OPTIMIZATION OF THE OPERATION OF WALLACE DAM AND SINCLAIR DAM AS A PUMPED STORAGE DEVELOPMENT

A THESIS

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By

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OPTIMIZATION OF THE OPERATION

OF WALLACE DAM AND SINCLAIR DAM

AS PUMPED STORAGE DEVELOPMENT

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CHAPTER I

INTRODUCTION

Scope of Study

The purpose of this study is to investigate the operation of two hydroelectric projects as one pumped storage development. Sinclair Dam, a conventional hydroelectric project completed in 1953, will form the lower reservoir and regulation pool for the Wallace Dam Project, a combination conventional and pumped storage development scheduled for completion in 1980. Both projects are located on the Oconee River near Milledgeville, Georgia, in the central portion of the State. Figure 1 shows the location of the two projects and the 2930 square mile drainage area.

The basic problem under study is the joint operation of two reservoirs. Features of the two projects complicate their operation. First is the large difference between the hydraulic capacities of the turbines of the two plants. The two conventional and four pump turbine units at Wallace Dam will have a combined capacity of 48,000 cfs. The two conventional turbines at Sinclair Dam have a hydraulic capacity of 6,800 cfs. To avoid spillage of water at Sinclair Dam, the operation of the two plants must be coordinated so that the Sinclair reservoir is drawn to a low enough level to store the large flows from Wallace Dam.

The second complicating factor is the local inflow into Sinclair Reservoir. The Little River flows into Sinclair Reservoir below Wallace

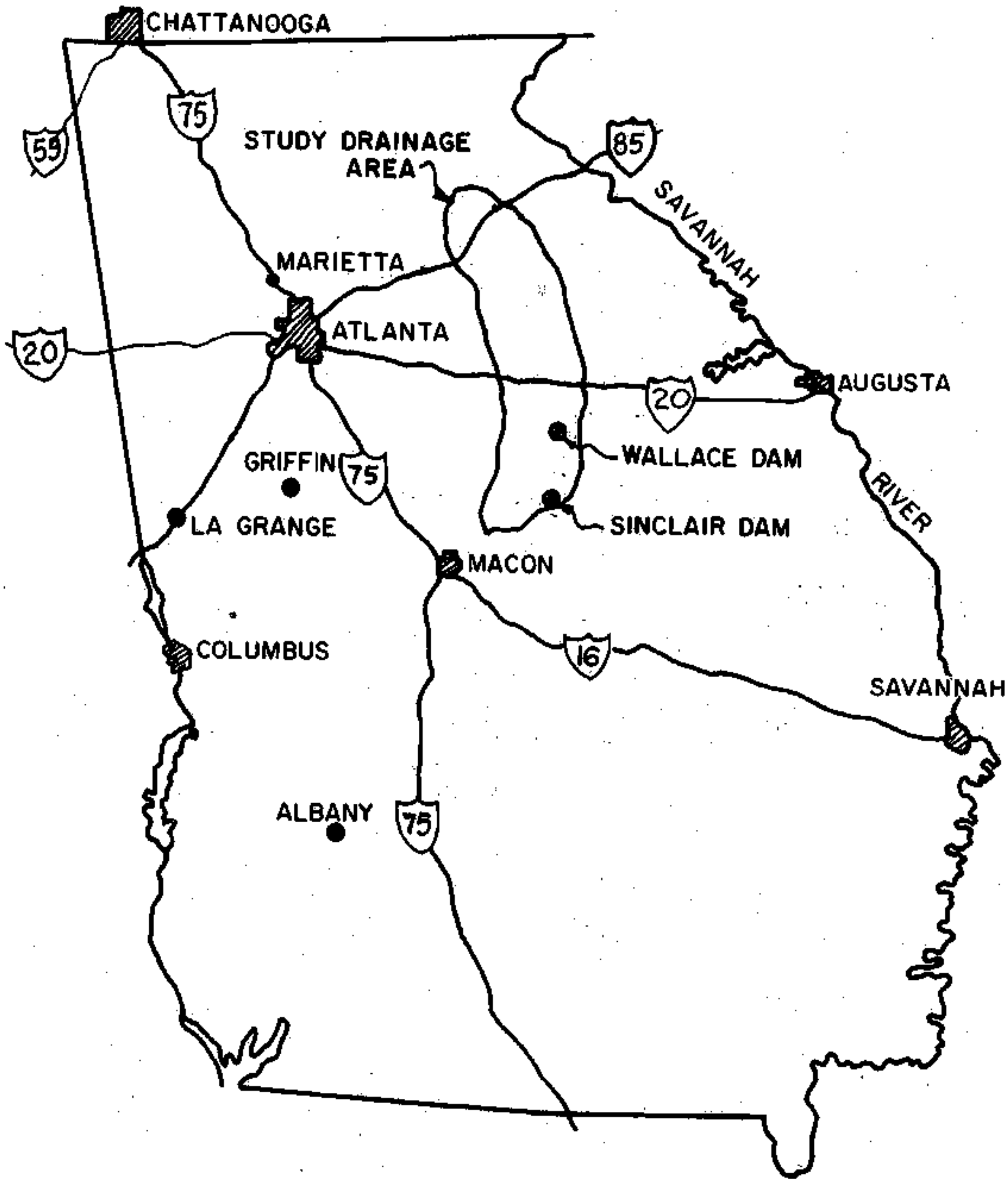

Figure 1. Location Map

Dam. There are no stream flow gages on this tributary. The flow from this large drainage area (1100 square miles) complicates the prediction of how far to lower the Sinclair Reservoir to accept the flow from Wallace Dam. As will be discussed subsequently, lowering of the reservoir below elevation 338.2 feet (Plant Datum) would adversely affect the pumped storage operation of Wallace Dam.

Therefore, this study is undertaken to define a procedure by which the two reservoirs might be operated interdependently. The elements of the study are twofold. First, inflows into the system must be predicted. Secondly, based on the predicted inflows, a set of operating rules must be established for the efficient operation of the two developments. The criterion chosen for the selection of the operating rules was a maximization of the net revenue from the two projects. These rules could then be used as an operation guide for the operator in the plant to govern his operating decisions or could be incorporated into a computer program for automatic operation of the two projects.

Other questions related to the operation of the projects (or other hydroelectric developments) have been investigated. Some of these questions which were analyzed are as follows:

(A) Feasibility of increasing the storage capacity of the existing Sinclair reservoir.

(B) Feasibility of adding additional generating capacity at Sinclair Dam.

(C) Estimation of average annual energy to be expected at Wallace Dam including estimates of the natural stream generation.

(D) Feasibility of expanding the methodology developed in the initial phase of the study into a computer program to automatically control the operation of Sinclair and Wallace Dams.

Subsequent chapters will detail the procedures used in the course of the study. Generally the study can be divided into the following phases:

(1) Data Collection and Processing.

(2) Development of methodology to predict the inflow into the system using available data.

(3) Development of a computer model to simulate the operation of the two reservoir systems for various sets of operating rules.

(4) Analysis of other problems associated with the operation of the projects.

(5) Evaluation of the results of the computer simulation and selection of the optimum set of operating rules.

Literature Review

The selection of reservoir operating rules which result in the optimum operation of a reservoir or reservoir system is a problem that has been studied by many. In most of the studies reviewed, dynamic programming has been used as the optimizing tool in determination of optimum operating policy (3), (4), (5), (10). Dynamic programming can be effectively used when the dimensionality of the problem is kept small. Computation time increases geometrically as decision and state variables increase (4). Many have decreased the dimensonality of the multi-reservoir problem by the use of parameters, assumed fixed throughout the analysis, to replace some of the decision and state variables (4).

Others have expanded the use of dynamic programming to the solution of problems involving a multi-lake system by combining dynamic programming and other optimization techniques (5).

Hall has illustrated the use of dynamic programming in a system involving the capability to pump back water as in the Wallace Dam and Sinclair Dam system. The operation of the Thermalito Forebay and Afterbay on the Feather River near Oroville, California was analyzed using dynamic programming. However, the expansion of the problem to a two reservoir system with pump back features is costly in terms of machine time requiring approximately two hours for operation of a seven year period (3).

In most of the reservoirs analyzed, there was available storage to be allocated in the optimization procedure. Such is not the case in the relatively small Wallace Reservoir and Sinclair Dam System. Drawdown of the Sinclair Reservoir in excess of approximately 1.8 feet physically separates the two projects and makes pump back impossible. Also, because of the difference in capacity of the turbines, large fluctuations in Wallace Reservoir would result in increased spillage at Sinclair Dam. Additionally, because of the size of the drainage basin and average stream flow, a long period of time would be required to recover reservoir levels should Wallace Dam storage be utilized in power generation.

Reservoir operation has been analyzed on a monthly basis in most of the papers reviewed. While sufficient on large reservoirs with large storage capacity, utilizing monthly stream flow for the Wallace and Sinclair system would result in a loss of the essence of the system. Since the reservoirs are operated at near full pond level, daily spillages would not be taken into account in a monthly operation. Additionally, one objective of the study was to develop a model which could be expanded into an operating program to be used in the daily operation of the projects.

For these reasons, a simulation approach was used to achieve an optimum or near optimum operation. An optimum operation determined using simulation can be the optimum only if every possible operation is included in the model. Therefore, the extremes of the Wallace Dam and Sinclair Dam operation were analyzed in the study.

The development of a daily stream flow simulation model has been studied by many, as described by Payne, Neuman, and Kerri (6). Most have developed simulation models with the objective of creating a record which has the same statistical properties of the historical flows (6). However, the final operational model to be developed for Wallace and Sinclair Dams will require a daily prediction of flows to be expected at each project so that decisions on daily power allocations can be made. Wilson and Kirdar have used multiple linear regression to develop forecast models for the Salt River Valley in Central Arizona (9). These writers used various physical parameters to develop sets of forecast equations for the rivers in the valley using multiple regression analysis. In the present study, the flows in the Oconee River at Wallace and Sinclair Dams were forecast using linear regression of data from upstream gages as described in Chapter III. Since a long period of record (over 60 years) was available at the upstream gages, the use of models described above was considered unnecessary.

CHAPTER II

DESCRIPTION OF SYSTEM

Description of the Development

The Sinclair Dam Project, located three miles upstream of the Milledgeville gage, provides the lower reservoir. The project includes a reservoir, powerhouse and intake, an earth fill dam, concrete gravity spillway and non-overflow sections, and a short earth abutment. Figure 2 is a perspective view of the Sinclair Dam Project. Physical details of the project and other pertinent data are listed in Table 1. A plan and elevation view of the project is included as Figure 3.

The Sinclair powerhouse contains two vertical Francis type turbines each having a rated output of 30,500 hp at a head of 92 feet. These turbines are directly connected to two generators. The two units have an installed capacity of 22,500 kilowatts each for a total generating capacity of 45,000 kilowatts. The hydraulic capacity of the two turbines total 6,800 cfs.

Lake Sinclair covers an area of 15,300 acres at the full pond elevation of 340.0 feet. The lake is used extensively for various recreational purposes and its shoreline is developed with second homes and private cabins. Plant Harllee Branch, a 1,539,700 kilowatt coal-fired thermal generating plant, is located on the shores of the lake. The Plant takes its cooling water from the lake and returns it after a once through cooling cycle.

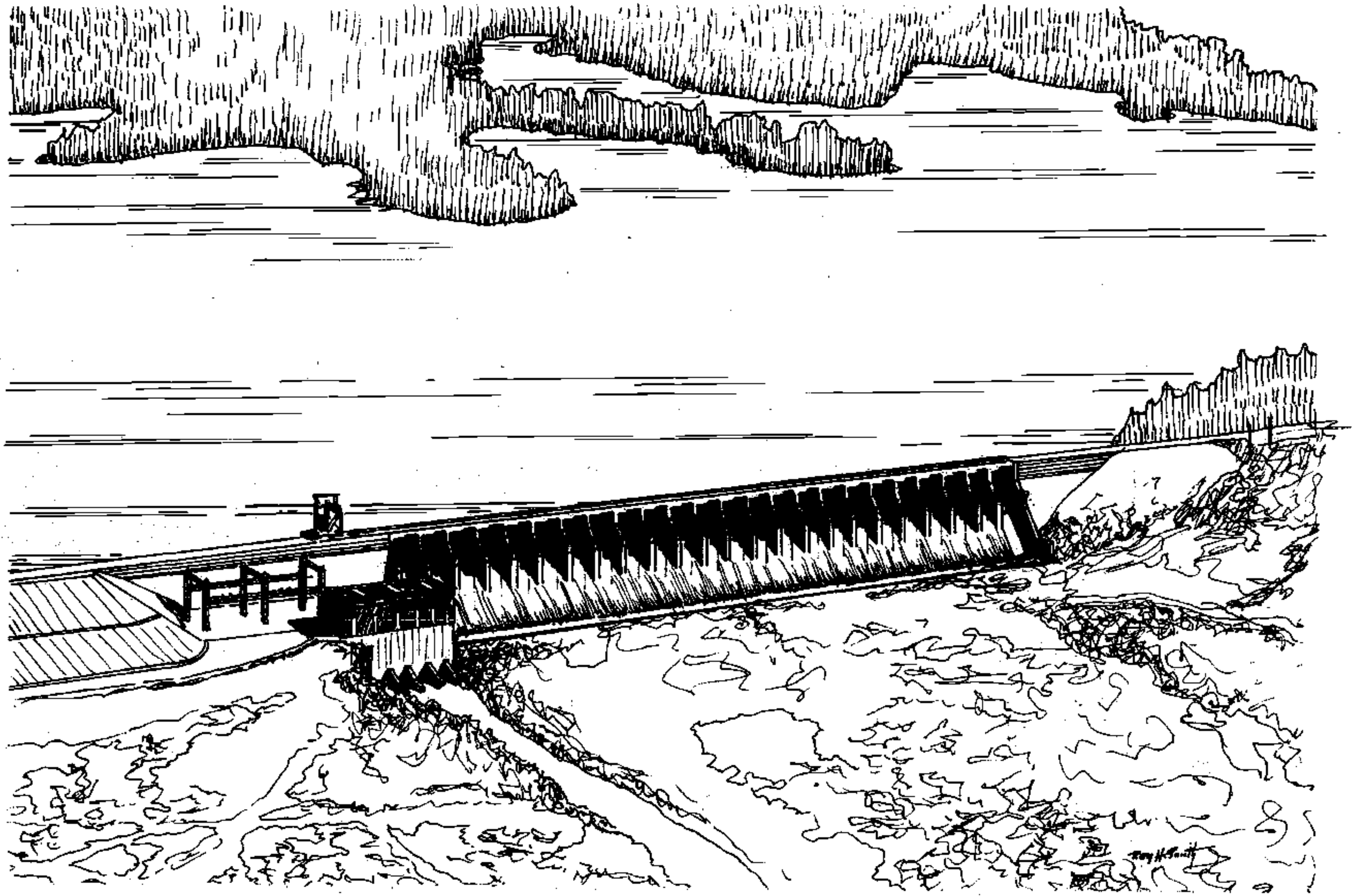

Figure 2. Perspective View of Sinclair Dam

TABLE 1. Sinclair Dam - Physical Data

General	
Stream	Oconee River
Drainage Area	2930 square miles
Normal Full Pond Elevation	340.0 feet Plant Datum
Surface Area at Full Pond	15,330 acres
Total Storage at Full Pond	334,000 acre feet
Dam Type	Earth Fill and Concrete Gravity
Height of Dam	104 feet
Reservoir Control Structures	24 - Taintor Gates (21 feet by 30 feet)
Spillway Crest Length	720 feet
Date Completed	April, 1953
Power Installation	
Total Number of Units	2
Total Installed Capacity	45,000 KW
Total Hydraulic Capacity of Units	6,800 cfs
Average Annual Energy	133,000,000 KWH
Gross Head	92 feet

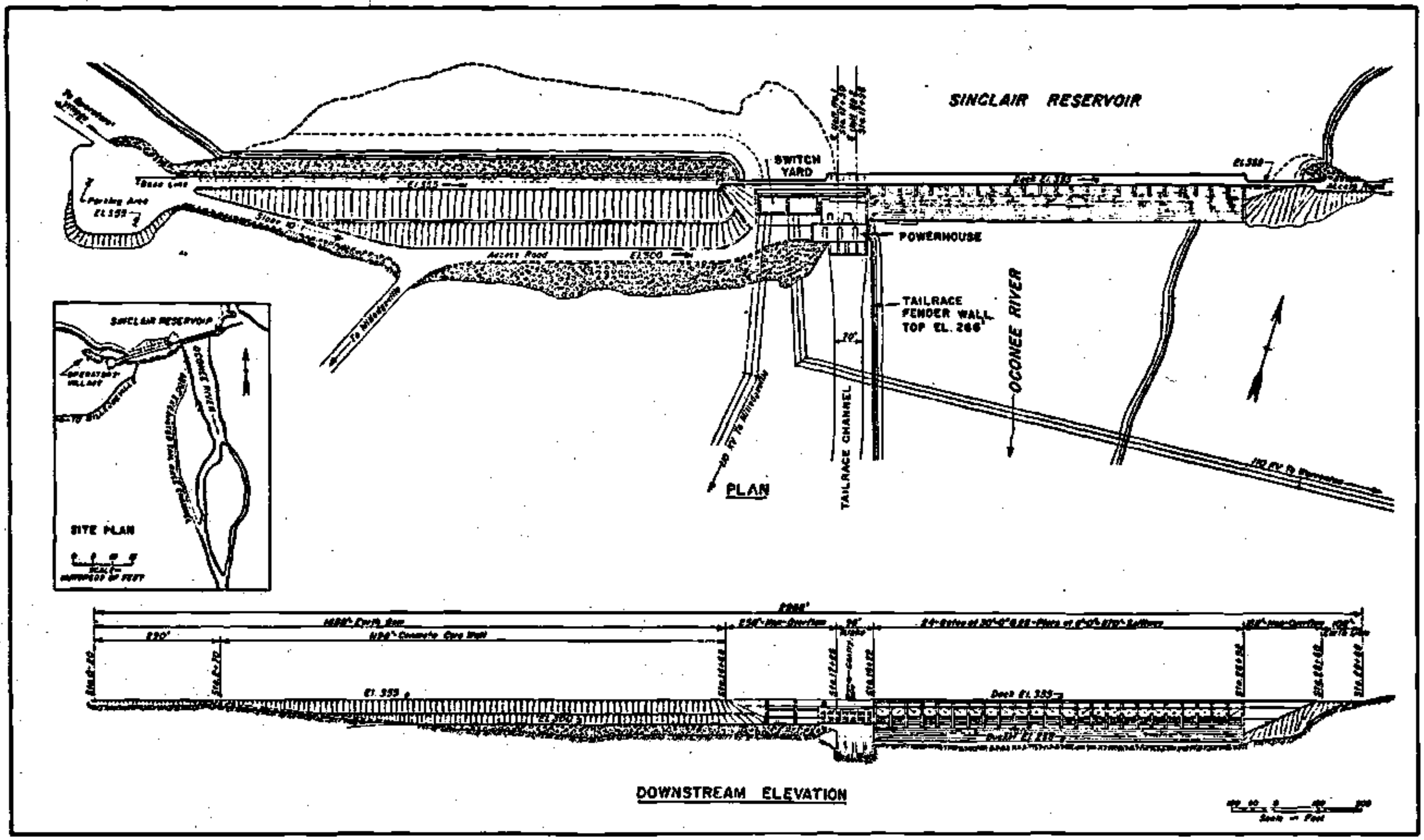

Figure 3. Sinclair Dam - Plan & Elevation

The Wallace Dam Project, located in the headwater of Lake Sinclair, will form the upper reservoir. The two projects will be connected by a tailrace approximately 20,000 feet in length. This tailrace will make it possible to pump and recycle water from Lake Sinclair during the pumped storage operation of the project. The development will include a reservoir, a powerhouse and intake constructed as an integral part of the dam, two earth fill abutment sections, concrete non-overflow sections, and a concrete gravity spillway (7). A perspective view of the project is included as Figure 4. Table 2 lists pertinent data for the Wallace Dam Project. A plan view of the project is included as Figure 5.

The Wallace Reservoir, which will cover an area of 18,000 acres at full pond, elevation 435 feet, includes portions of Putnam, Hancock, Greene, and Morgan Counties. The reservoir will extend approximately forty miles upstream and will have a shoreline length of 331 miles (7).

The Wallace powerhouse will contain six hydroelectric units with a rated capacity totaling 324,000 kilowatts. Two of the units will be conventional vertical, fixed-blade propellor type turbines with a rated output of 78,000 hp at a head of 89 feet directly connected to two vertical generators. The four reversible pump turbine units will each be rated at 73,000 hp at a head of 89 feet as turbines, while generating, and 82,800 hp at a head of 98 feet while pumping. Each will be directly connected to a vertical generator-motor unit rated at 66,700 KVA as a generator and 83,000 hp as a motor. The hydraulic capacity of the six units total 48,000 cfs (7).

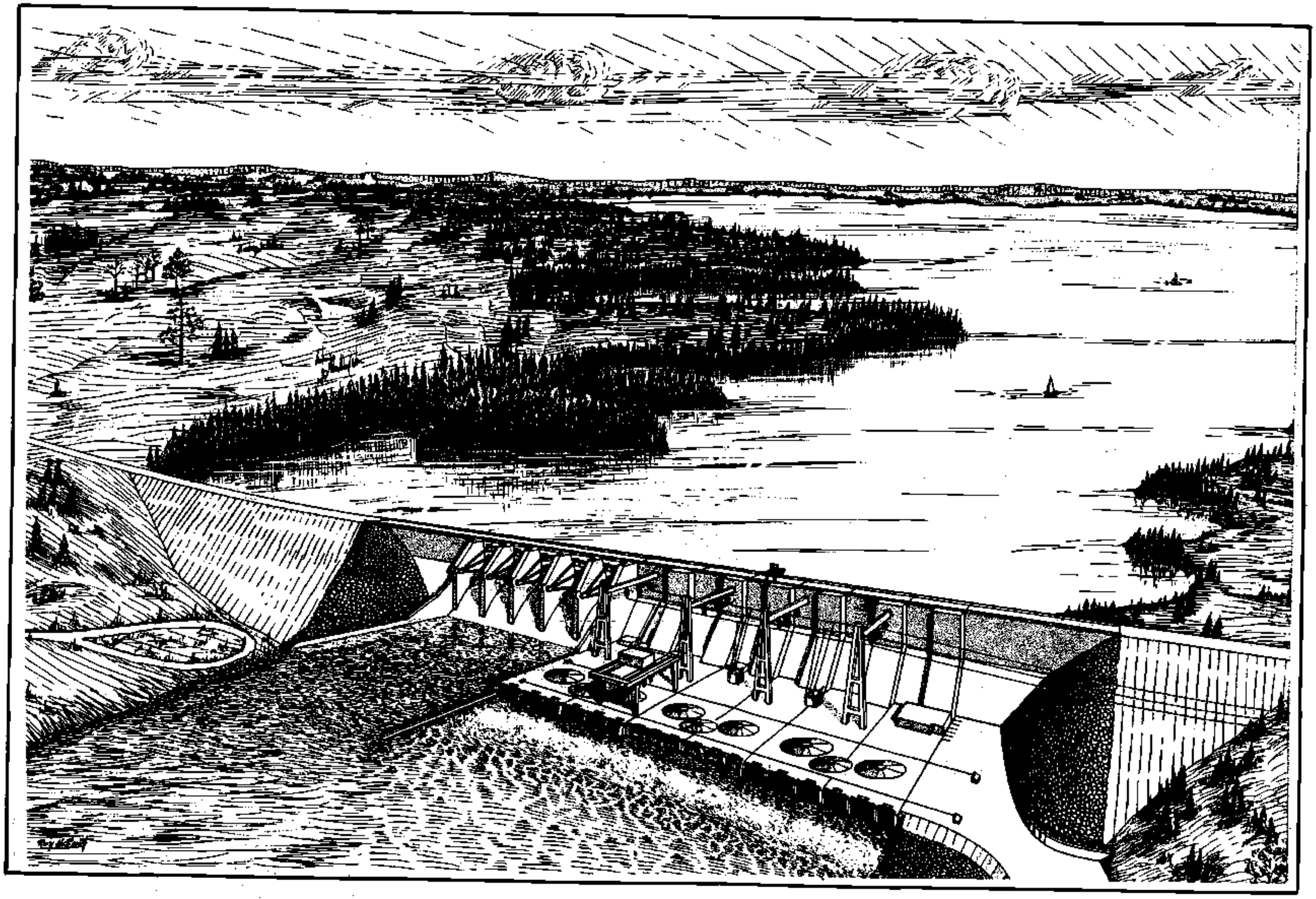

Figure 4. Perspective View of Wallace Dam

TABLE 2. Wallace Dam - Physical Data

General

Stream	Oconee River
Drainage Area	1830 square miles
Normal Full Pond Elevation	435.0 feet Plant Datum
Surface Area at Full Pond	18,000 acres
Total Storage at Full Pond	470,000 acre feet
Dam Type	Earth Fill and Concrete Gravity
Height of Dam	117 feet
Reservoir Control Structures	5 Taintor Gates (44 feet by 42 feet)
Date Completed	Under Construction

Power Installation

Total Number of Units	6
Pump-Turbine Units	4
Conventional Units	2
Total Installed Capacity	324,000 KW
Hydraulic Capacity of Turbines	
Pump Turbines - Generating Mode	32,000 cfs
Pump Turbines - Pumping Mode	26,800 cfs
Conventional Turbines - Generating	16,000 cfs
Total Hydraulic Capacity - Generating	48,000 cfs
Gross Head	95 feet

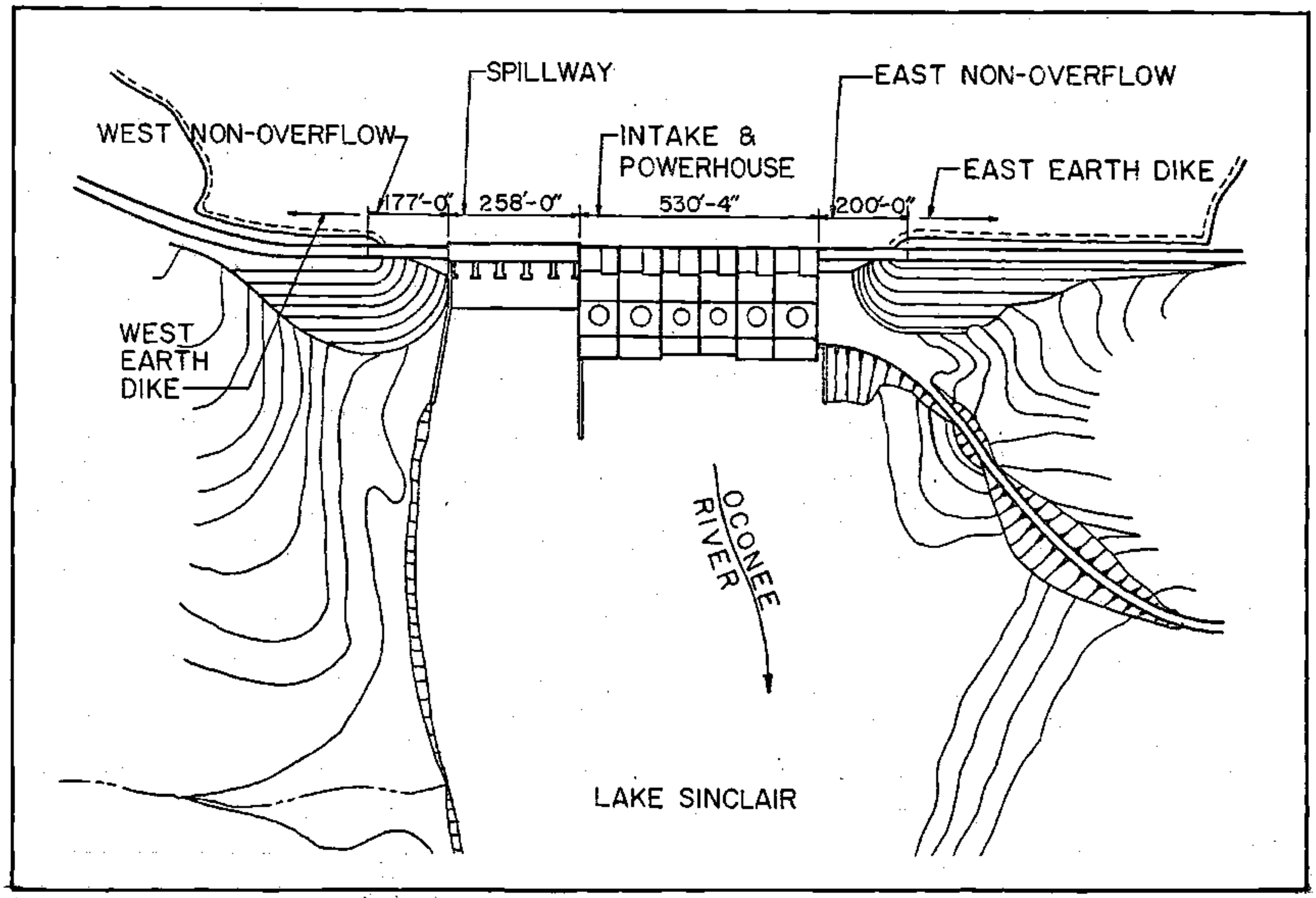

Figure 5. Wallace Dam – Plan of Site

Discussion of Pumped Storage Development

In order to better discuss the complexities involved in the economics and operation of a pumped storage development, an explanation of pumped storage and its place in an electric power system is required.

Figure 6 is a representation of a typical weekly load demand for an electric utility. The load which must be provided twenty-four hours a day is designated as base load. Generally, this load is provided by the newest, most efficient and/or economical generating units and would include fossil-fuel and nuclear power plants. A portion of the load peak, from twelve to twenty-four hours duration is also provided by base load type plants. The capacity of these plants would be lowered to a minimum without shut-down during the period in which the demand is not present. This results in operating these units at much less than their peak efficiency. The shorter duration demand during the remainder of the peak is provided by either hydroelectric projects or by combustion turbines because of the quick response time available from these types of power generating equipment.

Pumped storage is a form of hydroelectric power and uses water passing through turbines under a head to generate electricity. During off peak hours, however, the reversible pump turbines are used to recycle the water from a lower regulation reservoir back into an upper reservoir where it is stored until the capacity is needed to provide the peak power demand during the next day. The energy required during this pumping cycle is provided by the base load plants which have been cut back to nearly minimum load. This is illustrated in Figure 6. Because of the demand created by pumping, these plants can be operated

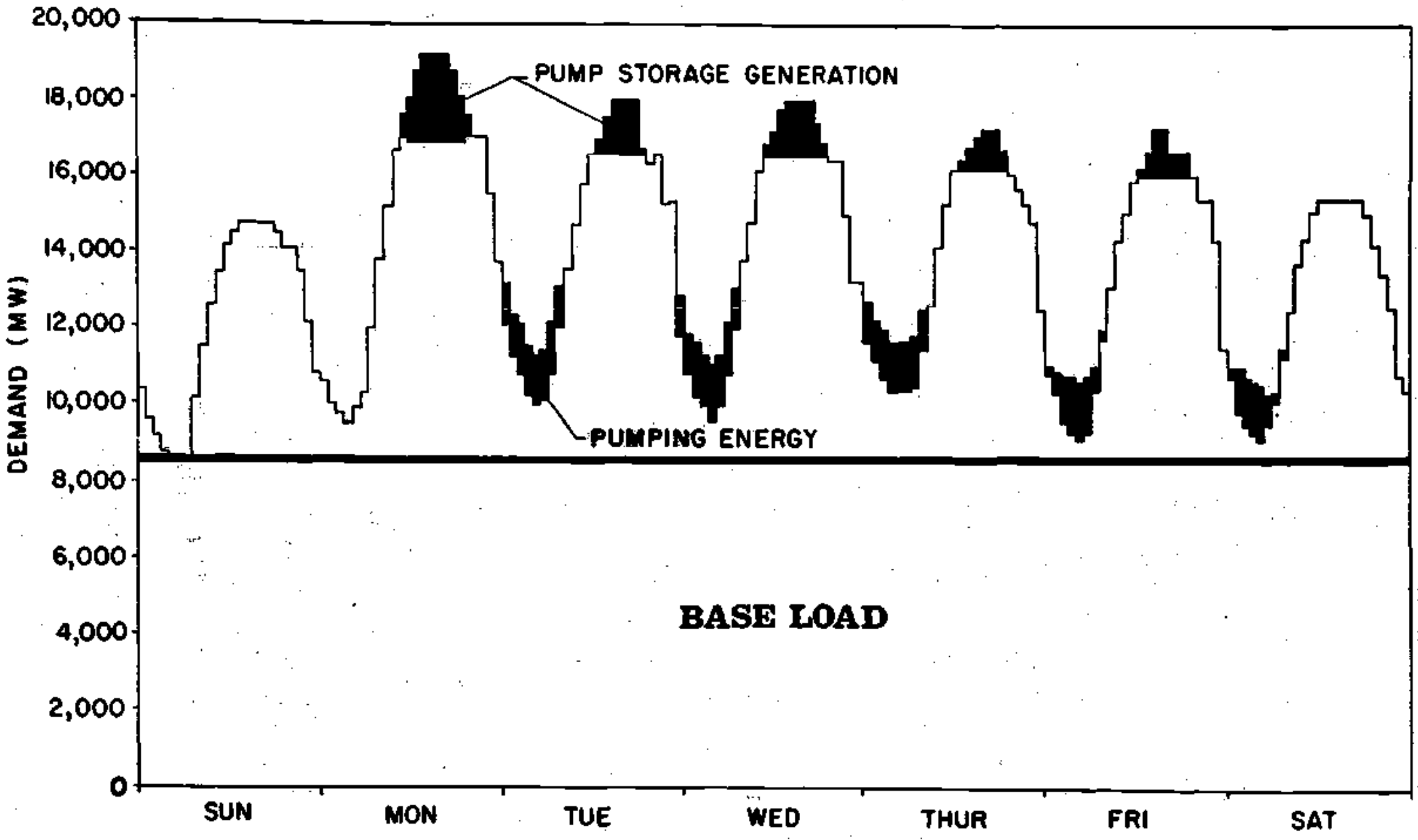

Figure 6. Projected Load Shape

at a more efficient load. This factor reduces the total cost of providing the pumping energy.

The Wallace Dam and Sinclair Dam pumped storage development will differ from a pure pumped storage development because of the conventional hydroelectric units at both plants. The natural stream flow from the Oconee River basin represents a potential energy source without the use of pumped storage. The inclusion of pump turbine units allows justification of a larger capacity plant than would be possible with conventional design.

Description of the Physical System

The physical system analyzed in the study is defined by the drainage basin above the two projects. The Oconee River drainage area above Sinclair Dam is generally rural and is shown on Figure 7. The two primary tributaries into Wallace Reservoir are the Apalachee River and the Oconee River. The drainage area is approximately 1830 square miles. Below Wallace Dam is the Sinclair Reservoir. The drainage area above Sinclair Dam is 2930 square miles with the difference primarily made up by the drainage into the Little River, a major tributary into Lake Sinclair.

A schematic diagram of the system as it was analyzed in the study is shown on Figure 8. The components of the system are shown and are designated as follows:

Iw - Inflow into the Wallace Reservoir

W - Storage capacity of the Wallace Reservoir

Gw - Flow through the Wallace Dam turbines

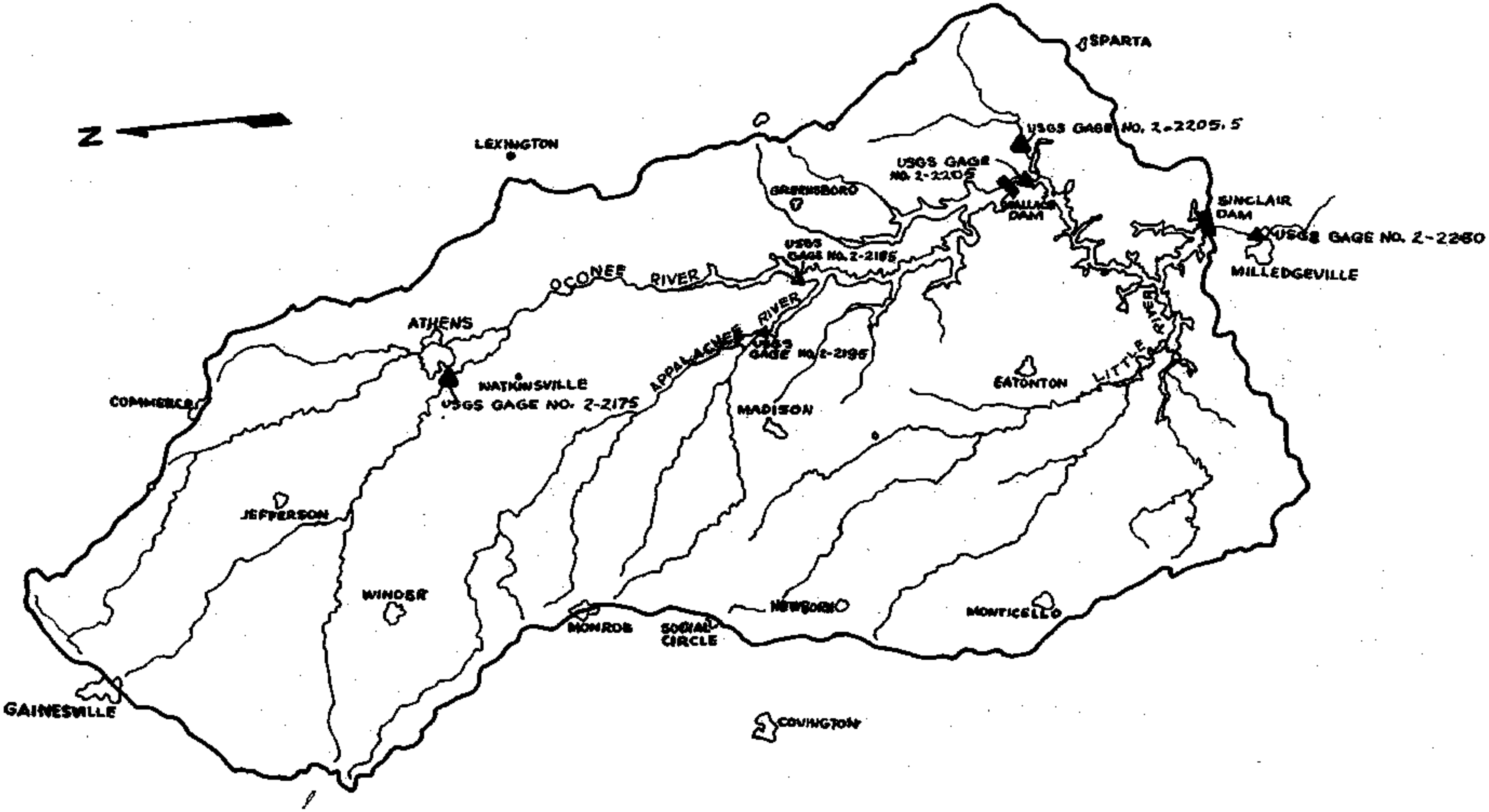

Figure 7. Drainage Area Map

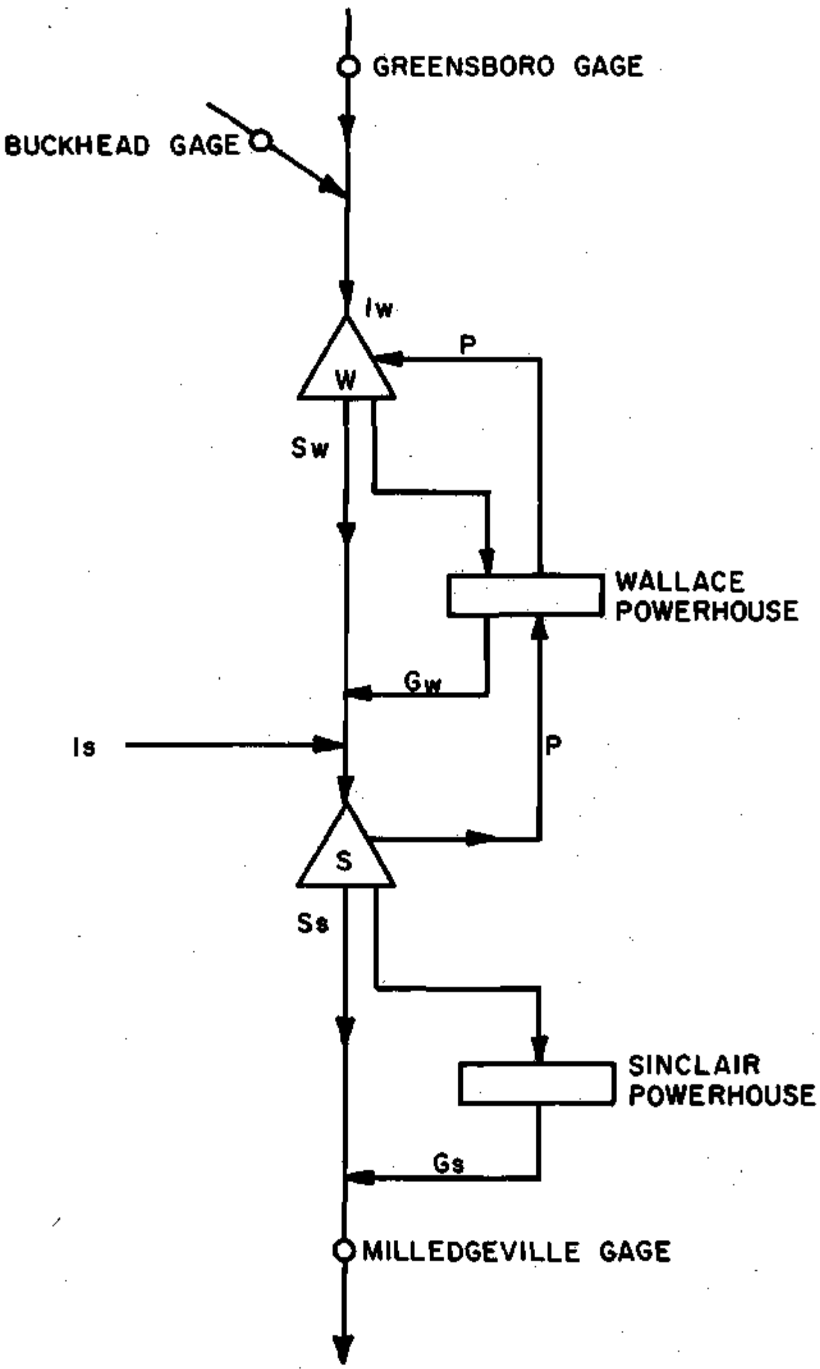

Figure 8. Schematic Diagram of Reservoir System

Sw - Water spilled over the Wallace Dam spillway

P - Water returned to the Wallace Reservoir during the pumping cycle from the Sinclair Reservoir

Is - Local inflow into the Sinclair Reservoir

S - Storage capacity of the Sinclair Reservoir

Gs - Flow through the Sinclair Dam turbines

Ss - Flow over the Sinclair Dam spillway

The inflow into the Wallace Reservoir, Iw, is an unknown which must be predicted. Similarly the local inflow into the Sinclair Reservoir, Is, is an unknown which must be predicted. The storage capacity of Wallace Reservoir, W, and the Sinclair Reservoir, S, are limited. When the maximum reservoir volume is exceeded water must be passed over the spillways. The volume of flow passed by the Wallace and Sinclair spillways are Sw or Ss, respectively. The volume passed through the turbines for electric power generation is designated as Gw or Gs. The volume of water recycled to the Wallace Reservoir through pumping from Sinclair Reservoir is designated as P.

The Objective Function

As stated, one purpose of the study is to determine the optimum set of operating rules for the two reservoirs. Simulation of the operation of the projects has been used to quantify differences in alternative sets of operating rules. Simulation of the system using the period of stream flow data results in estimates of volumes of water either generated, pumped or spilled. The simulation models are discussed in Chapter IV.

The results of these simulations have been evaluated to determine the optimum set. The criterion chosen for establishing the set of operating rules was the maximization of net revenue from the projects. The value of an objective function expressing this concept is dependent on the value of the power generated and on the cost of producing the power.

An evaluation of the value of the power generated is required. The value of the peak period energy produced by the two plants is a complex problem which involves the consumer demand for electricity, weather, and other interacting factors.

For summer periods, electricity is in peak demand in the southern states due to the power requirements for air conditioning systems. It is for this demand that power systems are taxed to their maximum potential. The value of power from a pumped storage project during these periods is the cost of supplying this energy with an alternative power source. The primary alternative source presently is the oil-fired combustion turbine. The efficiencies of these units vary as do the fuel and maintenance costs so that the exact value to the power company depends on which units would not need to be operated due to the operation of Wallace Dam. During high demand days when all units in the system are needed to meet the demand, these units are the highest cost units while during a lower demand day the lowest cost unit might be involved. In all cases the pumped storage project can produce the peak energy for less than it would cost to run the combustion turbine. Because the entire range of costs would be spanned during the summer period, the average cost of generation by an oil-fired combustion turbine was chosen as the value of peaking energy during the summer to be used in the study. A more accurate model for estimating these costs is possible and will be developed for use in a model for the operation mode.

A large demand is also experienced during the winter period. In the study, the value of peaking energy generated during the winter was also set at the average cost of generation by an oil-fired combustion turbine. During the spring and fall, the peak demand is much lower than during the winter and summer. During these low demand periods, maintenance is performed on the power system. Pumped storage projects and other types of peaking units are not generally needed to meet the peak loads. For this reason, their value to the system is lower. The peaking units can be used to replace the base load plants which are under maintenance repairs. The value used in the study for the peaking units during the fall and spring seasons is assumed to be the average cost of producing the energy with the base load nuclear and fossil-fuel steam plants.

An evaluation of the cost of producing power with the pumped storage project is also required. The cost is, of course, dependent on the cost of the pumping energy. Figure 9 is an incremental cost curve for producing power. This curve represents the cost per kilowatt hour to produce electric power. As illustrated, the lower the demand, the lower is the cost to provide the power. The cost of pumping energy is simply the cost of adding the pumping load to the consumer demand present at the time. As can be seen in Figure 6, the demand is con-

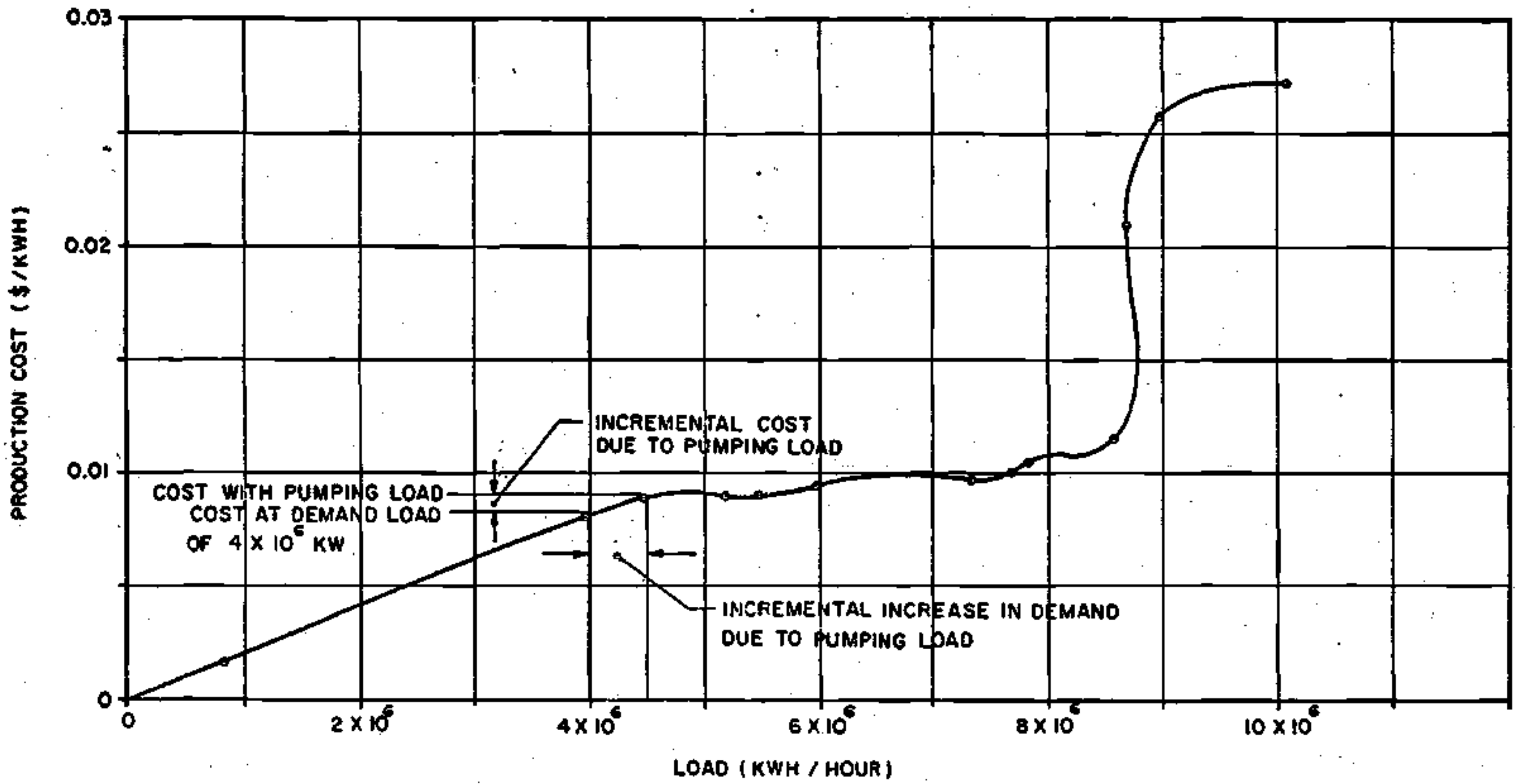

Figure 9. Incremental Cost Curve

stantly changing, so that the cost of pumping energy is constantly changing. The cost of pumping energy for a sample consumer demand is illustrated in Figure 9. In order to quantify the cost of pumping energy for the study, an analysis of the load patterns for various future load projections was made to determine which units would be available to provide the pumping energy requirements for Wallace Dam. As a result of this study of the projected loads and plants required to meet the load, an average pumping energy cost was determined.

The objective function can be expressed, in general terms, in the following form:

$$R = (Asw*(C*Gsw) + Afs * (B*Gs+C*Gfs)) - D*E*P \tag{1}$$

Where the constants and variables are defined as follows:

R - Value of net revenue in dollars per year

Gsw - Wallace generation during the summer and winter (KWH)

Gfs - Wallace generation during the fall and spring (KWH)

Asw - Constant equal to the cost of generating power by oil-fired units during the summer and winter peak demand periods ($/KWH)

Afs - Constant equal to the cost of generating power by base load units during the low fall and spring demand periods ($/KWH)

D - Constant equal to the cost of pumping energy per kilowatt hour ($/KWH)

B - Conversion factor for Sinclair generation (acre-feet to kilowatt hours)

C - Conversion factor for Wallace generation (acre-feet to kilowatt hours)

E - Conversion factor for pumping energy (acre-feet to kilowatt hours)

Gs, P - As defined previously

The value of the constants B, C, and D are dependent on the following relation:

$$KW = \frac{Q*H*e}{11.8} \tag{2}$$

Where KW - Kilowatts of power

Q - Flow through the turbines, cfs

H - Net head (Headwater minus Tailwater minus losses through the penstocks), feet

e - Efficiency of the turbines and generators

For the purpose of the study, the values of B, C, and D are constants whose value is dependent on the set of operating rules under study. This is possible due to the very small variation in the net head from day to day. The Wallace Reservoir is expected to fluctuate only 1.5 feet daily, approximately one percent of the total net head. The Sinclair Reservoir is expected to fluctuate only 1.8 feet daily, approximately two percent of the total head. Therefore, the net head, H, in Equation (2) varies only slightly and can be considered constant. The flow through the turbines, Q, and the plant efficiency, are also constant for an unvarying head. The generation from Sinclair Dam is not broken into seasons since Sinclair Dam is loaded prior to loading combustion turbines and therefore would not generally be used to replace these units in the loading order.

The values of the constants in Equation (1) are listed below:

Economic constants

$A_{sw} = \$0.0272/KWH$

$A_{fs} = \$0.0087/KWH$

$D = \$0.010/KWH$

Conversion Factors

$B = 83.36$ KWH/Acre Foot

$C = 81.67$ KWH/Acre Foot

$E = 114.34$ KWH/Acre Foot

Equation (1) can be reduced to the following final form:

$$R = (\$0.0272*(81.67*G_{sw})+\$0.0087*(83.36*G_s+81.67*G_{fs}) - \$0.010*114.34*P \quad (3)$$

System Constraints

The operation of the system and evaluation of the objective function are dependent on the choice of the constraints on the system. These constraints are summarized in Table 3.

The only constraint other than reservoir volumes and turbine capacities set during design that can not be relaxed during simulation of the system is Constraint (3), the minimum level in Sinclair Reservoir. This level represents a volume of 308,750 acre feet. The limiting factor for the level in Sinclair Reservoir is the Wallace Dam tail-race. When the Wallace Dam pump turbines are operated as pumps, a minimum water level must be maintained above the level of the pumps to prevent air from being drawn into the pump turbines necessitating

TABLE 3. Constraints on System

	Constraint	Value
(1)	Wallace Dam Maximum Reservoir Capacity	Wmax = 47,000 acre feet
(2)	Sinclair Dam Maximum Reservoir Capacity	Smax = 334,000 acre feet
(3)	Sinclair Dam Minimum Reservoir Level	Elevation 338.2 feet
(4)	Sinclair Dam Minimum Reservoir Capacity	Smin = 307,750 acre feet
(5)	Pumping Time available during off peak load demand periods	8 hours
(6)	Maximum hydraulic capacity of Wallace Dam turbines	48,000 cfs
(7)	Maximum hydraulic capacity of Sinclair Dam turbines	6,800 cfs
(8)	Maximum hydraulic capacity of Wallace Dam pump turbines operating as pumps	26,800 cfs

shutdown. The level in Sinclair Reservoir that corresponds to this minimum cover is 338.2 feet. Lowering of the tailrace floor is uneconomical due to rock in the channel bottom.

The limiting of pumping during off peak hours to eight hours is based on an evaluation of the power system load and primarily is dependent on the lack of economic pumping sources for more than eight hours. Should the shape of the power system load change in the future by broadening of the off peak period, this constraint could be relaxed.

During the simulation phase of the study, selected constraints are relaxed and the effects determined. The simulation phase is discussed in subsequent chapters.

Data Sources

The variables in the objective function, Gsw, Gfs, Gs, and P, are dependent on the inflow into the reservoirs and on the constraints set on the system. A discussion of the development of linear regression models to predict inflows, Iw and Is, is presented in Chapter III.

The data available on the Wallace and Sinclair Dam drainage basin are primarily in the form of stream flow and precipitation records. Rainfall gages within the basin are limited; however, the United States Geological Survey, Water Resources Division, has been measuring flows on the Oconee River for over 60 years. Long term records are available at the following stations:

Gage No. 2-2185 - Oconee River near Greensboro
(1904-1932; 1937 - Present)

Gage No. 2-2195 - Apalachee River near Buckhead
(1901-1908; 1937 - Present)

Gage No. 2-2230 - Oconee River at Milledgeville
(1903 - Present)

Several short term records are available. Only one is utilized in the study. This is Gage No. 2-2205, Oconee River at Sparta, 1951 to 1953. This gage is located very near the site for Wallace Dam.

The gage on the Oconee River at Milledgeville, subsequently referred to as the Milledgeville gage, is located in Milledgeville, Georgia at the water works intake structure approximately 3.8 miles downstream from Sinclair Dam. The records are available from August, 1903, to the current year with no gaps in the data. The gage is a water stage recorder. Prior to 1938, a non-recording gage was used. The location of the gage has been moved numerous times during the period of record (8).

The gage near Greensboro, subsequently referred to as the Greensboro gage, is located in Greene County five miles upstream of the mouth of the Apalachee River and five miles west of Greensboro, Georgia. Barnett Shoals Project, a run of the river hydroelectric plant operated by Georgia Power Company, is located twelve miles upstream of the gage. Records are available from July, 1903, to September, 1932 and from October, 1936, to the current year. The gage is a water stage recorder. Prior to 1938 a non-recording gage was used. The gage has not been moved throughout the period of record (8).

The gage on the Apalachee River, subsequently referred to as the Buckhead gage, is located nine miles upstream of the confluence of the Apalachee River with the Oconee River near Buckhead, Georgia. Records are available from January, 1901, to December, 1908, and from April, 1937, to the current year. The gage is a water-stage recorder. Prior to 1939, a non-recording gage was used. The gage has not been moved throughout the period of record (8).

The water-stage recorder at Sparta was located 1.5 miles downstream from the Wallace Dam site. Flow records were taken from October, 1949, to April, 1953 at which time backwater from Lake Sinclair inundated the site of the gage. The gage was discontinued in April, 1953 (8).

CHAPTER III

DEVELOPMENT OF FLOW RECORD

General

The initial part of the study involved the processing of a very large bank of stream flow data available from the United States Geological Survey, and development of models to predict the inflow into Wallace Dam, Iw and local inflow into Sinclair Dam, Is. Data from the Greensboro gage and the Buckhead gage are used in conjunction with the short term record at the Wallace Dam site (Sparta gage) to develop a linear regression model to predict the flow at the Sparta gage from the upstream gages. Records from the Milledgeville gage are used as the record of flow at Sinclair Dam. The local inflow, Is, is equal to the flow at Sinclair Dam, measured at the Milledgeville gage, minus Iw.

Collection and Processing of Data

The initial step in the study was to collect data on the system. Basically, this consisted of flow data on the Oconee River and its tributaries recorded by the United States Geological Survey. The daily flow data for the Greensboro, Buckhead and Milledgeville gages were requested and received for the entire period of record. The data were received in the form of data cards from the data center for the United States Geological Survey located in Reston, Virginia.

After receipt of the data cards, three data files were created. A separate file was created for the Buckhead gage, the Greensboro gage, and the Milledgeville gage. Since the Geological Survey was not able to furnish records of the Sparta gage, its three year period of record had to be entered by hand from the terminal. A computer program was then written to extract the daily flow data from the Geological Survey files and to store them in binary files.

During this process, some modifications were made in the data to simplify its use. This included truncating each leap year to a normal 365 day year and the use of complete water years. Any partial water years were not used. The three large files were then broken down into smaller more workable files since each was too large to be handled by file manipulation commands. The divisions were somewhat arbitrary but were basically dictated by gaps in the period of record and by the size of the files. The gaps in the period of record are summarized below:

Buckhead gage - Water Years 1909 through 1937

Greensboro gage - Water Years 1933 through 1936

Milledgeville gage - None

Development of Wallace Dam Inflow

The initial problem addressed in the study was the development of a synthetic flow record at the Wallace Dam site to approximate Iw. One possible method of generating synthetic flow data is through the use of a model to simulate the land phase of the hydrological cycle.

A complex land phase model was not chosen because of the lack of adequate precipitation and evaporation data, and because of the cost involved in simulating a watershed which covers several thousand square miles.

Because of the long gaged record, the problem was instead approached on a statistical basis. The flow records at the Greensboro and Buckhead gages were correlated with the flow records at the Sparta gage near the Wallace Dam site to develop a linear regression model for the Wallace Dam inflow.

Due to the gap in the record at the Buckhead gage, two models were required to develop a synthetic flow record at Wallace Dam. One model used the sum of the flows at the Buckhead and Greensboro gages to predict Sparta gage flows. The other involved only the use of the Greensboro gage. This model was used to predict flows for the period when no data was available at the Buckhead gage.

The initial model studied was one utilizing the sum of the flows. A model of the following form was assumed:

$$Qs = A + B * Qsum \tag{4}$$

Qs is defined as the flow at the Sparta gage. A and B are regression coefficients, and Qsum is the sum of the flow recorded at the Greensboro and Buckhead gages. No time lag was assumed between the confluence of the Oconee River and Apalachee River at the Wallace Dam site. A computer program developed by General Electric was used to perform the linear least squares regression (2). Prepared sets of data for the period of Water Year 1950 through Water Year 1952 were analyzed and the least squares regression coefficients were computed. The resulting model, Equation (5), was designated Model WD1.

$$Qs = -45.55 \text{ cfs} + 1.193 * Qsum \tag{5}$$

The coefficient of determination was calculated to be $r^2 = 0.803$ which indicated fair correlation between the data sets.

It has been shown by others that for hydrologic data, better correlation of this type of hydrologic data can sometimes be achieved by analyzing the log of the data sets (1). In an effort to improve the model, the correlation of the log of the data sets was investigated. This model, Equation (6), was designated WD2. The results of the regression are shown below:

$$\mathrm{Ln}\ (Qs) = -0.0538 + 1.026 * \mathrm{Ln}\ (Qsum) \tag{6}$$

The coefficient of determination was improved to a value of $r^2 = 0.960$ Equation (6) can be written in a more useful form as in Equation (7)

$$Qs = 0.948 * Qsum^{1.026} \tag{7}$$

In all other models investigated the log of the data was utilized.

As stated before, Models WD1 and WD2 had no time lag introduced into the data. An examination of daily flow records do not indicate an obvious lag in the data. The two points on the river are approximately 22 miles apart, so a time lag exists physically. Various time lags were introduced in the data and regression analyses made on the log of the lagged data. The highest coefficient of determination was achieved with a time lag of 12 hours. This time lag was introduced in the data by taking the average of the current and previous day's flow at Greensboro and Buckhead and correlating it with the current day's flow at the Sparta gage. The best of the lagged models, Equation (8), was designated WD3 and is shown below.

$$\mathrm{Ln}\ (Qs(t)) = -0.159+1.04*\mathrm{Ln}\ \frac{Qsum(t-1)+Qsum(t)}{2} \tag{8}$$

Qs(t) is defined as the flow at the Sparta gage for day t. Qsum(t-1) is the sum of the previous day's flow at the Greensboro and Buckhead gages. Qsum(t) is the sum of current days flow at the upstream gages. Lagging the flow in this manner resulted in an increased value of the coefficient of determination to $r^2 = 0.974$. Equation (9) is an expression of WD3 in a more useful form.

$$Qs(t) = 0.853 * \frac{Qsum\ (t) + Qsum\ (t-1)}{2}^{1.04} \qquad (9)$$

Similarly, a regression model was developed to predict the flow into Wallace Dam from the Greensboro gage to be used to develop a flow record during gaps in the Buckhead gage record. The best coefficient of determination was again achieved with a lagged model of the log of the Greensboro and Sparta flow. The resulting model, Equation (10), was designated WD5.

$$LnQs(t) = 0.145 + 1.045 * Ln \frac{Qg(t) + Qg(t-1)}{2} \qquad (10)$$

Qs(t) is defined as before, and Qg(t) and Qg(t-1) are the current and previous day flows at the Greensboro gage. Model WD5 can be expressed in a more useful manner as in Equation (11)

$$Qs(t) = 1.57 * \frac{(Qg(t) + Qg(t-1)}{2}^{1.045} \qquad (11)$$

At this point an analysis was made of the residuals calculated using model WD3 for the three year period of record at the Sparta gage (1950 to 1953). The residuals were the calculated flows at the Sparta gage based on model WD3 minus the actual recorded flows of the gage. The following statistical characteristics were calculated for the residuals. These characteristics are listed below:

Mean of Residuals - -11.4 cfs

Median of Residuals - -7.1 cfs

Variance - 3.179×10^5

Standard Deviation - 563.8 cfs

A plot of the residuals versus time for Water Year 1950 is shown in Figure 10. No seasonal variation in the residuals is apparent from the plot. However, large residuals were observed in all four seasons of the year. In an attempt to explain these large errors between the calculated and actual flows, precipitation records were analyzed for Water Year 1950.

The Thiessen method was used to divide the drainage area into average rainfall areas. The only precipitation gages close enough to represent the drainage area between the Greensboro and Sparta gages are rainfall gages located near Greensboro, Georgia, and near Sparta, Georgia, locations of which are shown on Figure 7. Precipitation records for these stations were obtained from "Climatological Records for Georgia" published by the Weather Bureau, United States Department of Commerce. The average daily precipitation over the drainage area between the Greensboro and Sparta stream gages was calculated for Water Years 1950 through 1952. The coincidence of large errors in the residuals and large recorded rainfalls indicated inclusion of precipitation in the model could be beneficial. The large residuals were then plotted against the corresponding average daily precipitation. The plot is shown in Figure 11. The large scatter in the plot would indicate no apparent functional relationship between the precipitation and the large errors. However, a dependency of Qs on rainfall in the

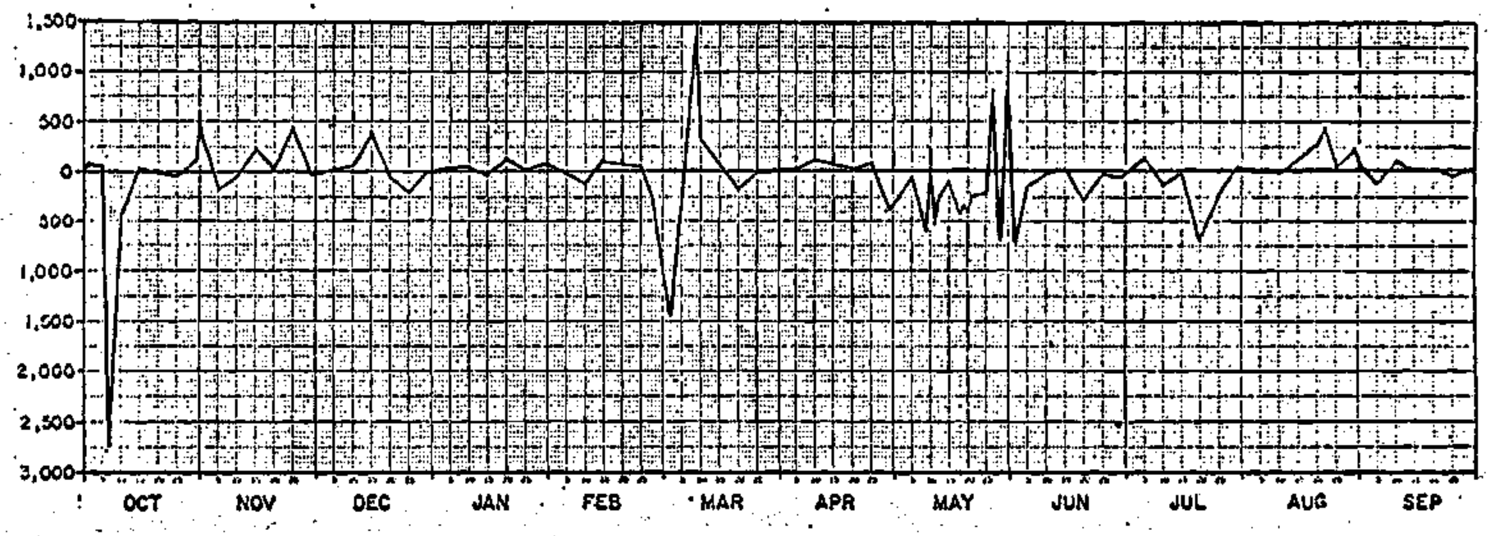

Figure 10. Plot of Residuals, Model WD 3, Water Year 1950

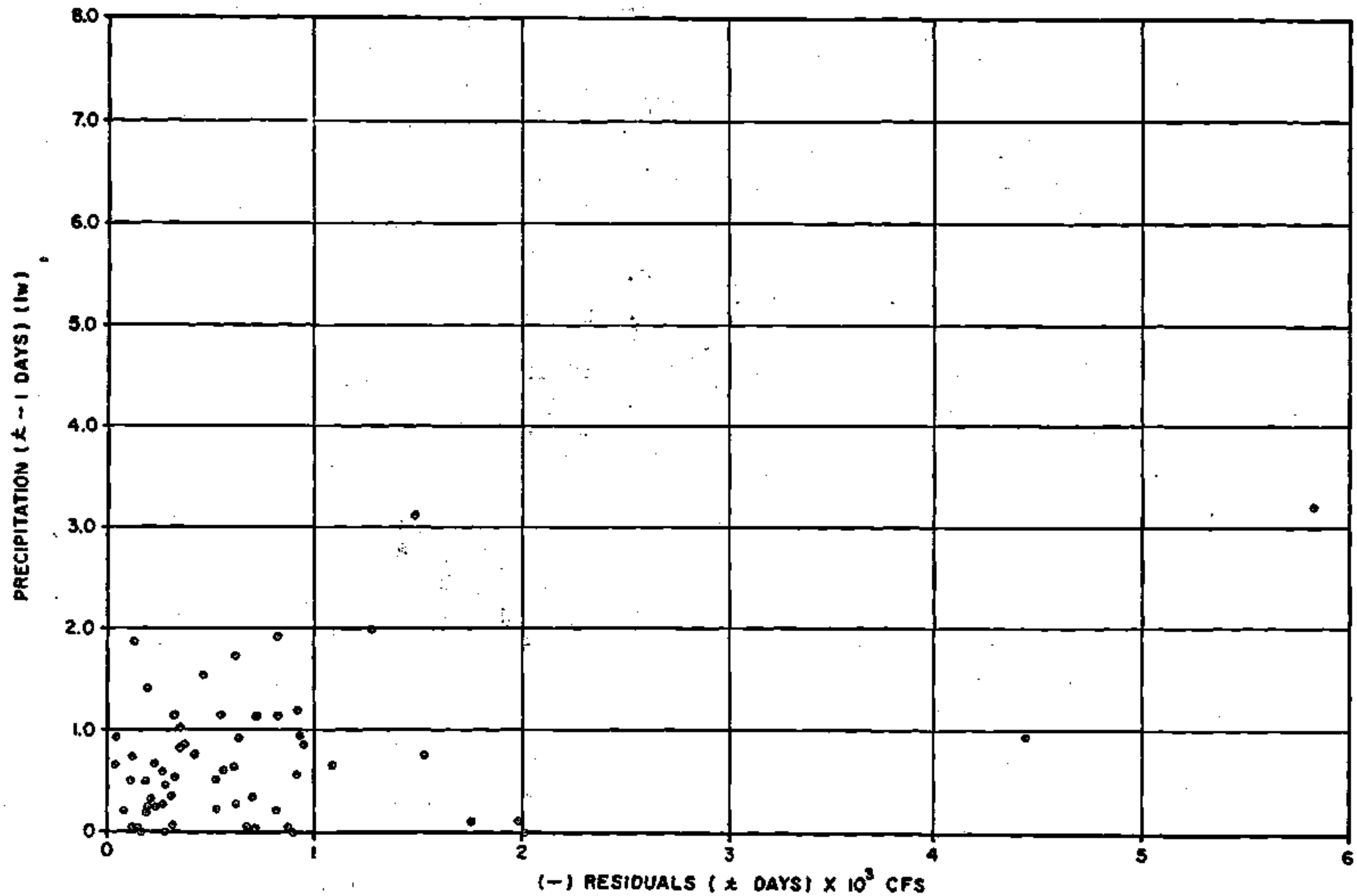

Figure 11. Wallace Dam Residuals for WD 3 vs Precipitation Computed Minus Actual

was June through November of each year. Again a lagged model of the logs of the flow was analyzed. The sum of the flows at the Greensboro and Buckhead gages was used. The following model, Equation (14) and Equation (15), was designated as models WD6 and WD7 respectively.

Wet Season Model - WD6

$$\text{Ln } Qs(t) = 0.0169 + 0.997 * \text{Ln } \frac{Qsum\ (t) + Qsum\ (t-1)}{2} \tag{14}$$

The coefficient of determination was calculated as $r^2 = 0.870$.

Dry Season Model - WD7

$$\text{Ln } Qs\ (t) = 1.672 + 1.04 * \text{Ln } \frac{Qsum(t) + Qsum\ (t-1)}{2} \tag{15}$$

The coefficient of determination was calculated as $r^2 = 0.867$, the reduction compared to the single season model being a result of decreasing the variance of the dependent variables when a multi-season model is used. Based on the results of this analysis, utilization of a wet season and dry season model was not justified.

In summary, the best correlation of data was achieved with a lagged model using the log of the flows. Model WD3 was adopted to predict the Wallace Dam inflow during the period 1904 to 1908, and 1938 to 1973. Model WD5 was adopted to predict the Wallace Dam inflow during the gap in the Buckhead gage data from 1909 to 1932. No upstream flow records were available for the period 1933 to 1937. Model WD5 was used for 1937 flow prediction. Table 4 contains a summary of the regression analyses made in this phase of the study.

An error was discovered in this phase of the study at the completion of the project. The coefficients of determination shown in Table 4 for Model WD2 through Model WD7 were calculated based on the lower part of the watershed was examined statistically by adding precipitation to the model. The assumed linear form analyzed was as follows:

$$\mathrm{Ln}(Qs(t)) = A+B*\mathrm{Ln}\,\frac{(Qsum(t) + Qsum(t-1)}{2} + C*Rf \tag{12}$$

Where: A,B,C - Regression constants

Qs(t), Qsum(t), Qsum(t-1) - as defined previously

Rf - Average daily precipitation over the area

A multiple regression program was used to calculate the regression constants (2). The resulting model, Equation (13), was designated as WD4.

$$\mathrm{Ln}Qs(t) = -0.1078 + 1.03 * \mathrm{Ln}\ \frac{Qsum(t) + Qsum(t-1)}{2} + 0.073*Rf \tag{13}$$

The coefficient of determination was improved only slightly to a value of $r^2 = 0.976$.

An analysis of the residuals from this model was then made. The large errors observed in the residuals from model WD3 were also apparent in model WD4. Various time lags and higher order relationships of precipitation were introduced in an attempt to reduce the large stream flow errors, but there was no significant improvement. Model WD4 was not used any further in the study. Even though slightly better correlations were obtained by introducing precipitation, the added computer costs involved in the processing and storage of the precipitation records was not considered justifiable.

Next, a correlation of wet season and dry season flows was examined to determine whether better correlation could be achieved. The wet season was assumed to be December through May and the dry season

Table 4. Summary of Regression Models

Model	Coeficient of Determination r^2
WD1: $Qs = -45.55 + 1.193 * Qsum$	0.803
WD2: $Qs = 0.948 * Qsum^{1.026}$	0.960
WD3: $Qs(t) = 0.853* \left(\frac{Qsum(t) + Qsum(t-1)}{2}\right)^{1.04}$	0.974
WD4: $LnQs(t) = (-0.1078 + 1.03 * Ln \left(\frac{Qsum(t) + Qsum(t-1)}{2}\right)^{1.03} + 0.73 * P$	0.976
WD5: $Qs(t) = 1.157 * \left(\frac{Qg(t)+Qg(t-1)}{2}\right)^{1.045}$	0.956
WD6: Wet Season $LnQs(t)=0.0169 + 0.997*Ln \frac{(Qsum(t)+Qsum(t-1))}{2}$	0.870
WD7: Dry Season $LnQs(t) = -1.672+1.04*Ln \frac{(Qsum(t)+Qsum(t-1))}{2}$	0.867

log of the data set, and therefore should not have been compared with the coefficient of determination for Model WD1.

Therefore, the coefficient of determination for Model WD3, the model selected for use in the simulation, phase of the study was recalculated. Additionally, a new model was developed based on a time lag of 12 hours to be compared with Model WD3. This model was designated WD8 and is given by Equation (16).

$$Qs(t) = -6.658 + 1.167 * \frac{(Qsum(t-1)+Qsum(t))}{2} \tag{16}$$

A comparison of models WD3 and WD8 is shown below. Standard errors are also included for each model.

Model	r^2	S.E.
WD3	.910	645
WD8	.916	623

There is little difference between the coefficients of determination and standard errors for Models WD3 and WD8. Therefore, no changes were made in the simulation phase of the study which was based on inflows calculated using Model WD3.

Stream flow estimates are currently available at the Wallace Dam construction site during flood flows on the Oconee River. Flood flows which occurred in March 14 through March 17, 1975, were monitored at the site. Flow records for the Buckhead and Greensboro gages were obtained for this period from the United States Geological Survey in Atlanta, Georgia. Table 5 compares the recorded flow at the Wallace Dam site and the flows calculated from models WD3 and WD5. The correlation of the calculated flow and measured flow was good for the

Table 5. Comparison of Calculated Wallace Flow and Measured Flow

Date	Greensboro Gage (CFS)	Buckhead Gage (CFS)	Calculated Flow at Wallace (WD3) (CFS)	Calculated Flow at Wallace (WD5) (CFS)	Measured* Flow at Wallace (CFS)
3/13/75	4,370	2,180			
3/14/75	10,700	8,690	16,200	13,000	20,600
3/15/75	18,600	10,400	30,900	26,100	24,500
3/16/75	19,100	5,150	34,100	34,000	29,500
3/17/75	14,300	3,060	26,400	29,900	27,600
Avg. for Period			26,900 cfs	25,750 cfs	25,550 cfs

*Flow gaged over Low Block at El. 341.

three day period. Large errors in the predicted flows occurred on the peak day. It is felt that most of the large errors from the model would be during flood periods. This is indicated both by the above measurements and the analysis of the residuals from model WD3 discussed previously.

CHAPTER IV

THE OPERATIONAL MODEL

The next step in the study was to develop a synthetic stream flow record for Wallace Dam from the available data. Using Model WD3 and WD5 as described in Chapter III, a record for Wallace inflow, Iw, was estimated for the period of study, Water Year 1904 through 1973 with the exception of a gap in the data from 1932 to 1937. The flow record at the Milledgeville gage was used as the total inflow into Sinclair. The local inflow, Is, was estimated by the flow at the Milledgeville gage minus Iw. Two external files were created and stored in the computer. The files were designated as a SIM file, record of Iw, and a SIN file, Milledgeville flow record.

Next an operational model is developed for computer simulation of the operation of the pumped storage development for various sets of operating rules and sets of constraints. The programs are written in the BASIC computer language and stored under the file name WALLACE. The operating model maintains a daily budget of the volumes of inflow into Wallace and Sinclair Reservoirs. The daily inflow into Wallace Dam is taken from the synthetic flow record predicted from the Greensboro and Buckhead gages using the flow models developed in the initial phase of the study. The total inflow into the system is taken from the Milledgeville gage. The model allocates the daily volumes of inflow to volumes of generation at Wallace Dam and Sinclair Dam, volume of pumping back into Wallace Reservoir, and spillage at

Wallace and Sinclair Dams when flows exceeded generation capacities of the projects. The allocation of the inflow volume is based on various sets of operating rules and constraints on the system. Evaporation has been neglected.

In the simulation of the operation of the two projects, the daily operation is divided into two periods of twelve hours. The first period is designated as the generating cycle. During the generating cycle, a volume of inflow is allocated to generation at Wallace Dam based on a designated set of operating rules. The total volume in the Wallace Reservoir at the end of the generating cycle is then calculated by summing the inflow, predicted from the upstream gages, the volume in Wallace Reservoir at the start of the period, and subtracting the allocated volume of generation at Wallace Dam. This volume is then compared with the maximum volume possible in Wallace Reservoir, and any volume over the maximum is allocated to spillage at Wallace Dam. Next the operation at Sinclair Dam is simulated. The generation at Sinclair Dam is also allocated by designated operating rules, but generally is set at the volume of total inflow above Sinclair Dam up to the maximum generation constraint. The volume in Sinclair Reservoir at the end of the period is then calculated by summing the local inflow during the period, the volume in Sinclair Reservoir at the start of the period, the discharge from Wallace Dam and by subtracting the volume used for generation at Sinclair Dam. If this volume exceeds the maximum volume possible in Sinclair Reservoir, the excess is spilled.

Next the pumping cycle is simulated. The volume to be pumped back into Wallace Reservoir is based on the set of operating rules. The volume in Wallace Reservoir at the end of the pumping cycle is then calculated by summing the volume left in Wallace Reservoir at the end of the generating cycle, the local inflow during the period, and the volume pumped from Sinclair Reservoir. As is done at the end of the generating cycle, the total volume in Wallace Reservoir is compared with the maximum and any excess spilled. If no pumping volume is required, the pumping period is used for more generation if needed, to avoid spillage at Wallace Dam. Next the operation of Sinclair Dam is simulated. The volume in Sinclair Reservoir at the end of the pumping cycle is calcualted by summing the volume left in Sinclair Reservoir at the end of the generating cycle, discharge from Wallace Dam if any, and local inflow during the period, and by subtracting the volume pumped into Wallace Reservoir and any volume used for generation from Sinclair Dam. Generation at Sinclair Dam during the pumping cycle is necessary if the total daily inflow exceeds the volume passed through the Sinclair turbines during the twelve hour generating cycle plus the volume pumped back into Wallace Reservoir.

This daily operation is simulated for each day in the period of record. Daily volumes of flow for power generation at Wallace Dam and Sinclair Dam, daily volumes of pumping, and daily volumes of spillage are totaled for each year and for the period or record. Average annual generation and pumping are used to evaluate the objective function for each set of operating rules and constraints. The total generation at Wallace Dam is divided into generation during the summer-winter seasons and fall-spring seaons for use in the objective function.

In order to explain each set of operating rules and illustrate the operational model, the operation of the system under various conditions of stream flow into the two reservoirs is described. Variables which are used in the model are defined in Table 6. The three cases of stream flow selected are defined in the following paragraph.

A low stream flow is defined as a total average daily stream flow above Sinclair Dam of less than 6,800 cfs, the maximum hydraulic capacity of the Sinclair turbines (i.e. $Iw+Is < 6800$ cfs). This stream flow condition usually occurs during the summer and fall seasons. When the total daily inflow exceeds an average flow of 6800 cfs and when the local inflow volume into Wallace Reservoir is less than 46,600 acre feet per day, the flow is designated as an intermediate stream flow. A volume of 46,600 acre feet (47,000 cfs for 12 hours) is the maximum volume that can be passed through the Wallace turbines in twelve hours, the length of the generating cycle. The differences in the hydraulic capacities shown in Table 2 and the values assumed in the models are due to differences in heads simulated in the models. For flows in excess of the intermediate stream flow, generation during the pumping cycle would be required at Wallace Dam to avoid spillage and no pumping would be necessary. Flows in excess of intermediate stream flows are designated as the high stream flow condition. To illustrate the operation of Wallace Dam and Sinclair Dam the following examples of the three flow conditions are used.

Table 6. Definitions of Variables in Model

Gwmax	- Volume passed through Wallace turbines in twelve hour period. Gwmax = 46600 acre feet.
Gsmax	- Volume passed through Sinclair turbines in twelve hour period. Gsmax = 6732 acre feet.
Wg	- Volume passed through Wallace turbines during generating cycle.
Wp	- Volume passed through Wallace turbines during pumping cycle.
P	- Volume of water pumped back into Wallace Reservoir from Sinclair Reservoir.
Pmax	- Maximum volume which can be pumped in 8 hours. Pmax = 16800 acre feet.
Sg	- Volume passed through Sinclair turbine during generating cycle.
Sp	- Volume passed through Sinclair turbines during pumping cycle.
Sw	- Spillage at Wallace Dam.
Ss	- Spillage at Sinclair Dam.

Case		Flow rate (cfs)	
	Iw	Is	I Total
(1) Low stream flow	2,000	1,500	3,500
(2) Intermediate stream flow	20,000	10,000	30,000
(3) High stream flow	30,000	15,000	45,000
		Daily Flow Volume (Acre Feet)	
	Iw	Is	I Total
(1) Low stream flow	3,960	2,970	6,930
(2) Intermediate stream flow	39,600	19,800	59,400
(3) High stream flow	59,400	29,700	89,100

For each set of operating rules, the initial conditions of the two reservoirs are set as follows:

Volume in Wallace Reservoir - Wmax or 470,000 acre feet

Volume in Sinclair Reservoir - Smin or 308,750 acre feet

The constraints on the system are as listed in Table 3. Following is a discussion of each set of operating rules and constraints investigated in the study.

Operational Model Wallace 1

The initial set of operating rules investigated the effect of maximizing the generation at Wallace Dam. The generation at Wallace Dam comes from two sources, natural stream flow and pumped water. The maximum pumping time listed in Table 3 is eight hours. This constraint is based on an analysis of the shape of the power demand curve. Energy for pumping beyond eight hours would have to be provided by higher cost, lower efficiency steam plants. The volume of water which can be returned to Wallace Reservoir during the eight hours of pumping by the four reversible pump turbines is 16,800 acre feet. The generation at Wallace Dam for this initial set of operating rules is determined by the sum of 16,800 acre feet from pumped water and the natural inflow into Wallace Reservoir, Iw. Iw is the anticipated inflow based on the measured stream flow at the Greensboro and Buckhead gages. At the end of each day of operation, if possible, the volume in Wallace Reservoir should be equal to Wmax, the maximum, and the volume in Sinclair Reservoir should be equal to Smin, the minimum level. A flow diagram for Wallace 1 is included for reference in Figure 12. The operation of Wallace Dam and Sinclair Dam for the three flow conditions is discussed to illustrate the mechanics of the model.

Low Stream Flow Condition

In Case (1) Iw is equal to 3960 acre feet/day; Is is equal to 2970 acre feet/day for a total inflow; I total, of 6930 acre feet/day. The initial reservoir conditions are assumed as follows:

W = Wmax = 470,000 acre feet

S = Smin = 308,750 acre feet

Generating Cycle - At Time t = 0 the generating cycle begins. The program tests to determine if Iw exceeds Gwmax or 46,600 acre feet. Since it does not, the generation at Wallace Dam during the generating cycle, Wg, is set as follows:

Wg = Pmax + Iw

Wg = 16,800 acre feet + 3,960 acre feet

Wg = 20,760 acre feet

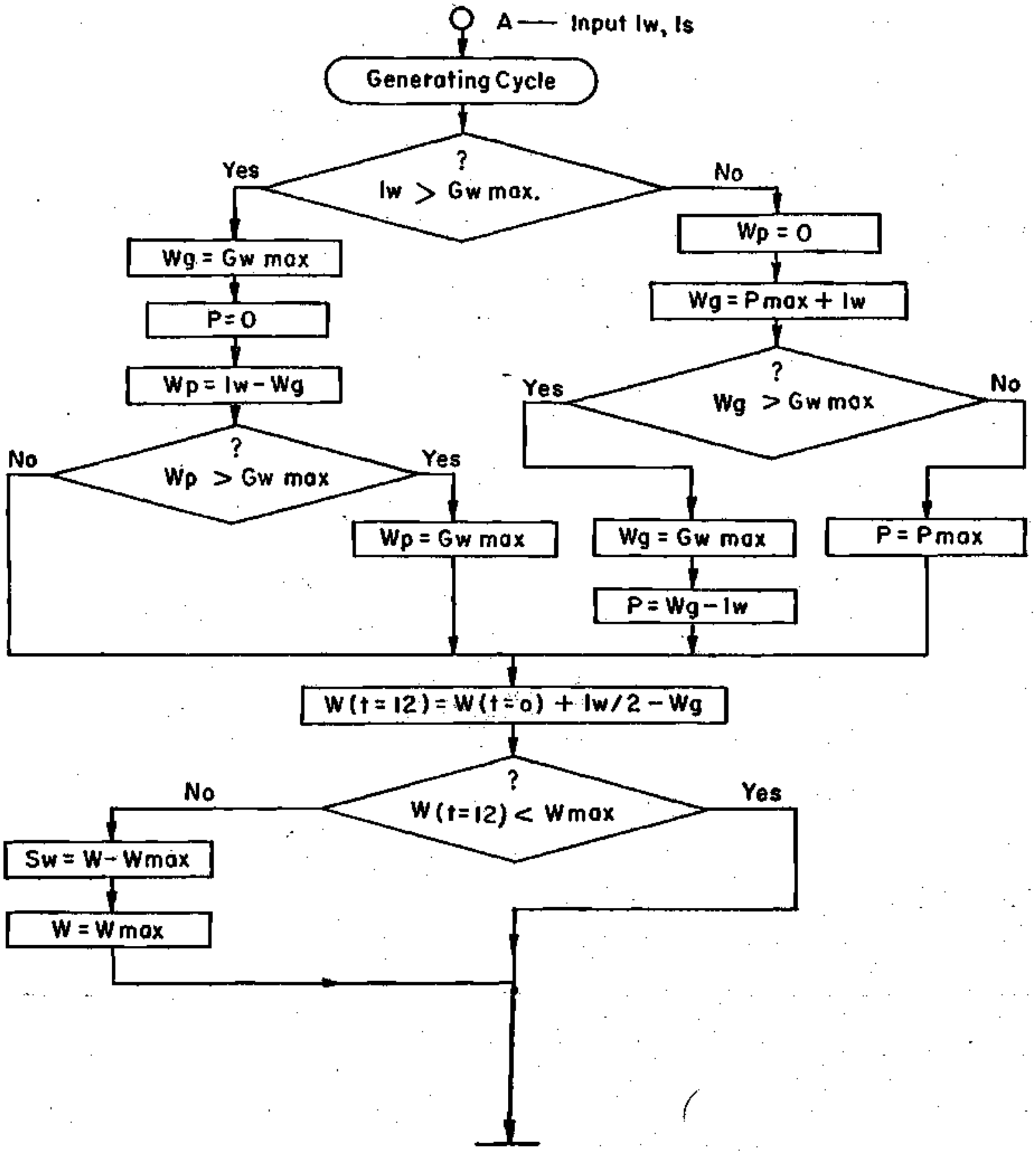

Figure 12. Flow Diagram for Wallace I, Sheet I

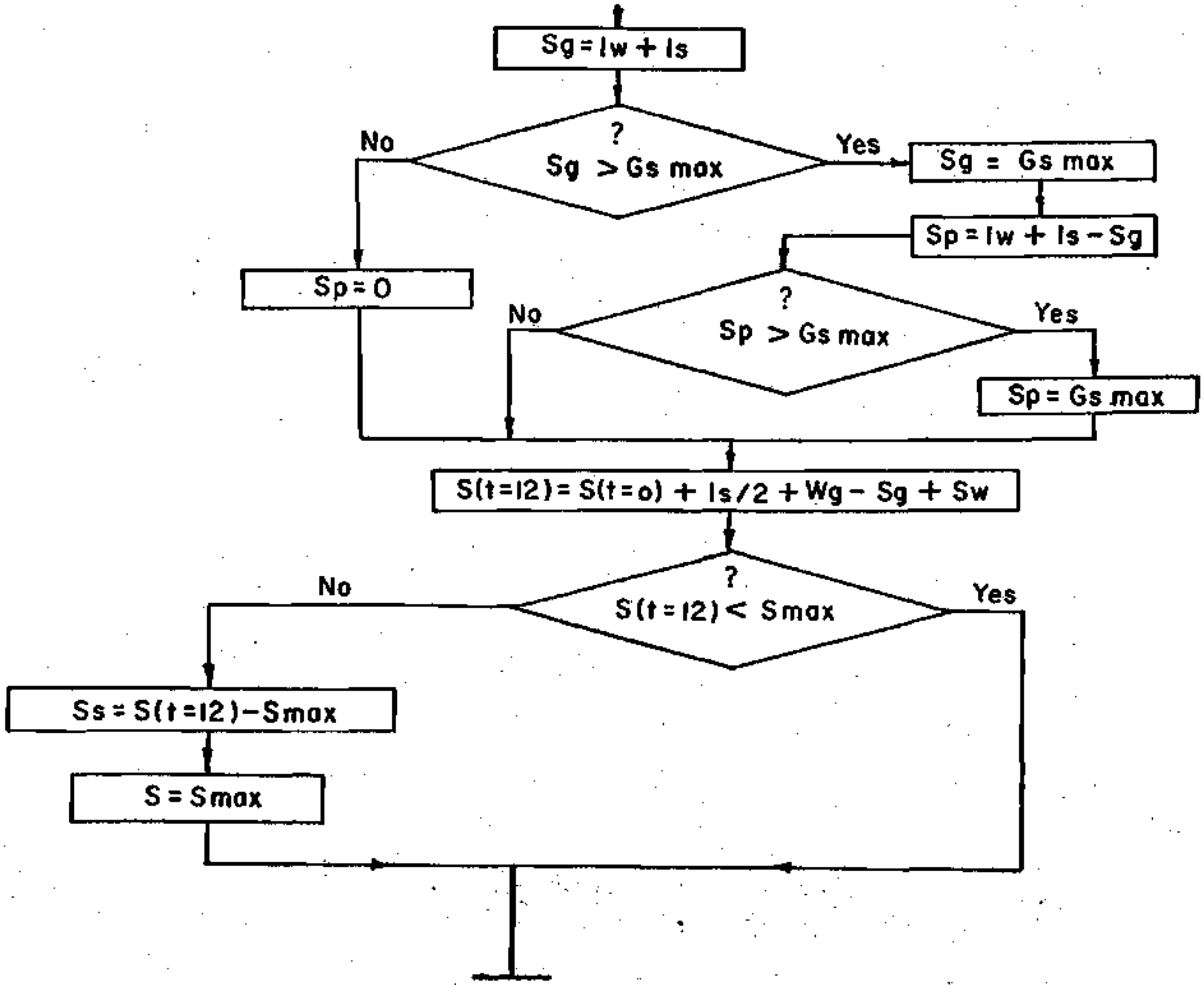

Figure 12. Flow Diagram for Wallace 2, Sheet 2

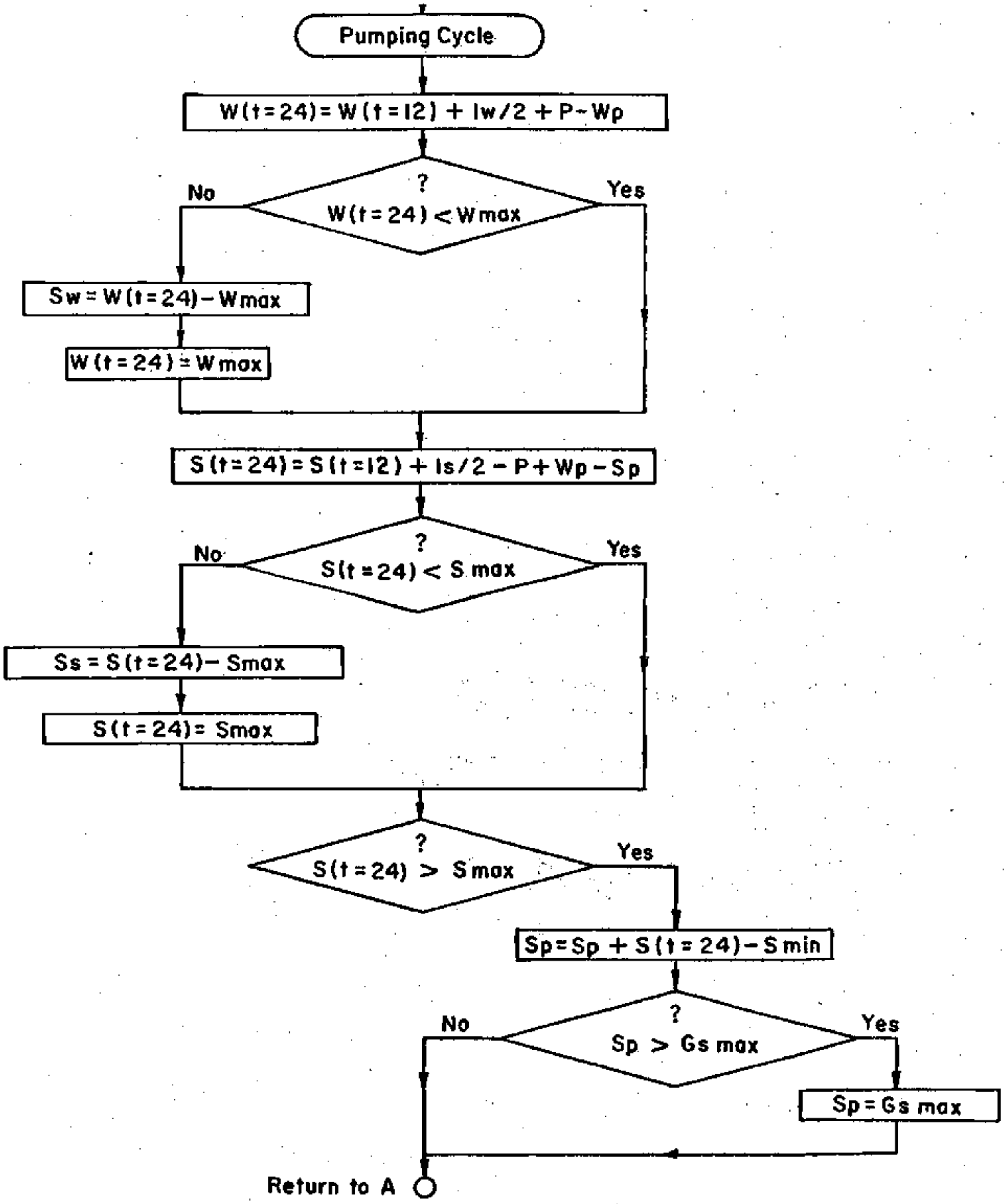

Figure 12. Flow Diagram for Wallace I, Sheet 3

During the twelve hour generating cycle the natural inflow into the two reservoirs are as follows:

Natural Inflow to W = Iw/2 = 1980 acre feet

Natural Inflow to S = Is/2 = 1435 acre feet

The program next tests to determine if Iw exceeds Gwmax. For Case 1), it does not, therefore Wg is set at 20,760 acre feet, Wp is set at zero, and the pumping volume P to be pumped during the pumping cycle is set at Pmax or 16,800 acre feet. Next the volume of Wallace Reservoir at the end of the generating cycle is calculated as follows:

At t = 12 hours

W(t=12) = W(t=0) + Iw/2 - Wg

W(t=12) = 470,000 + 1,980 - 20,760

W(t=12) = 451,220 acre feet

Since the volume in Wallace Reservoir is less than Wmax, no spillage occurs.

Next the operation of Sinclair Dam is simulated. The generation at Sinclair Dam is set at the total inflow above Sinclair Dam. In this case, more than twelve hours are required to pass the total inflow of 6930 acre feet. The generation at Sinclair Dam during the generating cycle, Sg, is therefore set at Gsmax, 6732 acre feet. The remaining inflow is stored in the reservoir and passed through the turbines during the pumping cycle which follows. The total inflow into Sinclair Dam during the generating cycle is calculated as follows:

Inflow to S = Is/2 + Wg = 1435 + 20,760

Inflow to S = 22,195 acre feet

The storage in Sinclair Reservoir at the end of the generating cycle is calculated as follows:

At t = 12

S(t=12) = S(t=0) + Inflow - Sg

S(t=12) = 308,750 + 22,195 - 6732

S(t=12) = 324,263 acre feet

Since the volume in Sinclair Reservoir is less than Smax, no spillage occurs.

Pumping Cycle - Next the program simulates the pumping cycle. The natural inflow into the two reservoirs is equal to Iw/2 and Is/2 or 1,980 acre feet and 1,435 acre feet respectively. As determined previously, the pumping volume to be pumped from Sinclair Reservoir back into Wallace Reservoir is set at Pmax or 16,800 acre feet. The volume in Wallace Reservoir at the end of the pumping cycle is calculated as follows:

At t = 24 or t = 0 for next day operation

W(t=24) = W(t=12) + Iw/2 + P - Wp

W(t=24) = 451,220 + 1,980 + 16,800

W(t=24) = 470,000 acre feet

Therefore Wallace Reservoir is restored to its maximum level as desired. Next the operation at Sinclair Dam is simulated. During the pumping cycle the portion of the designated generation volume at Sinclair Dam that could not be passed during the generating cycle is used for generation. The volume of that generation Sp is calculated as follows:

Sp = I total - Sg

$Sp = 6930 - 6732$

$Sp = 198$ acre feet

The volume in Sinclair Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 for next day operation

$S(t=24) = S(t=12) + Is/2 - P - Sp + Wp$

$S(t=24) = 325{,}263 + 1485 - 16{,}800 - 198 + 0$

$S(t=24) = 308{,}750$ acre feet

Sinclair Reservoir is restored to its minimum level for the next day of operation.

Intermediate Stream Flow Condition

In Case (2) Iw is equal to 39,600 acre feet/day; Is is equal to 19,800 acre feet/day for a total inflow, I total, of 59,400 acre feet/day. Again the initial reservoir conditions are assumed as follows:

$W = Wmax = 470{,}000$ acre feet

$S = Smin = 308{,}750$ acre feet

Generating Cycle - At the start of the generating cycle, the program tests to determine if Iw exceeds Gwmax. Since it does not, the generation at Wallace Dam is again set as follows:

$Wg = Pmax + Iw$

$Wg = 16{,}800 + 39{,}600$

$Wg = 56{,}400$ acre feet

The program then tests to see if Wg exceeds Gwmax for twelve hours or 46,600 acre feet. Since it does, Wg is set equal to Gwmax, 46,600 acre feet, Wp is set equal to zero, and the pumping volume to be returned to Wallace Reservoir during the next pumping cycle must be reduced by the excess to avoid spillage at Wallace Dam. The volume of pumping required to restore Wallace Reservoir to full pond at the end of the pumping cycle is calculated as follows:

$$\text{Wmax} = \text{Wmax} + \underset{\text{Generating Cycle}}{(\text{Iw}/2 - \text{Gwmax})} + \underset{\text{Pumping Cycle}}{(\text{Iw}/2 + \text{P})}$$

$$\text{P} = \text{Gwmax} - \text{Iw}$$

$$\text{P} = 46{,}600 - 39{,}600$$

$$\text{P} = 7000 \text{ acre feet}$$

The volume in Wallace Reservoir at the end of the generating cycle is then calculated as follows:

At $t=12$

$$W(t=12) = W(t=0) + \text{Iw}/2 - \text{Wg}$$

$$W(t=12) = 470{,}000 + 19{,}800 - 46{,}600$$

$$W(t=12) = 443{,}200 \text{ acre feet}$$

Since W is less than Wmax, no spillage occurs. The total inflow above Sinclair Dam of 59,400 acre feet exceeds the volume the Sinclair turbines can pass in twenty-four hours. Therefore the Sinclair turbines are operated at a maximum in both the generating and pumping cycle (Sg = Sp = Gsmax). The volume of the Sinclair Reservoir at the end of the generating cycle is then calculated as follows:

At $t = 12$

$$S(t=12) = S(t=0) + \text{Is}/2 + \text{Wg} - \text{Sg}$$

$$S(t=12) = 308{,}750 + 9{,}900 - 46{,}600 - 6732$$

$$S(t=12) = 358{,}518 \text{ acre feet}$$

Since S exceeds Smax, spillage occurs during the generating cycle which is calculated as follows:

At $t = 12$

$Ss = S - Smax$

$Ss = 358{,}518 - 334{,}000$

$Ss = 24{,}518$ acre feet

The volume in Sinclair Reservoir at the end of the generating cycle remains at Smax or 334,000 acre feet.

Pumping Cycle - The program next simulates the pumping cycle. The volume to be pumped has been determined previously to be equal to 7000 acre feet. The volume of Wallace Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 for next day of operation

$W(t=24) = W(t=12) + Iw/2 + P - Wp$

$W(t=24) = 443{,}200 + 19{,}800 + 7000 - 0$

$W(t=24) = 470{,}000$ acre feet

Therefore Wallace Reservoir is restored to Wmax at the end of the day. The volume in Sinclair Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 next day of operation

$S(t=24) = S(t=12) + Is/2 - P - Sp + Wp$

$S(t=24) = 334{,}000 + 9{,}900 - 7{,}000 - 6{,}732 + 0$

$S(t=24) = 330{,}168$ acre feet

Therefore, Sinclair Reservoir is left at a level higher than desired, the desired elevation being Smin. During the following days of operation, the generation is increased to a maximum of Gsmax until the level in Sinclair at the end of the day is restored to Smin.

High Stream Flow Condition

During Case (3), Iw is equal to 59,400 acre feet; Is is equal to 29,700 acre feet for a total inflow, I total, of 89,100 acre feet. The initial reservoir conditions are again assumed as follows:

W - Wmax = 470,000 acre feet

S = Smin = 308,750 acre feet

Generating Cycle - At the start of the generating cycle, the program tests to determine if Iw exceeds Gwmax for twleve hours. Since it does the Wallace turbines must be operated longer than twelve hours to pass the inflow, Iw. Therefore no pumping is required during the pumping cycle since no decrease in storage would occur during the day. Generation during the generating cycle, Wg, is set at Gwmax.

The volume in Wallace Reservoir at the end of the generating cycle is calculated as follows:

At t=12

W(t=12) = W(t=0) + Iw/2 - Wg

W(t=12) = 470,000 + 29,700 - 46,600

W(t=12) = 453,100 acre feet

Therefore since W is less than Wmax, no spillage occurs during the generating cycle. The program then simulates the operation of Sinclair Dam. The generation at Sinclair Dam will again be set at the maximum for twenty-four hours since I total exceeds Gsmax (Sg = Sp = Gsmax). The volume in Sinclair Reservoir at the end of the generating cycle is calculated as follows:

At t=12

S(t=12) = S(t=0) + Is/2 + Wg - Sg

$S(t=12) = 308{,}750 + 14{,}850 + 46{,}600 - 6732$

$S(t=12) = 363{,}468$

Therefore S exceeds Smax and spillage occurs during the generating cycle. The spillage is calculated as follows:

For $t = 0$ to $t = 12$

$Ss = S(t=12) - Smax$

$Ss = 363{,}468 - 334{,}000$

$Ss = 29{,}468$ acre feet

The volume in Sinclair Reservoir remains at Smax or 334,000 acre feet because of the spillage.

Pumping Cycle - Next the program simulates the pumping cycle. As explained, the Wallace turbines must be operated during the pumping cycle to prevent spilling. No pumping is needed. The generation required during the pumping cycle to prevent spillage, Wp, is calculated as follows:

$Wp = Iw - Wg$

$Wp = 59{,}400 - 46{,}600$

$Wp = 12{,}800$ acre feet

The volume in Wallace Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 for the next day of operation

$W(t=24) = W(t=12) - Iw/2 - Wp + P$

$W(t=24) = 453{,}100 + 29{,}700 - 12{,}800 + 0$

$W(t=24) = 470{,}000$ acre feet

Therefore the volume in Wallace Reservoir is restored to the desired maximum. The volume in Sinclair Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 for the next day of operation

$S(t=24) = S(t=12) + Is/2 + Wp - P - Sp$

$S(t=24) = 334{,}000 + 14{,}850 + 12{,}800 - 0 - 6732$

$S(t=24) = 354{,}918$ acre feet

Again S exceeds Smax and spillage occurs during the pumping cycle also.

For t=12 to t=24

$Ss = S(t=24) - Smax$

$Ss = 354{,}912 - 334{,}000$

$Ss = 20{,}912$

The total spillage during the day is the sum of the spillage during the generating and pumping cycles.

The volume in Sinclair Reservoir at the end of the day is 334,000 acre feet or Smax which is greater than Smin, the desired volume. Operation of the Sinclair turbines would be increased during subsequent days until the desired minimum level was achieved.

For flows in excess of those illustrated in Case (3), the generation at Wallace Dam during the pumping cycle, Wp, is increased to a maximum of Gwmax. Beyond this point, spillage occurs at Wallace Dam.

Wallace 1 in summary provides for the maximum possible generation at Wallace Dam. The generation at Wallace Dam is set at the sum of Pmax and Iw. If this sum exceeds the maximum generation capacity of Wallace Dam for twelve hours, the pumping required during the pumping cycle to restore Wallace Reservoir to full pond can be reduced by the excess. For inflows into Wallace Reservoir in excess of 46,600 acre feet, no pumping is required and generation at Wallace Dam is necessary during the pumping cycle to avoid spillage. The generation at Sinclair Dam is set at the total inflow into the system. When the inflow exceeds the capacity of Sinclair Dam during the generating cycle, generation is necessary at Sinclair Dam during the pumping cycle to avoid spillage.

Operational Model Wallace 2

The second model, Wallace 2, was used to investigate the effects of minimizing the pumping required at Wallace Dam, thus minimizing the cost of operating Wallace Dam. In Wallace 1, generation was generally set equal to the total volume of inflow plus the maximum volume which could be restored in eight hours during the pumping cycle. The installed power capacity for Wallace Dam is designed to meet a minimum five hour peak load during the peak demand period. In Wallace 2, the generation at Wallace Dam is restricted to this five hour operation. The volume required by this generation is 16,800 acre feet which is equal to the maximum daily eight hour pumping volume. Therefore, Wallace Dam is designed to meet this minimum five hour operation with no local inflow. In Wallace 2, the local inflow is stored in Wallace Reservoir which reduces the volume of pumping required to restore Wallace Reservoir to full pond for the next day's operation. When the local inflow exceeds 16,800 acre feet, no pumping is required and the excess can be allocated to increased generation at Wallace Dam. A flow diagram for Wallace 2 is included for reference in Figure 13. The

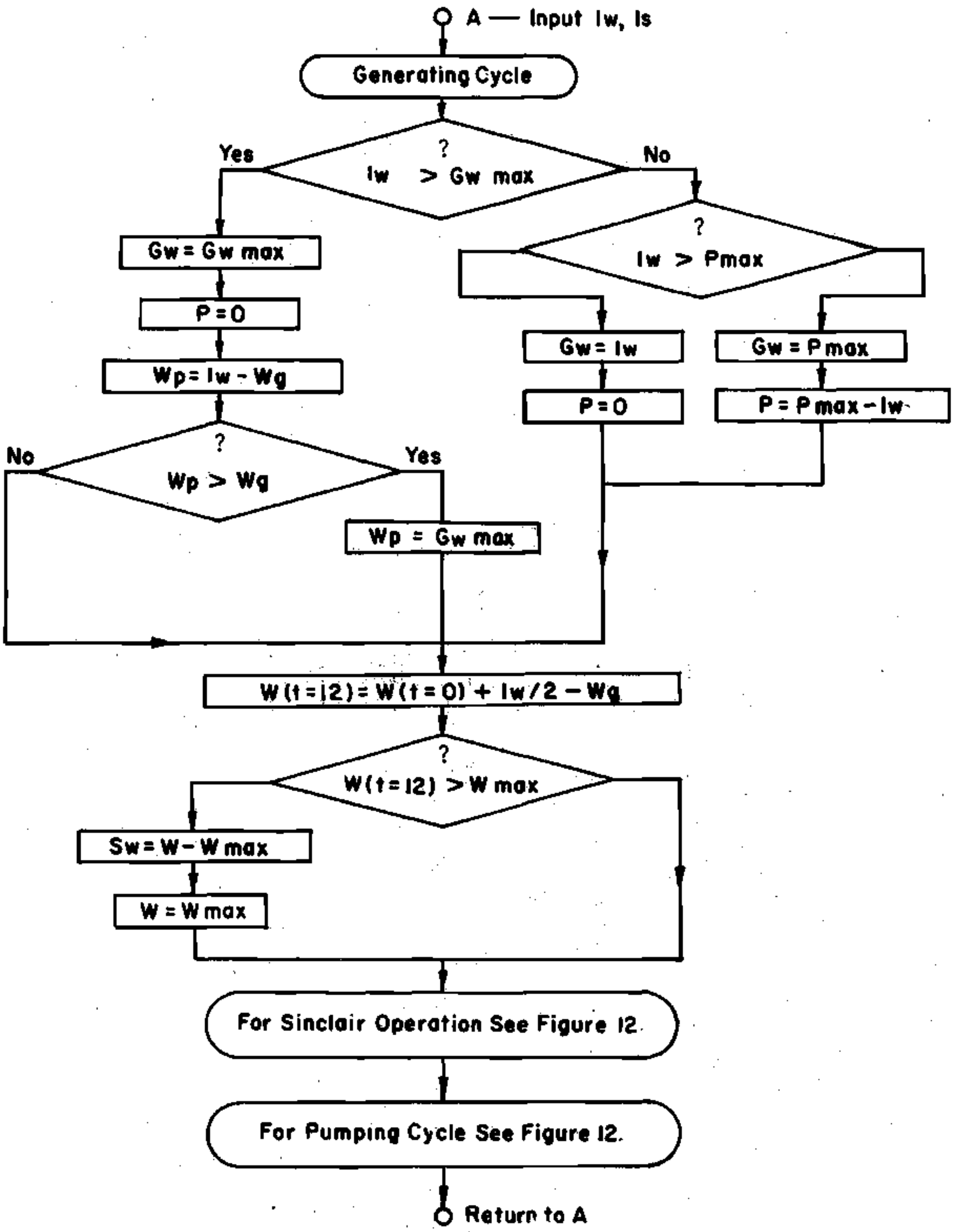

Figure 13. Flow Diagram - Wallace 2

operating rules for Wallace 2 are illustrated for the three stream flow cases in the following section.

Low Stream Flow Condition

The inflow into the reservoirs and initial reservoir conditions, as illustrated for Wallace 1, are restated below.

Iw = 3960 acre feet/day

Is = 2970 acre feet/day

I total - 6930 acre feet/day

W = Wmax = 470,000 acre feet

S = Smin = 308,750 acre feet

Generating Cycle - At the start of the generating cycle, the program tests to determine whether Iw exceeds Gwmax. In this case, it does not. Next the program tests to determine whether Iw exceeds Pmax. In this case it does not and Wg is set at Pmax or 16,800 acre feet and Wp is set at zero. The pumping required during the pumping cycle to restore W to Wmax is reduced by Iw as follows:

P = Pmax - Iw

P = 16,800 - 3960

P = 12,840 acre feet

The volume in Wallace Reservoir at the end of the generating cycle is calculated as follows:

At t=12

W(t=12) = W(t=0) + Iw/2 - Wg

W(t=12) = 470,000 + 1,980 - 16,800

W(t=12) = 455,180 acre feet

Next the generation at Sinclair Dam is simulated. The generation at

Sinclair Dam is identical to that for Wallace 1. For Case (1), Sg is set at the maximum of 6732 acre feet and Sp is set at 198 acre feet during the pumping cycle. The volume in Sinclair Reservoir at the end of the generating cycle is calculated as follows:

At t=12

S(t=12) = S(t=0) + Is/2 + Wg - Sg

S(t=12) = 308,750 + 1485 + 16,800 - 6732

S(t=12) = 320,303 acre feet

Pumping Cycle - Next the pumping cycle is simulated. The required pumping is equal to 12,840 acre feet determined previously. The volume in the Wallace Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 for the next day of operation

W (t=24) = W(t=12) + Iw/2 + P - Wp

W (t=24) = 455,180 + 1,980 + 12,840 - 0

W (t=24) = 470,000 acre feet

The volume in Wallace Reservoir is restored to the desired maximum. The volume in Sinclair Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 for the next day of operation

S(t=24) = S(t=12) + Is/2 - P - Sp + Wp

S(t=24) = 320,303 + 1,485 - 12,840 - 198 + 0

S(t=24) = 308,750 acre feet

Therefore at the end of the day, the volume in Wallace Reservoir is restored to Wmax and the volume in Sinclair Reservoir is restored to Smin as desired.

Intermediate Stream Flow Condition

The inflow into the reservoir and the initial reservoir conditions are the same as for Case (2) as illustrated for Wallace 1 and are restated below:

Iw = 39,000 acre feet/day

Is = 19,800 acre feet/day

I Total = 59,400 acre feet/day

W = Wmax = 470,000 acre feet

S = Smin = 308,750 acre feet

Generating Cycle - At the start of the generating cycle, the program tests to determine whether Iw exceeds Gwmax. In this case, it does not. Next the program tests to determine if Iw exceeds Pmax. In this case it does, and Wg is determined as follows:

Wg = 16,800 acre feet + Excess inflow over 16,800 acre feet

Wg = 16,800 acre feet + (Iw - 16,800)

Wg = Iw

No pumping is required during the pumping cycle and Wp is set equal to zero. The volume in Wallace Reservoir at the end of the generating cycle is calculated as follows:

At t=12

W(t=12) = W(t=0) + Iw/2 - Wg

W(t=12) = 470,000 + 19,800 - 39,600

W(t=12) = 450,200 acre feet

The program next simulates the generation at Sinclair Dam. The generation is set at the maximum generation for both the generating and pumping cycle as in Wallace 1 (Sg = Sp = Gsmax). The volume in Sinclair Reservoir at the end of the generating cycle is calculated as follows:

At t=12

S(t=12) = S(t=0) + Is/2 + Wg - Sg

S(t=12) = 308,750 + 9,900 + 39,600 - 6732

S(t=12) = 351,518 acre feet

Therefore, since S exceeds Smax, spillage occurs during the generating cycle which is calculated as follows:

For t = 0 to t = 12

Ss = S(t=12) -Smax

Ss = 351,518 - 334,000

Ss = 17,518 acre feet

The volume in Sinclair Reservoir remains at Smax or 334,000 acre feet.

Pumping Cycle - The program next simulates the pumping cycle. The volume in Wallace Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 for the next day of operation

W(t=24) = (W(t=12) + Iw/2 + P - Wp

W(t=24) = 450,200 + 19,800 + 0 - 0

W(t=24) = 470,000 acre feet

The volume in Wallace Reservoir is restored to the desired maximum. The volume in Sinclair Reservoir at the end of the pumping cycle is calculated as follows:

At t=24 or t=0 for next day of operation

S(t=24) = S(t=12) + Is/2 - P - Gs + Wp

$S(t=24) = 334{,}000 + 9{,}900 - 0 - 6732 + 0$

$S(t=24) = 337{,}168$ acre feet

Therefore, since S exceeds Smax, spillage occurs during the pumping cycle.

For $t = 12$ to $t = 24$

$Ss = S(t=24) - Smax$

$Ss = 337{,}168 - 334{,}000$

$Ss = 3{,}168$ acre feet

The total spillage during the day is the sum of the spillage during the generating and pumping cycles for a total of 20,686 acre feet. The volume in Sinclair Reservoir would remain at 334,000 acre feet, Smax.

As in Wallace 1, the operation of the Sinclair turbines would be increased during subsequent days until the desired minimum level was achieved.

As can be seen by comparing the spillage for Wallace 1 and for Wallace 2, the operating rules for Wallace 2 reduced the total spillage at Sinclair Dam.

High Stream Flow Condition

During the high stream flow condition, there is no change in the operation of the two projects. Wallace and Sinclair are operated at the maximum capacity to avoid spillage.

In summary of Wallace 2, the projects are operated to minimize the required pumping. For low flow conditions, this was accomplished by storing the inflow into Wallace Reservoir and reducing the required pumping P by Iw. This procedure was continued until the pumping required (Pmax - Iw) was reduced to zero. After this point, the generation was set at Iw and no pumping was required.

Operational Models Wallace 3, Wallace 4, Wallace 5

The two previous models were investigated to establish the maximum range of possible operation. By analyzing the net revenue possible from each model, the best set of operating rules or a combination of the two sets of operating rules could be selected. The following four models were investigated to determine the effect of relaxing one or more of the constraints which are placed on Wallace 1 and Wallace 2, listed in Table 3. The first of these models investigated the effect of operating Wallace Reservoir on an operating rule curve to decrease spillage at Wallace Dam and increase the generation.

Operational Model Wallace 3

The purpose of operating on an operating rule curve is to decrease spillage. By operating the reservoir at lower levels during the wet seasons, a flood storage pool is created in the reservoir. This may decrease spillage, but the generation during the wet seasons would be at a decreased head. Therefore, the maximum capacity during the wet season is reduced. To be economical, the increased generation gained by decreasing spillage must exceed the loss in capacity. The operating rule curve investigated in Wallace 3 is shown in Figure 14. The reservoir is operated at full pond at Elevation 435 feet during the summer. The drawdown of the reservoir would begin on the first day of October and the minimum pool of Elevation 430 feet would be reached on the last day of November. The reservoir would be operated at this lower level during the winter and spring and refilling would begin on the first day of March with a full pond reached on the last day of April.

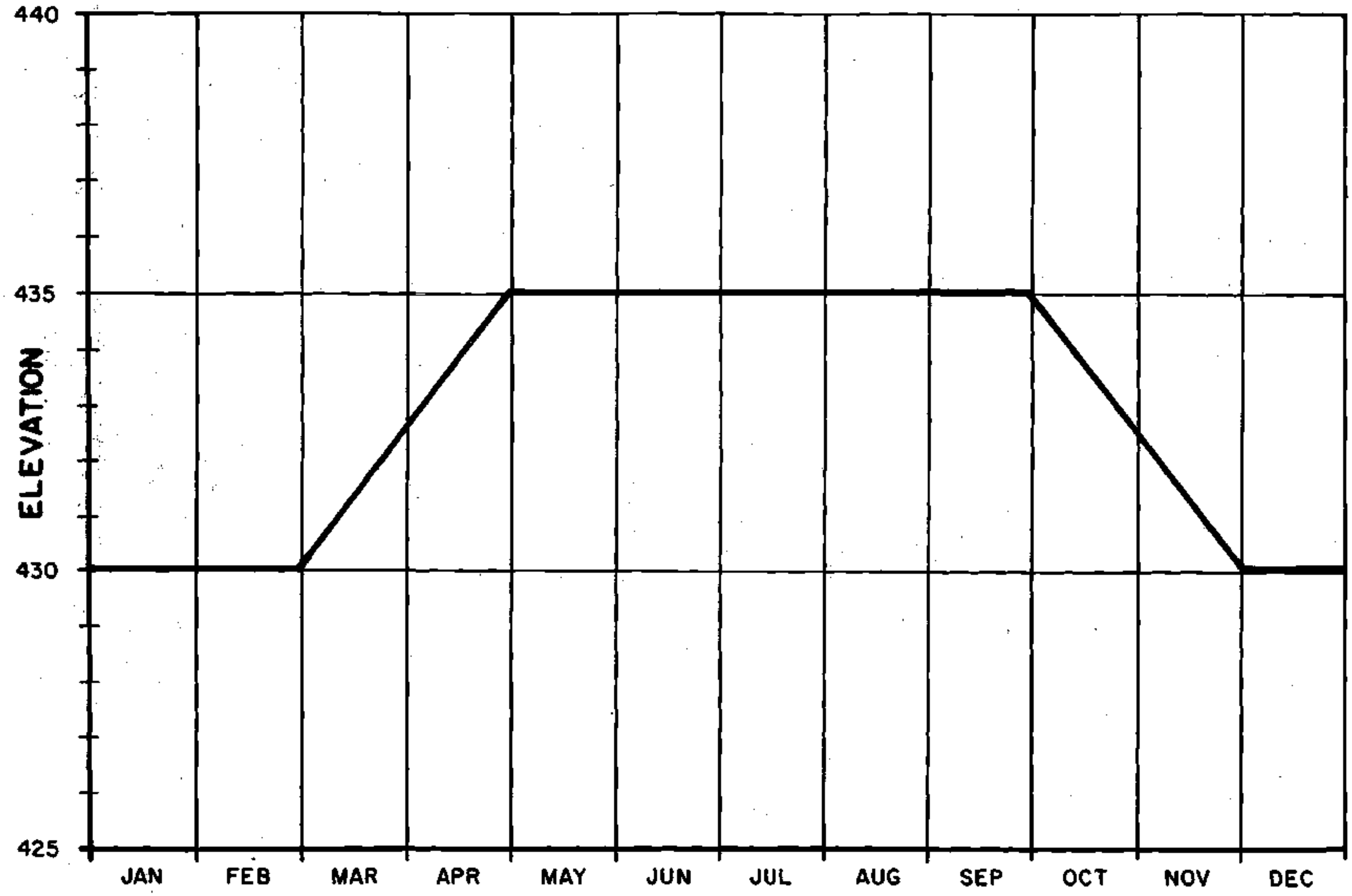

Figure 14. Operating Rule Curve - Wallace Dam

The reservoir would be operated at full pond until the first day of October.

Two simulations were run with Wallace 3, one using the operating rules described in Wallace 1, and the other using the operating rules described in Wallace 2. The two simulations were made for two reasons. First, the effect of the operating rule curve could be determined for both of the operating extremes. Secondly, the two simulations were used to determine the seasonal generation at Wallace Dam for use in evaluating the objective function. The demand for electricity is greatest during the summer and winter and a minimum during the spring and fall. The operating rule curve changes effectively divide the year into these periods. Therefore, the two simulations for Wallace 3 were used to determine the proportion of the generation at Wallace Dam which occurred during the high and low demand periods.

The next two operation models investigated relaxation of constraints which would require physical modifications at Sinclair Dam. The simulations in these cases would be used to determine the feasibility of making the required modifications. Wallace 4 investigated the effects of increasing the maximum reservoir elevation at Sinclair Dam. Increases in the maximum reservoir elevation of 2.5 feet, 5 feet, and 7.5 feet were investigated. Wallace 5 investigated the effects of adding additional generating capacity at Sinclair Dam, thus increasing the maximum hydraulic capacity of the turbines.

<u>Operational Model Wallace 4</u>

By increasing the maximum reservoir elevation, a flood storage pool would be created in Sinclair Reservoir. The additional flood storage would decrease the spillage at Sinclair Dam and thus increase the generation. The added benefit of the increased generation would be balanced by the cost of the modifications. Three alternative reservoir levels were investigated to establish a range of benefits. The results of the simulations, in conjunction with the cost estimates of the modifications could be used to analyze the economics of the additions.

Operational Model Wallace 5

By increasing the hydraulic capacity at Sinclair Dam by adding additional generating capacity, the spillage at the plant could be reduced. The maximum generating capacity which can be installed at a hydroelectric site is dependent on the stream flow and the shape of the power load curve. Since the duration of the peak demand is approximately five to six hours, the redeveloped project should be capable of operating for a minimum of five hours.

Currently Sinclair Dam operates an average of approximately eight hours per day. The average volume passed through the turbines can be calculated as follows:

$$Gs = 6800 \frac{\text{cubic feet}}{\text{second}} \times 8.16 \text{ hours} \times 3600 \frac{\text{seconds}}{\text{hour}} \div 43{,}560 \frac{\text{square feet}}{\text{acre}}$$

$$Gs = 4885 \text{ acre feet/day}$$

If this volume were passed through the turbines in five hours, the following turbine discharge would be required.

$$Q \text{ turbines} = \frac{4585 \text{ acre feet}}{5 \text{ hours}} \times \frac{43{,}560 \text{ square feet}}{\text{acre}} / 3600 \text{ seconds/hour}$$

$$Q \text{ turbines} = 11{,}100 \text{ cfs}$$

The current hydraulic capacity of the two existing turbines is 6800 cfs. The addition of one other unit equivalent in size to the existing units would increase the hydraulic capacity to 10,200 cfs. For simplicity and to facilitate the calculation of cost estimates for the new genrating capacity, a three unit power plant was analyzed. The addition would require a new section of intake, penstocks, powerhouse, generator, draft tube and other power related equipment. To be economical, the increased generation must offset the added capital expenditures. An economic analysis of the addition would have to be made. The simulation would provide the data needed to estimate the benefits of an addition.

CHAPTER V

RESULTS

The purpose of the study to this point was a determination of the set of operating decisions which would result in the maximum net revenue from the Wallace Dam and Sinclair Dam Projects. In this chapter the results of the simulations run for each of the sets of operating decisions will be discussed and analyzed. In each case, the model was used to simulate the system for the period 1904 through 1932 and 1938 through 1971.

Evaluation Of Model Wallace 1

The objective of Wallace 1 was the maximization of the generation at Wallace Dam. The results of the simulation for the period of record are summarized below.

	Total for Period (10^6 acre feet)	Average/Year (10^6 acre feet)
Sinclair Generation, Gs	127.304	1.989
Wallace Generation		
Summer and Winter, Gsw	330.404	5.163
Fall and Spring, Gfs	170.260	2.660
Pumping Volume	390.869	6.107
Sinclair Spillage	30.450	-
Wallace Spillage	0.177	-

The objective function was evaluated using the average values obtained for the Sinclair and Wallace generation and pumping. The net annual revenue which would be obtained by operating the system to maximize the Wallace generation is calculated below.

$$R = (\$0.0272 * (81.67*Gsw) + \$0.0087 * (83.36 * Gs + 81.67 * Gfs) - \$0.010 * 114.34 * P$$

$$R = \$11,468,300 + \$3,332,500 - \$6,982,700$$

$$R = \$7,818,100$$

The results of this simulation were then used as a base for evaluating the effects of changing the operating procedure and constraints.

Evaluation Of Model Wallace 2

The objective of Wallace 2 was the minimization of the pumping energy required. This operation would minimize the total cost of operating Wallace Dam. This reduction in the pumping costs would be achieved by the loss of generation from the natural stream flow into Wallace Dam which was used to reduce the required pumping. The results of the simulation of the system using Wallace 2 are summarized below.

	Total for Period (10^6 acre feet)	Average (10^6 acre feet)
Sinclair Generation, Gs	129.800	2.028
Wallace Generation		
Summer and Winter, Gsw	264.592	4.134
Fall and Summer, Gfs	138.809	2.169
Pumping Volume	293.605	4.588
Sinclair Spillage	27.942	-
Wallace Spillage	0.177	-

The change in the operating procedures resulted in a reduction in the spillage at Sinclair Dam. The spillage was reduced from a total of 30,450,000 acre feet using Wallace 1 to a total of 27,942,000 acre feet. The generation at Sinclair Dam was increased by the reduction in the spillage. The pumping volume was reduced from an average of 6,107,000 acre feet/year using Wallace 1 to an average of 4,588,000 acre feet/year.

To determine the economic effect of the changes in the operation, the objective function was evaluated using the average values obtained for the Wallace and Sinclair generation and pumping. The net revenue, obtained using Wallace 2, is calculated below.

$$R = (0.0272 * (81.67*Gsw) + 0.0087 * (83.36 * Gs + 81.67 * Gfs)) - 0.010 * 114.34 * P$$

$$R = \$9,183,400 + \$3,011,900 - \$5,245,900$$

$$R = \$6,949,400$$

Thus by minimizing the pumping volume required, a decrease in the net revenue would be achieved. The better operation would involve maximizing the Wallace Dam generation.

Evaluation Of Model Wallace 3

Having determined the most economical way to operate the system, the effects of relaxing the constraints were analyzed. Wallace 3 investigated the effect of creating a flood storage pool in Wallace Reservoir during the high stream flow periods. This would be achieved by operating Wallace Dam on an operating rule curve. The projects were operated to maximize the Wallace generation using Wallace 1. The results of the simulation of the system for the period of record are summarized below.

	Total Period (10^6 acre feet)	Average (10^6 acre feet)
Sinclair Generation, Gs	132.159	2.065
Wallace Generation		
Summer and Winter, Gsw	330.428	5.1629
Fall and Spring, Gfs	170.260	2.660
Pumping Volume	390.869	6.107
Sinclair Spillage	25.854	-
Wallace Spillage	0.152	-

In addition to a reduction of spillage at Wallace Dam, a reduction was also achieved at Sinclair Dam. The reduction of spillage at Wallace and Sinclair Dams resulted in increases in the generation of the two projects. However, the reduction at Wallace Dam would be achieved by a reduction in head during the high stream flow periods. This reduction in head represents a reduction in capacity. Therefore a value for the constant C had to be evaluated for the different values of head.

The Wallace Reservoir would be oeprated at two levels. During the summer period, the maximum reservoir level would be maintained at elevation 435 feet. During the winter the maximum reservoir level would be maintained at elevation 430 feet. Therefore during the spring, when the reservoir is filled, and during the fall, when the reservoir is drawn down, the level in the reservoir would be between the maximum and minimum values. A break down of the average Wallace generation according to the reservoir elevation maintained is shown below.

	@ 435'	Average @ 432.5	@ 430
Wallace Generation, Gw/year (10^6 acre feet)	3.0367	2.6603	2.1263

The capacity at Wallace Dam when operated at the reduced reservoir elevation is a function of the flow through the turbines, the head, and the efficiency of the units. Based on model tests on the Wallace Dam turbines, the values for the efficiency and flow through the turbines do not vary significantly for the small head ranges experienced.

The capacity at the reduced head is based on Equation (2).

$$KW = \frac{Q\ H\ e}{11.8} \qquad (2)$$

The capacity at a reservoir level of 432.5 feet, Plant Datum was calculated to be 314,900 KW. The capacity at a reservoir level of 430 feet, Plant Datum would be 305,800 KW. The corresponding values for the constant C in the objective function are as follows:

	C
Reservoir @ El. 432.5	79.38
Reservoir @ El. 430.0	77.09

To determine the economic effect of operating Wallace Dam on an operating rule curve to reduce spillage, the objective function was evaluated assuming different C values for each head condition.

$$R = (\$0.0272*((81.67*3.0367*\text{x}10^6 + 77.09*2.1263\text{x}10^6))$$

$$+0.0087*(83.36*2.065\text{x}10^6 + 79.38*2.6603)$$

$$-0.010*114.34*6.107$$

$$R = \$11,204,300 + \$3,334,800 - \$6,982,700$$

$$R = \$7,556,400$$

Since this net revenue is less than for Wallace 1, the reduction in the spillage at Wallace Dam was not sufficient to justify operating Wallace Dam on an operating rule curve.

Effect Of Increasing Sinclair Reservoir Storage, Wallace 4

The next model, Wallace 4, investigated the effect of creating a flood storage pool in Sinclair Reservoir to reduce the spillage at that project. Increases of 2.5 feet, 5.0 feet, and 7.5 feet in the maximum reservoir elevation were analyzed. The increases would result in flood storage pools of 30,000 acre feet, 84,000 acre feet, and 130,000 acre feet respectively. The projects were operated using the operating rules established for Wallace 1. The results of the simulations are listed below. Included are the net revenue and net benefit of increasing the flood storage.

	Total Period (10^6 acre feet)	Average (10^6 acre feet)
Sinclair Generation		
Increase to 342.5	134.430	2.100
Increase to 345.0	140.475	2.195
Increase to 347.5	143.359	2.240
Wallace Generation		
Summer and Winter, Gsw	330.404	5.1626
Fall and Spring, Gfs	170.260	2.660
Pumping Volume	390.869	6.107
Sinclair Spillage		
Increase to 342.5	23.312	-
Increase to 345.0	17.267	-
Increase to 347.5	14.383	-

Wallace Spillage	0.177	-
Net Revenue/Benefit		Annual Benefit
Increase to 342.5	$7,898,300	$ 80,494
Increase to 345.0	$7,967,490	$149,390
Increase to 347.5	$8,000,123	$182,023

The net benefits are plotted for the three flood storage levels evaluated in Figure 15. The plot shows that the maximum rate of increase in incremental benefits was obtained by increasing the reservoir level from Elevation 340.0 to Elevation 342.5. Decreasing marginal benefit increases were achieved by further increases in flood storage which would require increased capital expenditures.

The evaluation of the cost of increasing the maximum reservoir elevations is not within the scope of this study. In addition to the physical changes required at Sinclair Dam, an evaluation of the effect on the recreational use of the reservoir would be required. Depending on the level of the reservoir, cabins, second homes, docks and marinas would be affected. Economic analysis of the increases would have to be made to determine the most desirable level at which to operate Sinclair Reservoir.

Feasibility Of Adding Generating Capacity At Sinclair Dam, Wallace 5

The final model, Wallace 5, investigated the effect of increasing the maximum hydraulic capacity of the Sinclair turbines by adding generating capacity. As was discussed in Chapter IV, the addition of a third generating unit was assumed. The addition would increase the total installed capacity to 67,500 KW. The constant B, in the objective function would be equal to a value of 82.61 KWH/acre feet. The system

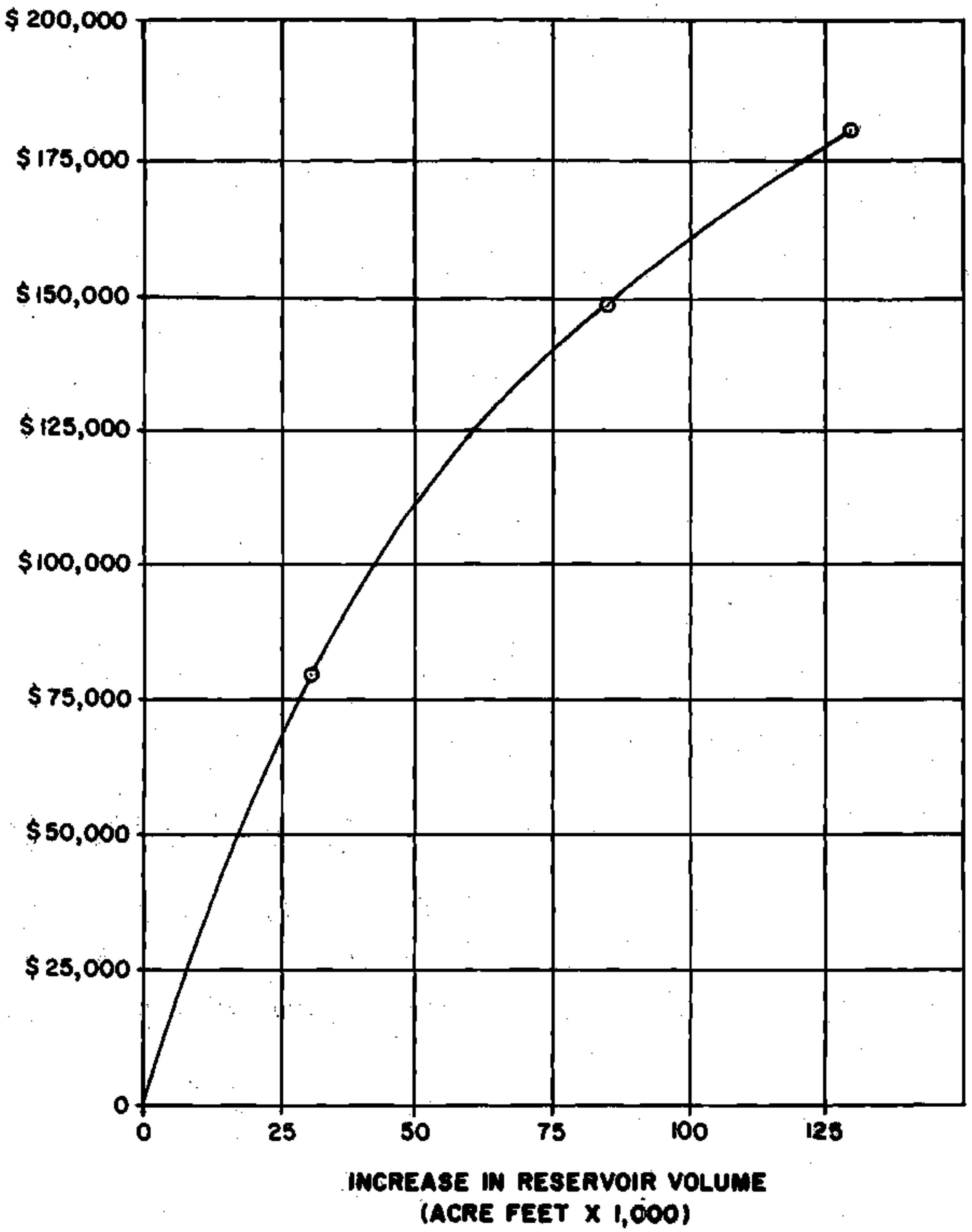

Figure 15. Annual Benefits of Sinclair Storage Increase

was simulated using the operating rules for Wallace 1 for the period of record and the increased capacity. The results of the simulation and the value of the net revenue are tabulated below.

	Total Period (10^6 acre feet)	Average (10^6 acre feet)
Sinclair Generation, Gs	137.170	2.143
Wallace Generation		
Summer and Winter, Gsw	330.404	5.1626
Fall and Spring, Gfs	170.260	2.660
Pumping Volume	390.569	6.107
Sinclair Spillage	20.658	-
Wallace Spillage	0.177	-
Net Revenue	$7,911,496/year	-
Net Annual Benefit	$ 93,396/year	-

The increased net revenue was achieved by a reduction in the spillage at Sinclair Dam. The spillage was decreased from a total of 30,450,000 acre feet determined by simulating Wallace 1 to a total of 20,658,000 acre feet. The net benefit achieved must be compared with the cost of adding the capacity. The estimate of cost is not within the scope of the study. An economic analysis would be required to determine if the capacity addition should be made; however, the small increases in net revenue would not justify a large investment of capital for capacity additions.

Summary Of Average Annual Generation

Through the simulation of the system operation for various cases of operating rules and under various constraints, the optimum set of rules was determined. The higher net revenue from Wallace 1 indicates that the system should be operated to maximize the generation at Wallace Dam.

The average annual generation at Wallace and Sinclair Dam determined from the simulation of Wallace 1 can be considered an optimum of the cases analyzed. Although increases in the generation at Sinclair Dam can be achieved through additions of flood storage capacity, economic analyses are required to determine their feasibility. The estimated average annual generation at Wallace Dam from operating under Wallace 1 is shown below. The total generation has been divided according to the portion attributable to pumped water and that attributable to natural stream flow.

Annual Generation from Pumped Water -	498,760,000 KWH
Annual Generation from Natural Stream Flow -	140,140,000 KWH
Total	638,900,000 KWH

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

It has been shown through the course of this study that the systems engineering approach of simulation is a very effective tool in the analysis of hydroelectric developments. Through the use of a model to simulate the operation of Wallace Dam and Sinclair Dam, a set of operating rules was developed that would maximize the net revenue from the two projects. This set of operating rules can form the basis for the operation of the two reservoir systems upon completion of Wallace Dam.

The operating rules proposed for operation of the two projects are summarized below:

(I) For volumes of inflow, Iw

$0 \leq Iw < 29{,}800$ acre feet (15,000 cfs for 24 hours)

Generation at Wallace Dam - $Wg = Iw + Pmax$

Pumping into Wallace Reservoir - $P = Pmax = 16{,}800$ acre feet

Generation at Sinclair Dam - $Gs = Iw+Is$ but less than Gsmax for 24 hours

(II) For volumes of inflow, Iw

29,800 acre feet $\leq Iw <$ 46,600 acre feet

Pumping into Wallace Reservoir - $P = Gwmax - Iw$

Generation at Sinclair Dam - $Gs = Iw+Is$ but less than Gsmax for 24 hours

(III) For volumes of inflow, Iw

$46{,}600$ acre feet $\leq Iw < 93{,}200$ acre feet (47,000 cfs for 24 hours)

Generation at Wallace Dam - $Wg = Iw$

Pumping into Wallace Reservoir - $P = 0$

Generation at Sinclair Dam - $Gs = Iw+Is$ but less than Gsmax for 24 hours

(IV) For volumes of inflow, Iw

$Iw \geq 93{,}200$ acre feet

Generation at Wallace Dam - $Wg = 93{,}200$ acre feet

Pumping into Wallace Reservoir - $P = 0$

Generation at Sinclair Dam - $Gs = Iw+Is$ but less than Gsmax for 24 hours

Recommendations For Future Study

Studies at other Plants

The electric utility industry is faced today with ever increasing fuel costs for fossil-fueled generating plants. Because of this fact, it is essential that all natural resources be used in the most efficient manner, including water. Therefore investigations of schemes to increase the capacity or efficiency of existing hydroelectric plants become increasingly important.

Since the completion of this study, Georgia Power Company has undertaken a reassessment of the hydroelectric projects on its system. An operation program is currently being developed to operate its Morgan Falls Project to maximize the power benefits from this project while serving to regulate flows in the Chattahoochee River between the Corps of Engineers Buford Dam and Morgan Falls to provide minimum flows in the Chattahoochee River and meet water supply contracts for Atlanta, Georgia. Plans have been made to analyze the operation of other existing projects in a similar manner. The use of simulation and techniques used in this study are expected to be an effective tool in these investigations.

Development of Operational Model

The present location of the Greensboro and Buckhead gages will be inundated by the headwaters of Lake Wallace. Additionally the larger errors experienced in the predicted flow into Wallace Dam are undesirable in the operational model by which power allocations will be determined. In the study, the errors did not make significant difference in the final results because the same synthetic record was used to analyze all conditions. However, in the development of the operational model these errors should be reduced as much as possible.

This possibly can be realized by the establishing of a network of rain gages in the drainage area and re-establishing the Buckhead and Greensboro gages upstream of the headwater of Lake Wallace. Additionally, a new gage is required upstream of Lake Sinclair on the primary tributary below Wallace Dam, Little River. The projects will not be put into combined operation together until 1980. During this time, data could be gathered and a new inflow model developed either by using a model of the land phase of the hydrological cycle or a regression model.

Using the predicted inflow, predicted power demand, and the operation policy developed in this study a model can be created to determine the volume available for generation and volume required for pumping. Incorporating this information with predicted power demand, the hour by hour operation of the two projects can be established.

Therefore, it is recommended that the network of stream flow gages be established by the Georgia Power Company and the new operation model be developed to operate the Wallace Dam and Sinclair Dam Projects. The operation should follow the operation policy established in this study.

Feasiblity of Increasing Capacity of Sinclair Reservoir

Finally, it is recommended that the feasibility of increasing the flood storage in Sinclair Reservoir be investigated using the estimates of benefits established in this study.

BIBLIOGRAPHY

(1) Benjamin, Jack R. and Cornell, C. Allen, "Probability, Statistics, and Decision for Civil Engineers," copyright 1970, McGraw Hill.

(2) General Electricl Information Services Business Division, "Users Guide, Statistical Analysis System, STATSYST," December 1971, Revised September 1972.

(3) Hall, Warren A., and Roefs, Theodore G., "Hydropower Project Output Optimization," Journal of the Power Division, ASCE, Vol. 92, No. PO 1, Proc. Paper 4628, Jan., 1966, pp. 67-79.

(4) Harboc, Ricardo C., Mobasheri, Fereidoun, and Yeh, William W-G, "Optimal Policy for Reservoir Operation," Journal of the Hydraulic Division, ASCE, Vol. 96, No. HY11, Proc. Paper 7673, Nov. 7970, pp. 2297-2308.

(5) Liu, Chin-shu, and Tedrow, Allan C., "Multilake River System Operation Rules," Journal of the Hydraulics Division, ASCE, Vol. 99, No. HY9, Proc. Paper 10021, Sept., 1973, pp. 1369-1381.

(6) Payne, Kip, Newman, W.R., Kerri, K.D., "Daily Streamflow Simulation," Journal of the Hydraulics Division, ASCE, Vol. 95, No. HY4, Proc. Paper 6665, July, 1969, pp. 1163-1179.

(7) Thompson, Major H., Jr., "Wallace Dam," Journal of the Power Division, ASCE, Vol. 98, No. PO2, Proc. Paper 9259, October, 1972, pp. 33-348.

(8) United States Department of the Interior, Geological Survey, "Water Resources Data for Georgia."

(9) Wilson, T.T., and Kirdar, Edib, "Use of Runoff Forecasting in Reservoir Operations," Journal of the Irrigation and Drainage Division, ASCE, Vol. No. 1R3, Proc. Paper 7541, Sept., 1970, pp.299-308.

(10) Young, George K., "Finding Reservoir Operating Rules," Journal of the Hydraulics Division, ASCE, Vol. 93, No. HY6, Proc. Paper 5600, Nov., 1967, pp. 297-321.