcan System

The hydro-electric system of the Aluminum Company of Canada consists of three main reservoirs and six powerhouses with a total installed capacity of 2687 megawatts. The watershed has a drainage area of 30,000 square miles and a yearly average runoff of 50,800 c.f.s. Figure 1 illustrates the layout of the System and Table 1 gives a list of power plant and reservoir capacities.

The Company supplies all loads in the Saguenay and Chibougamau regions, either directly or indirectly through Hydro Quebec, the provincial power authority. These loads consist of aluminum smelters, paper mills, copper mines, as well as municipal domestic and commercial loads in the local area. Tie lines of 345 KV and 240 KV are maintained with the Hydro Quebec system which serves the remainder of the province.

The operation sequence of the various reservoirs follows a pattern closely related to the seasonal variation of natural inflows. Figure 2 illustrates a typical yearly hydrograph, as well as demonstrates the variation in reservoir levels throughout a typical year. Basically, surplus waters during the spring freshet are stored in the reservoirs for consumption during the following winter. Starting about the 1st of December, reservoirs are drawn down and reach a minimum level near the end of April. Depending upon starting conditions the previous fall, loads throughout the winter and natural inflows, a carryover may or may not remain in the upper reservoirs at the end of the drawdown. Normally Lake St. John refills by mid-June, whereas, the upper reservoirs may or may not refill, but will reach their maximum level near the end of September or October.

Objectives of Computer Simulation

Computer simulators are mathematical models of physical processes, which are designed to evaluate the interaction between dependent and independent variables existing within or exterior to the process. In our case, the input to the process is the water flowing into the various reservoirs, the process is the conversion of potential energy to electrical energy via generators, and the product or output is the energy produced.

The objective of simulating the operation of an hydroelectric system is to determine system response to a given set of load, reservoir status, and hydrological conditions. Wherever possible, a secondary aim is to develop operating procedures which optimize the process. The gains to be achieved are increased production for a given consumption of water, or inversely, a reduced consumption of water for a given energy production.

The use of high speed digital computers permits detailed analysis of complex processes, which would be impossible or would require significant simplification, if the processes were to be analized using conventional desk calculators, slide rules or graphical methods.

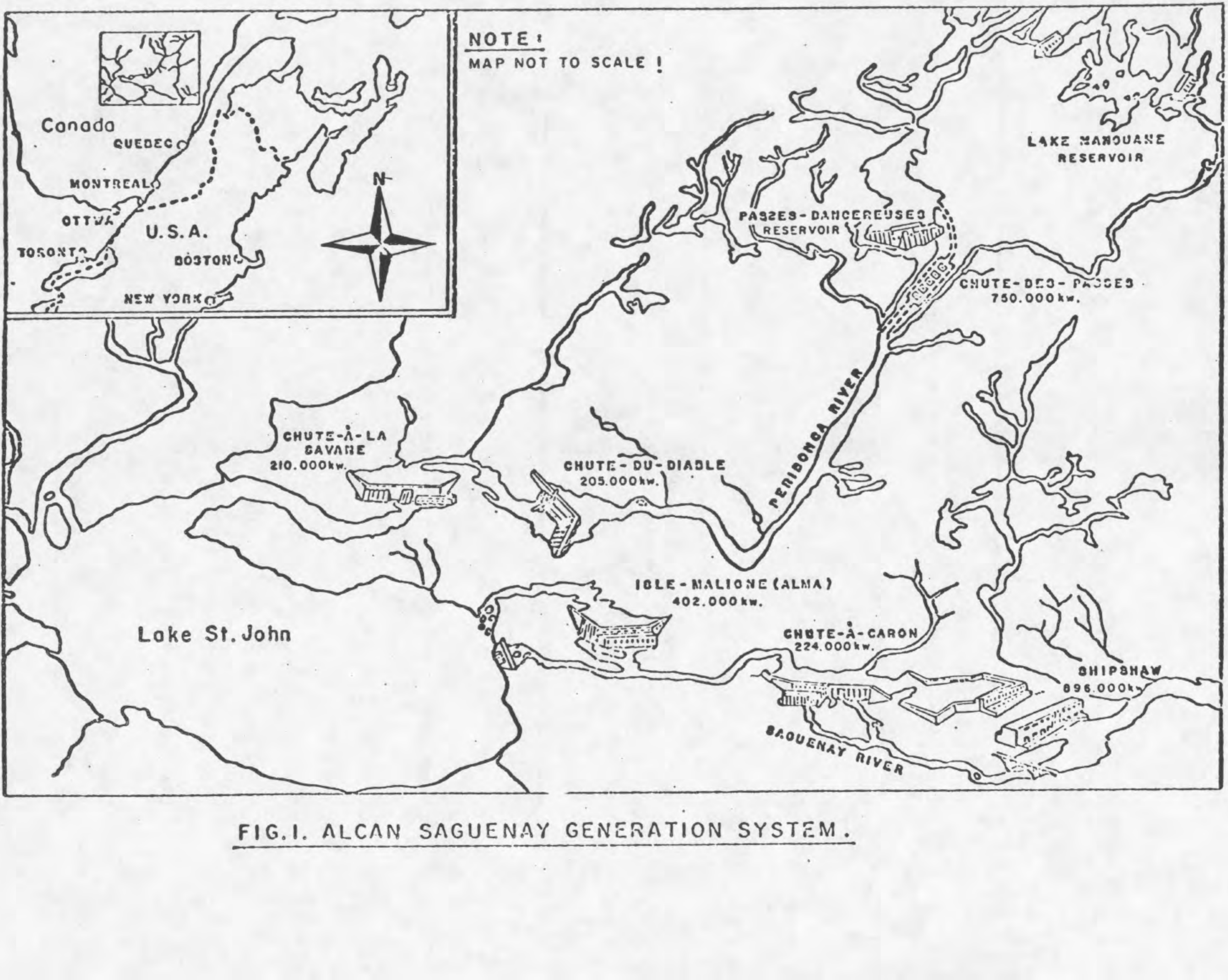

FIG. I. ALCAN SAGUENAY GENERATION SYSTEM.

TABLE 1. -- RESERVOIR AND POWERHOUSE DATA

(a)

STORAGE RESERVOIR	LIVE STORAGE CAPACITY	
	BCF	MAF **
Passes-Dangereuses	180	4.13
Lake Manouan	90	2.06
Lake St. John	140	3.21
	410	9.40

* Billions of Cubic Feet
** Millions of Acre Feet
1 BCF = 23,000 Acre Feet

(b)

LOCATION	AVERAGE NET HEAD (ft)	INSTALLED TURBINE CAPACITY (MW)	(HP)	NUMBER OF TURBINES
Shipshaw	210	896	1,200,000	12
Chute-à-Caron	160	224	300,000	4
Isle-Maligne	90-110	402	540,000	12
Chute-à-la-Savane	110	210	280,000	5
Chute-du-Diable	110	205	275,000	5
Chute-des-Passes	470-640	750	1,000,000	5
Total		2,687	3,595,000	43

With high speed computer calculation, it has been possible to develop models which duplicate in detail the hydraulic operation of the ALCAN hydroelectric facilities. Prior to describing several of these models, it would be advantageous to examine the basic elements of simulation, how the elements are translated into executable statements, and how these executable statements are grouped to form subroutines and complete programs. Figure 3 aids in vizualizing the elements being modelled and the interaction of input data, characteristics of the system, and output information.

Modelling Techniques

The first step in the preparation of a mathematical model of a hydro system, is the definition of the basic hydraulic characteristics of the various components of the system.

For a powerhouse, it is necessary to know: the elevation of the forebay, the number and efficiency characteristics of the turbines and generators, the hydraulic losses through canals and penstocks, the tailrace relationships, the discharge through the station, as well as the capacity of spillways, if any exist.

For reservoirs, it is necessary to know: the relationship between elevation and volume, the quantities of controlled inflows, the interrelationship of the various reservoirs in the System, as well as their operating limits. In addition to these basic relationships, for all reservoirs, it is necessary to define reservoir operation policies which take into account the time of the year, the rate of inflow and outflow from the reservoir, the energy production level, as well as the status of the reservoir prior to the time period being considered.

In order to use digital computers, it is necessary to express in executable computer statements all of the above mentioned relationships. Most of the hydraulic characteristics can be represented by graphical relationships. A curve fit technique has been developed for converting these graphical relationships into empirical formulas of the form:

$$Y = A + BX + CX^2 + DX^3 . . . . + KX^{10}$$

where Y = dependent variable
X = independent variable
$A, B, C, D, ... K$, are coefficients

The coefficients in the above formulas are obtained by a least means square statistical analysis of points extracted from each graphical relationship.

After having established mathematical equations for the various components of a particular powerhouse, subroutines are written which simulate the operation of the entire powerhouse under various conditions of units available, head and discharge. The subroutines evaluate unit and station generation, water spillages, optimum number of units to use, etc.

Similarly for each reservoir, subroutines are written which calculate rates of storage, average reservoir volumes, water releases and storages, as well as performing checks to see that the reservoir elevations are maintained within permissible operating limits.

Subroutines describing and simulating the operations of reservoirs and powerhouses, are grouped together to form master simulators which tie together the various functions performed by each subroutine, in order to solve a particular system operating problem.

All programming has been written in FORTRAN IV for execution on an IBM-360-Model 40 computer having a core capacity of 128K.

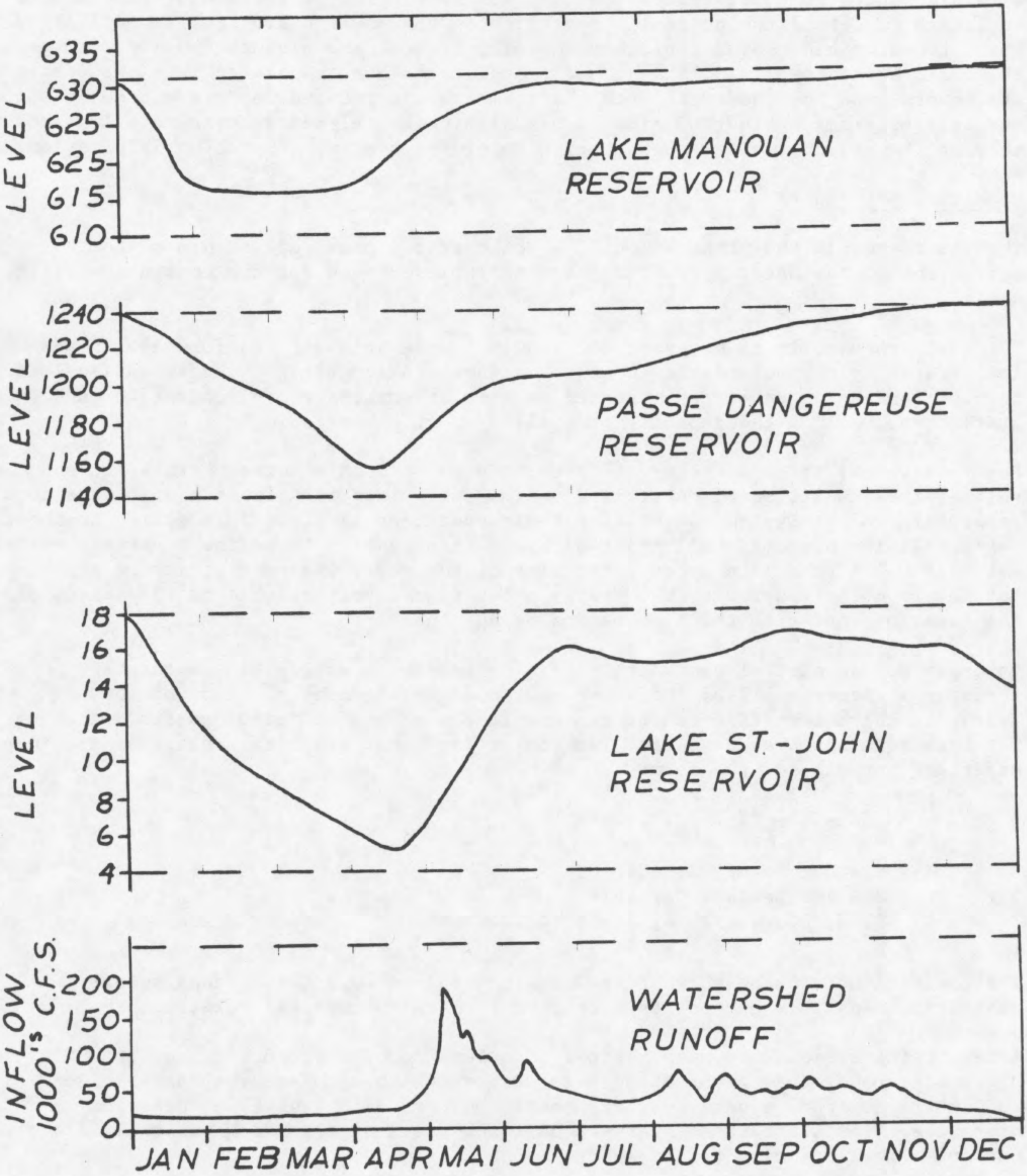

FIG. 2

TYPICAL

ANNUAL OPERATION

ALCAN SAGUENAY SYSTEM

Simulators

A universal hydraulic simulator, capable of solving all operational problems is neither practical nor feasible to develop. As a result, numerous simulation programs have been developed for various specific purposes. Programs are custom built for the ALCAN system, which is a pure hydro system. Nevertheless, techniques and methods used are undoubtedly similar to those which would be required for the simulation of other hydroelectric systems. The following sections will describe two simulators. One is a long term simulator for establishing overall operating policies, the other is an optimization simulator designed to determine the best operating policy for a given medium range time period. Each has been designed to solve a specific water resources management problem.

Long Term Simulator

The long term simulator has been developed to evaluate the effects of yearly variations in hydrological conditions, and for determining system response to various long term generation policies. This program has proved to be quite useful in determining the long range energy capability of the system, and in determining policies which aid in assuring that given levels of firm energy could be carried through dry years.

The simulator consists of a series of FORTRAN subroutines which simulate the operation of the powerhouse and reservoirs, and others which look after the handling of input and output information, control of generation and reservoir schedules, choosing natural inflows, altering of system restrictions and preparation of intermediate and final reports.

Simulation starts with the definition of the initial status of the reservoirs, (just prior to a drawdown period) and continues from one period to another in steps of from 5 to 15 days. For each time period, the scheduled generation is determined, a controlled discharge from the Lake Manouan reservoir is calculated, a change in the volume of Lake St. John reservoir is computed, discharge for the Peribonka River is estimated and station generations are calculated. An iterative process, which varies either the Peribonka discharge or changes the rate of storage in Lake St. John, adjusts flows until the scheduled generation is just met. If reservoirs are nearly full, and inflows permit, above scheduled generation is accepted. Conversely, if reservoir levels are too low to permit meeting of the scheduled generation a deficit is accepted. Prior to going on to the next time period, a hydraulic balance for each reservoir is calculated and termination volumes and elevations are established which then become starting conditions for the next period.

Output from this simulator consists of listings of unit, station, and system generations and discharges at each plant, number of units in operation, average energy conversion factors and reservoir status at the end of each period. A graphing technique permits tracing up to 6 variables throughout each study.

Part of the results of a four year simulation are summarized in Figure 4, which indicates the reservoir status throughout the study.

Optimal Path Simulator

To meet a given production schedule, over a specified time period, it is possible to draw water from the reservoirs at various rates. That is, generation can be distributed between the stations in more than one way. For example, if it were decided that during a particular drawdown period, the Lake St. John reservoir was to be emptied during a four month period, and that a given generation schedule was to be met during this period, the reservoir could be drawn down following various paths of time versus elevation. Due to the characteristics and heads of

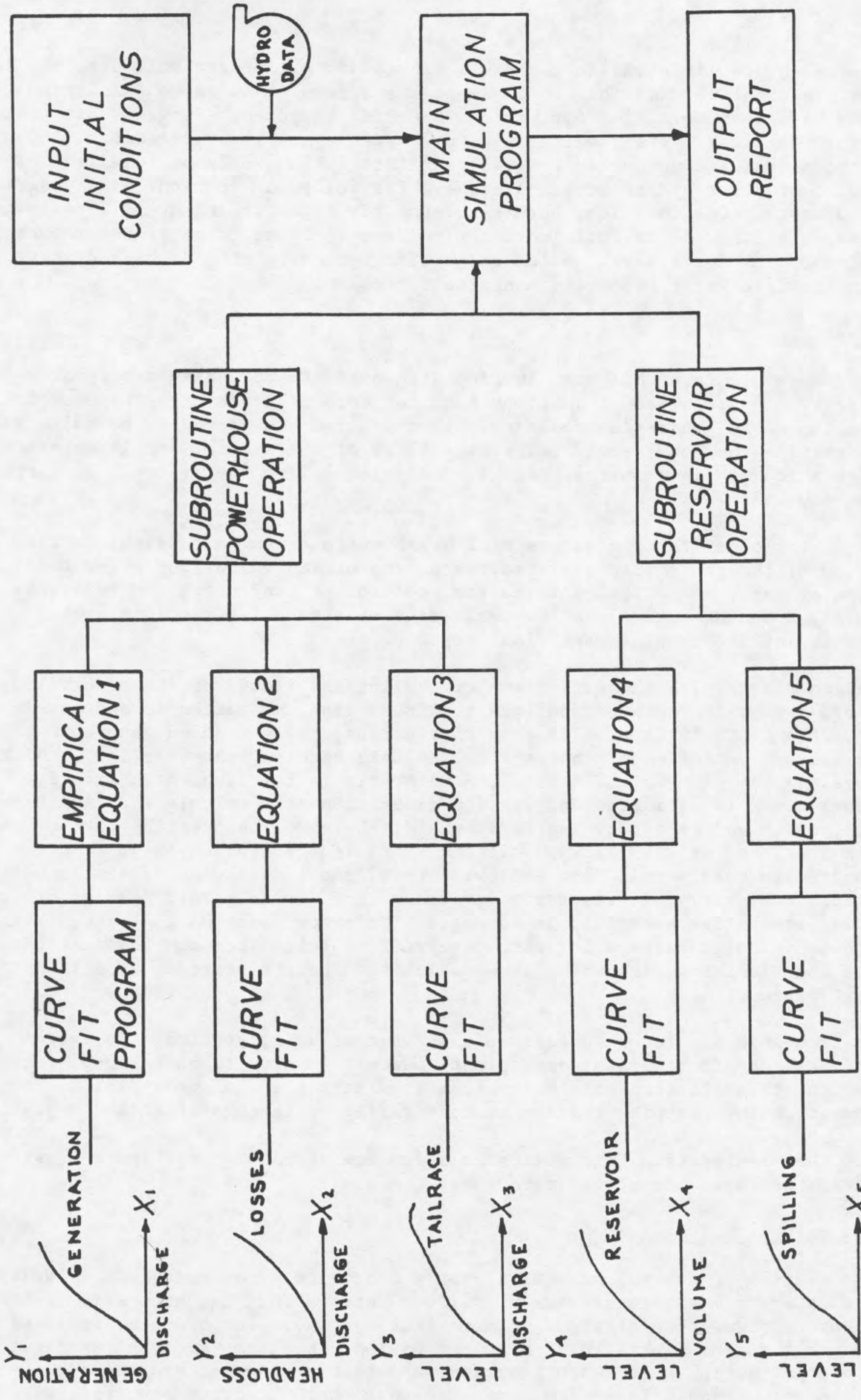

FIG. 3

LOGIC DIAGRAM HYDRAULIC SIMULATION

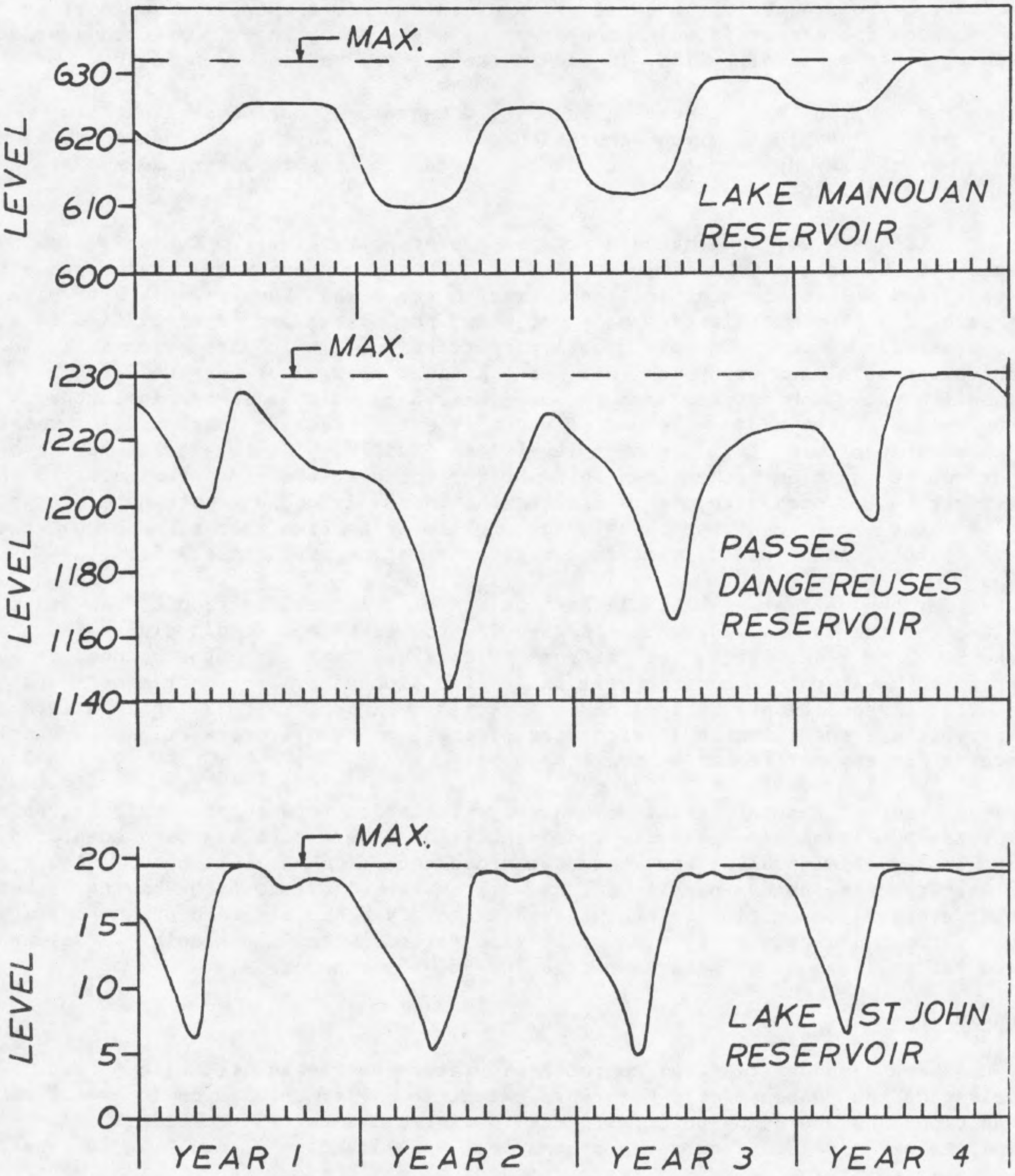

FIG. 4
SIMULATED RESERVOIR OPERATION

the various powerhouses, the consumption of water from the upper reservoirs would depend upon the manner in which the reservoirs were drawn down. An optimization problem presents itself which, in general terms, can be stated as follows:

> "For a given total change in Lake St. John volume, during a given time period, and for a given generation requirement, what is the optimum way of drawing down Lake St. John in order to consume a minimum amount of upper storage water?"

In the ALCAN system, Lake Manouan acts as a storage reservoir. During a drawdown period its operation is relatively simple. Gates are opened and remain open until a specified volume of water is transferred to the Passes-Dangereuses reservoir. As such, from the optimization point of view, the system can be simplified to a two reservoir system. Dynamic programming techniques, which are essentially controlled trial and error analysis methods, lend themselves very well to the establishment of an optimum path for one reservoir, which will result in the consumption of the minimum amount of water from the other. Figure 5 illustrates the drawdown of Lake St. John from level A to level B. The total time period of four months has been broken down into shorter time periods of approximately 8 to 10 days each. For each date, it is assumed the reservoir could be at any elevation between the upper and lower bands. The problem is to find that path through the grid which would result in a maximum carryover in the upper reservoir.

Input for the optimal path simulator consists of the specification of the start volume for the Passes-Dangereuses Reservoir, the start and final volumes for the Lake St. John Reservoir, a grid of reservoirs elevations and dates bounded by an upper and lower rule curve, as well as a definition of system restrictions and generation requirements during the period of simulation. Natural inflows into each reservoir are specified as a percentage of the long term average or past historical records for any particular year are used.

The dynamic programming technique controls simulation between the various possible elevations of each time period. Once simulation from A to B has been completed, via all feasible paths, a traceback technique determine the best path. Figure 6 illustrates the optimum path found, as well as two alternate paths having higher upper storage consumptions. Execution time for the determination of the optimum path through a matrix consisting of 16 time periods with 11 possible elevations per time period is about 30 minutes on the IBM-360-40 computer.

Conclusions

It has been demonstrated that computer simulators can be built, which permit evaluating the response of a major hydroelectric system to changes in hydrological conditions and operating policies. Much work remains to be done before full benefits are obtained from such mathematical modelling techniques. It is feasible to imagine, within the next 5 years, complex hydroelectric systems being controlled by computers, which account for variations in hundreds of variables, choose the best operating policy and even remotely control the turbines and other physical features.

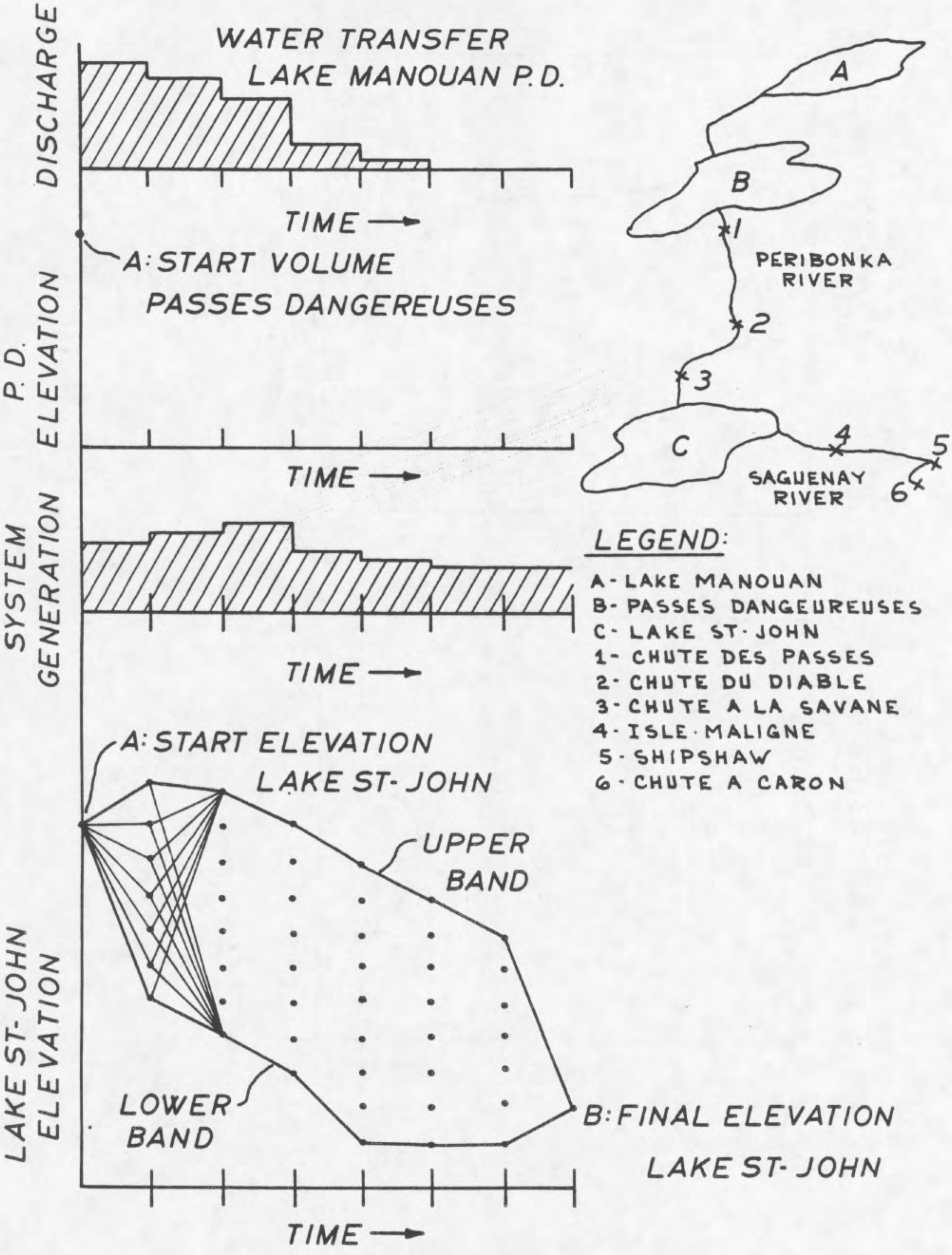

FIG. 5

OPTIMUM PATH SIMULATION

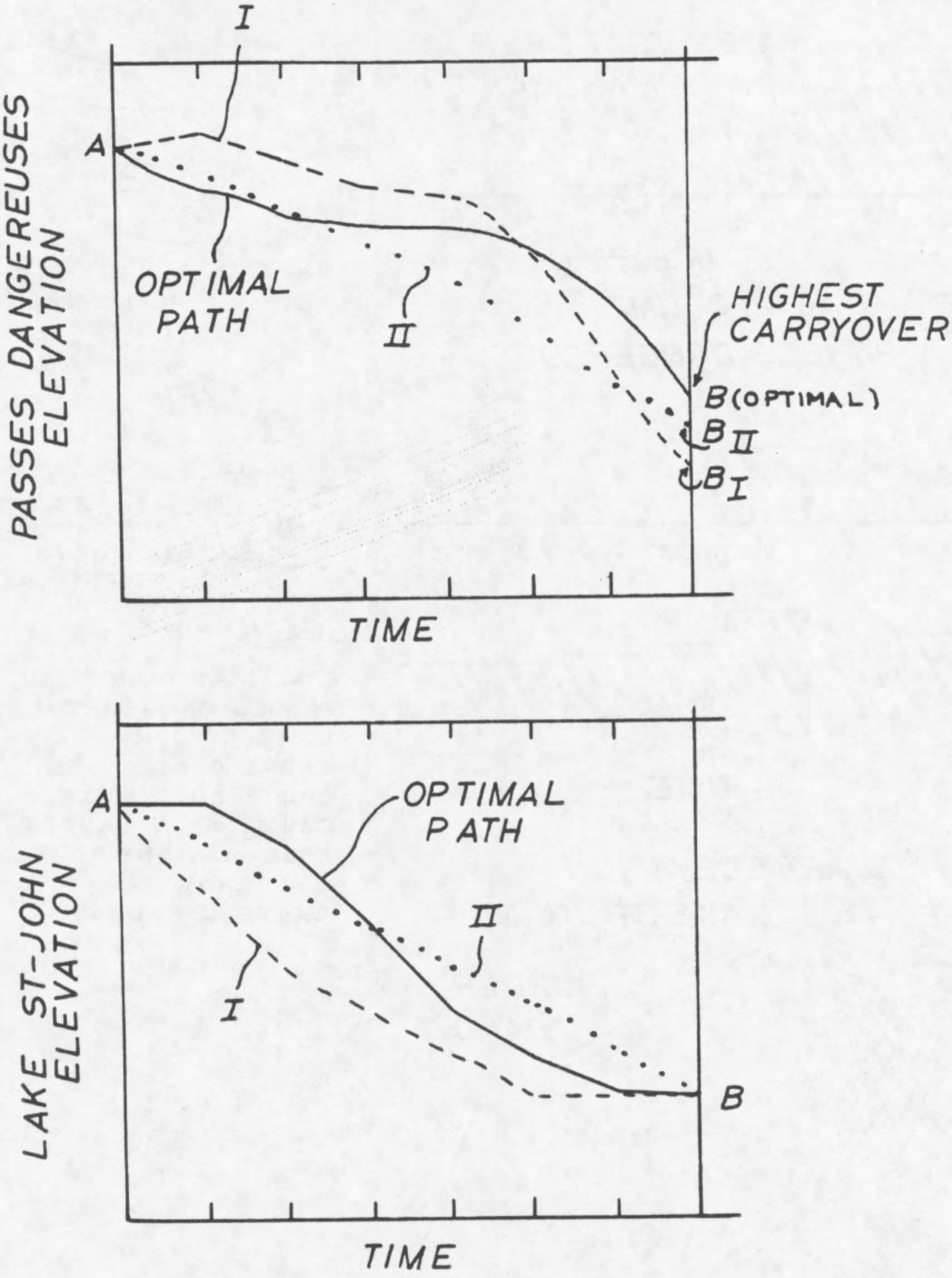

FIG. 6

OUTPUT OPTIMUM PATH SIMULATION