Analysis of water planning and management alternatives using interactive simulation
by Gerald Scott Michel

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University
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Abstract:
Planning and management engineers are concerned with proper water planning and management for river and reservoir systems. Although simulation and optimization have been successful in the analysis of these systems, an additional technique, known as interactive simulation, has been shown to be an effective research tool also. This study addresses the capability of interactive simulation in developing system operation guidelines for a complex, multipurpose reservoir system, and evaluates effects on reservoir operation when changes are made to the physical system.

This study has shown that interactive simulation is capable of determining system operation guidelines for long-range reservoir planning and management, based on subjective judgment. Interactive simulation based on subjective judgment is also capable of investigating the reaction of the reservoir system to various structural modifications.

ANALYSIS OF WATER PLANNING

AND MANAGEMENT ALTERNATIVES

USING INTERACTIVE SIMULATION

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Gerald Scott Michel

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Gerald Scott Michel

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

Feb 18 1986
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Date

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Chairperson, Graduate Committee

Approved for the Major Department

19 Feb 86
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Date

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Head, Major Department

Approved for the College of Graduate Studies

March 7, 1986
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Date

_____
Graduate Dean

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Date *Feb. 28, 1986*

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ABSTRACT

Planning and management engineers are concerned with proper water planning and management for river and reservoir systems. Although simulation and optimization have been successful in the analysis of these systems, an additional technique, known as interactive simulation, has been shown to be an effective research tool also. This study addresses the capability of interactive simulation in developing system operation guidelines for a complex, multipurpose reservoir system, and evaluates effects on reservoir operation when changes are made to the physical system.

This study has shown that interactive simulation is capable of determining system operation guidelines for long-range reservoir planning and management, based on subjective judgment. Interactive simulation based on subjective judgment is also capable of investigating the reaction of the reservoir system to various structural modifications.

INTRODUCTION

For many years engineers have been concerned with proper water planning and management for river and reservoir systems. Water that is managed properly is available for many purposes such as recreation, irrigation, domestic use, and power generation. Since precipitation is generally not supplied to a basin at a constant rate throughout the year, intelligent water planning and management must be utilized so that water is available to users as required.

Many factors must be considered when attempting to institute suitable water planning and management practices for a reservoir system. Water management practices must, for example, consider the problem of monthly inflow fluctuations which affect the amount of water available for downstream use. Water planning and management practices for reservoir systems must provide for a sufficient amount of water during low flow periods and must also provide sufficient storage of water during high flow periods to minimize flood flows downstream. Demands for water from municipal, agricultural, and recreational users, as well as demands for power generation, can also affect water planning and management policies. Consequently, problems can arise when the various demands on the water supply of the reservoir system exceed the capability of the system to supply the required amount of water. When this happens, only part of the water demands can be met. Decisions

must be made as to which demands will be satisfied and which ones will not. (1)

Other factors which may affect water planning and management include sedimentation and erosion control, land stabilization, fish and wildlife flow requirements, water quality management, and watershed management. All of these factors can impose constraints on reservoir management policies, which may result in situations in which not all constraints can be satisfied. Decisions must then be made as to which will be satisfied and which will be violated. (1)

It is apparent then that many alternatives must be examined in the management of a multipurpose reservoir system. Since some management alternatives will be more acceptable than others, the various alternatives must be screened to determine the best practical operation policies. Three techniques for this type of analysis are simulation, optimization, and interactive simulation.

Simulation is a process by which an attempt is made to model the behavior of a real-world system. A simulation model may be physical (such as a scale model in a laboratory), analog (such as a system of electrical components, resistors, and capacitors to model pipe resistances and storage elements), or mathematical (such as a series of equations which describe physical system processes). A simulation model can evaluate single events, or it can evaluate dynamic events which consider time-varying factors. Some simulation models can include elements of probability. The type of model used for a particular application depends on the nature of the system being studied and the type of results desired from the simulation. A simulation model

that can be developed and proved to represent a prototype system can provide, in seconds, answers about how the real system might perform over different periods of time and under many conditions of stress. Simulation can be limited, however, by oversimplification of the system model, data requirements that cannot be met, high development costs, difficulty in handling intangibles, and the inability to interact with the model during simulation. (2)

Optimization techniques employ a system model to determine a "best" or "optimum" method of achieving a certain goal or objective. The goal or objective, usually in economic terms, is defined by the modeler. Once this is accomplished, alternatives can be generated and analyzed based on maximization of benefits and/or minimization of costs, subject to various operating constraints. The constraints insure that the "optimum" solutions are feasible. Optimization is limited when all of the system constraints cannot be satisfied. In real-life situations, a "trade-off" between satisfaction of certain "major" constraints and violation of "less major" constraints is often required. This constraint trade-off cannot readily be accomplished with conventional optimization techniques. (2)

A third technique for the analysis of water planning and management alternatives is interactive simulation. Interactive simulation attempts to enhance the effectiveness of the other two techniques by introducing subjectivity and the consideration of constraint trade-offs into the analysis procedure. This is accomplished by allowing the use of a feedback mechanism as shown in Figure 1. The feedback mechanism allows the system manager to interact with the simulator during

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┌──────────┐                    ┌──────────────┐                  ┌─────────┐
│ CONTROL  │   set system       │MICROPROCESSOR│    output        │ DISPLAY │
│          ├────────────────────┤              ├──────────────────┤         │
│  PANEL   │   parameters       │(system model)│    variables     │  PANEL  │
└────┬─────┘                    └──────────────┘                  └────┬────┘
     │                                                                 │
     │                          ┌──────────────┐                       │
     └──────────────────────────┤FEEDBACK SYSTEM├──────────────────────┘
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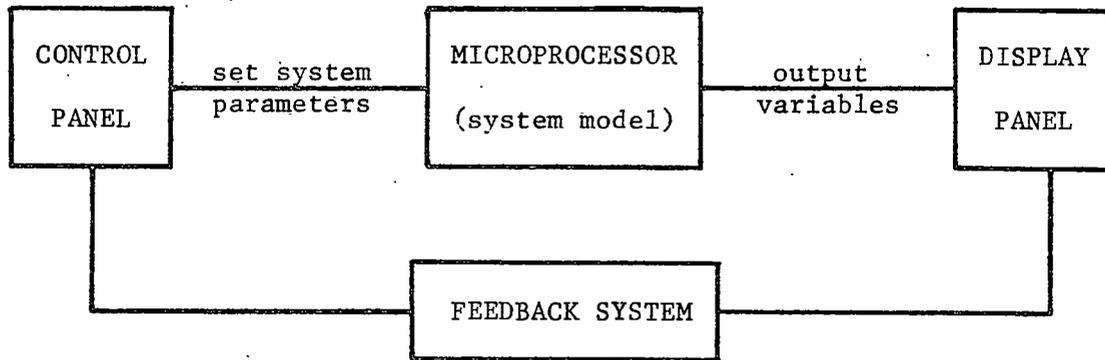
Figure 1.   Interactive Simulator Components.

simulation. In this feedback mechanism, system parameters can be adjusted at the subjective discretion of the system manager during simulation in order to screen alternatives. The system manager can also use the feedback mechanism to evaluate the constraint trade-offs of the reservoir system during simulation to determine permissible constraint violations if not all constraints can be satisfied. Enhancement of simulation techniques can therefore be accomplished by efficient identification of system management policies which are acceptable (though probably not optimal) given the existing level of system uncertainty. Enhancement of optimization techniques can also be accomplished by allowing the development of optimal operation policies based on subjective consideration of the constraint trade-offs of the system operation. With the use of subjective judgment in interactive simulation, simulation and optimization techniques can be rendered into forms which are more useable in the field by operational personnel and which more closely approach realistic system situations. (3)

To investigate the usefulness of interactive simulation in the water management and planning process, an interactive simulation model of the Madison River basin from Hebgen Lake to Ennis Lake in southwest Montana will be utilized. The simulator, known as the Madison River Water Management Simulator, will utilize interactive capability to model a complex, multipurpose reservoir system and determine useable planning and management alternatives for practical water management.

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Objectives

The purpose of this study is to use an interactive simulator, specifically the Madison River Water Management Simulator, to determine reservoir system operation guidelines for a complex, multipurpose reservoir system. The simulator will also evaluate the effects on reservoir operation if the system is physically changed. Physical changes can include varying dam elevations, turbine elevations, or penstock flow capacities. System operation guidelines will be determined by utilizing the simulator to develop, analyze, and screen planning and management alternatives for the reservoir system on a successive trial basis. From this research, insight will be gained regarding the use of interactive simulation for long-range reservoir operation planning and management. Insight will also be gained regarding the reservoir system sensitivity to proposed physical changes.

DESCRIPTION OF SYSTEMS OF INTERACTIVE SIMULATION

In order to aid in illustrating the features of interactive simulation and its usefulness in solving water management problems, a description of the Madison River Water Management Simulator and basin that it models will be outlined below.

Description of Madison River Basin

The drainage basin simulated by the Madison River Water Management Simulator consists of approximately 2000 square miles of the Madison River drainage. An overview map of this area is shown in Figure 2. The drainage basin extends from the northwest corner of Yellowstone National Park to Ennis Lake near McAllister, in southwest Montana. Shortly after the Madison River exits the park, it flows into Hebgen Lake, located west of Yellowstone River and about 8 miles north of the city of West Yellowstone, Montana. Hebgen Lake, a man-made lake formed by Hebgen Dam, extends for a length of about 22 miles from the Madison River inlet to Hebgen Dam. Approximately two miles downstream from Hebgen Dam is Quake Lake, which was formed by a landslide resulting from a massive earthquake in the Madison Canyon in 1959. Between Quake Lake and Ennis Lake, the river winds its way for about 48 miles, being fed along the way by many small streams, the largest of which is the West Fork of the Madison River. In this reach of river, a minimal amount of water is diverted for agricultural usage. The Madison River

McAllister

Madison Dam

Ennis Lake

Ennis

Bozeman

Madison   River

Quake Lake

Hebgen Dam

Montana

Wyoming

Hebgen Lake

Grayling

West Yellowstone

Yellowstone
National Park

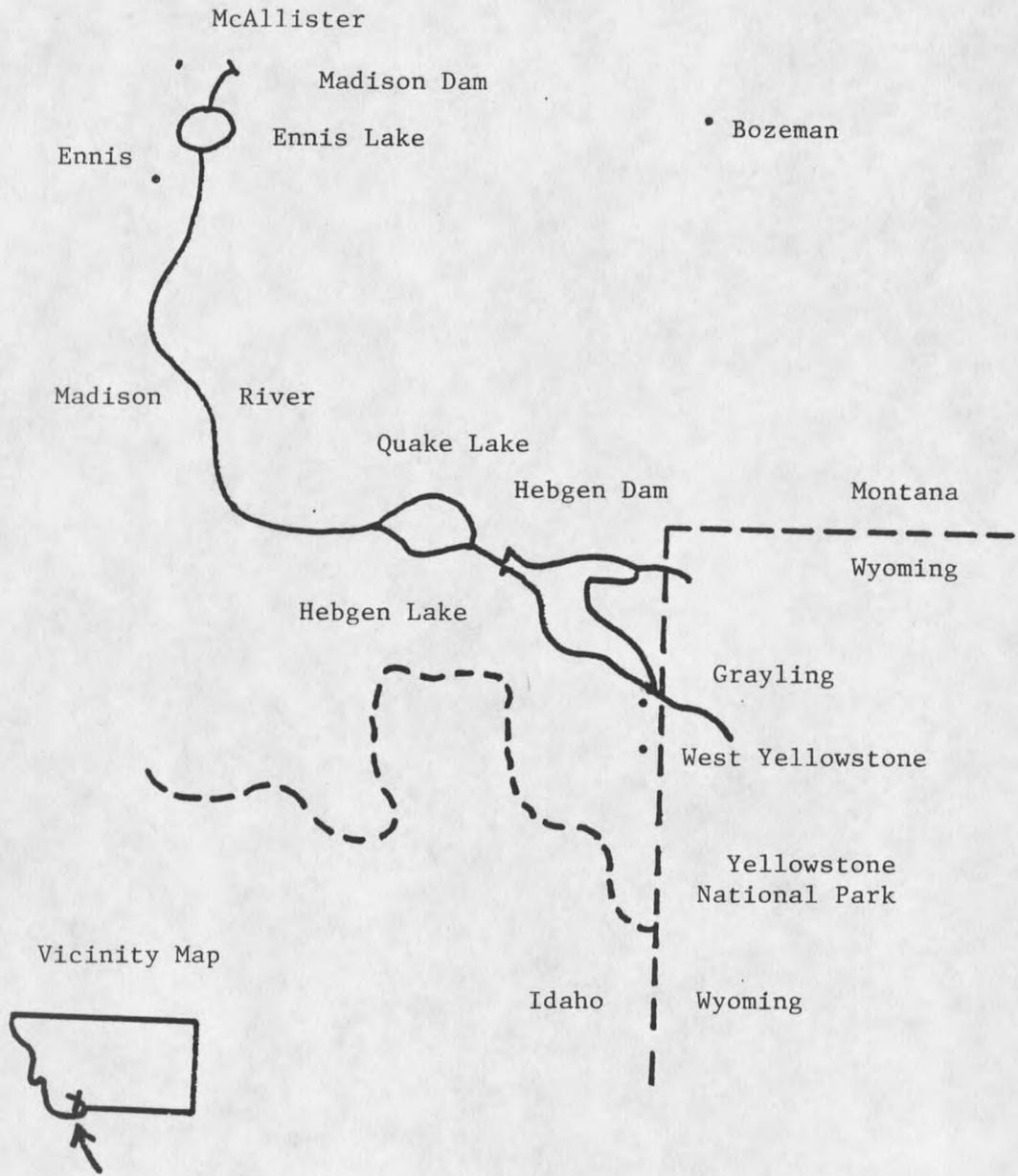Vicinity Map

Idaho   Wyoming

Figure 2.   Schematic Map of the Madison River Basin (Not to Scale).

then empties into Ennis Like, formed by the Madison Dam near McAllister, Montana. Madison Dam, as well as Hebgen Dam, are both equipped with hydropower installations. The basin is bounded by the Continental Divide, the Gravelly Range, and the Tobacco Root Mountains on the west side of the Madison River, and by the Madison Range on the east side. These mountainous areas are largely pine covered.

Land elevations in this area of the Madison River basin range from 4800 feet at Ennis Lake to over 11000 feet in the mountains of the Madison Range.

The population in the basin is primarily rural, with agriculture being the main industry. No major communities over 1000 inhabitants exist here.

Description of Madison River Water Management Simulator

The Madison River Water Management Simulator is contained within three fairly compact components. The front panel of the first and largest of the components is shown in Figure 3. The panel shows a schematic layout of the three lake system from Hebgen Lake to Quake Lake to Ennis Lake. Also shown on the panel are several labeled rectangles corresponding to digital display readouts for certain variables. These variables include streamflow, reservoir water surface elevations, reservoir releases, and power generation.

The second component (not shown) is primarily a control panel with switches for inputting and altering data, switches for inflows to be generated by random or programmed methods, a button for advancing the program through each time step, and buttons for resetting and
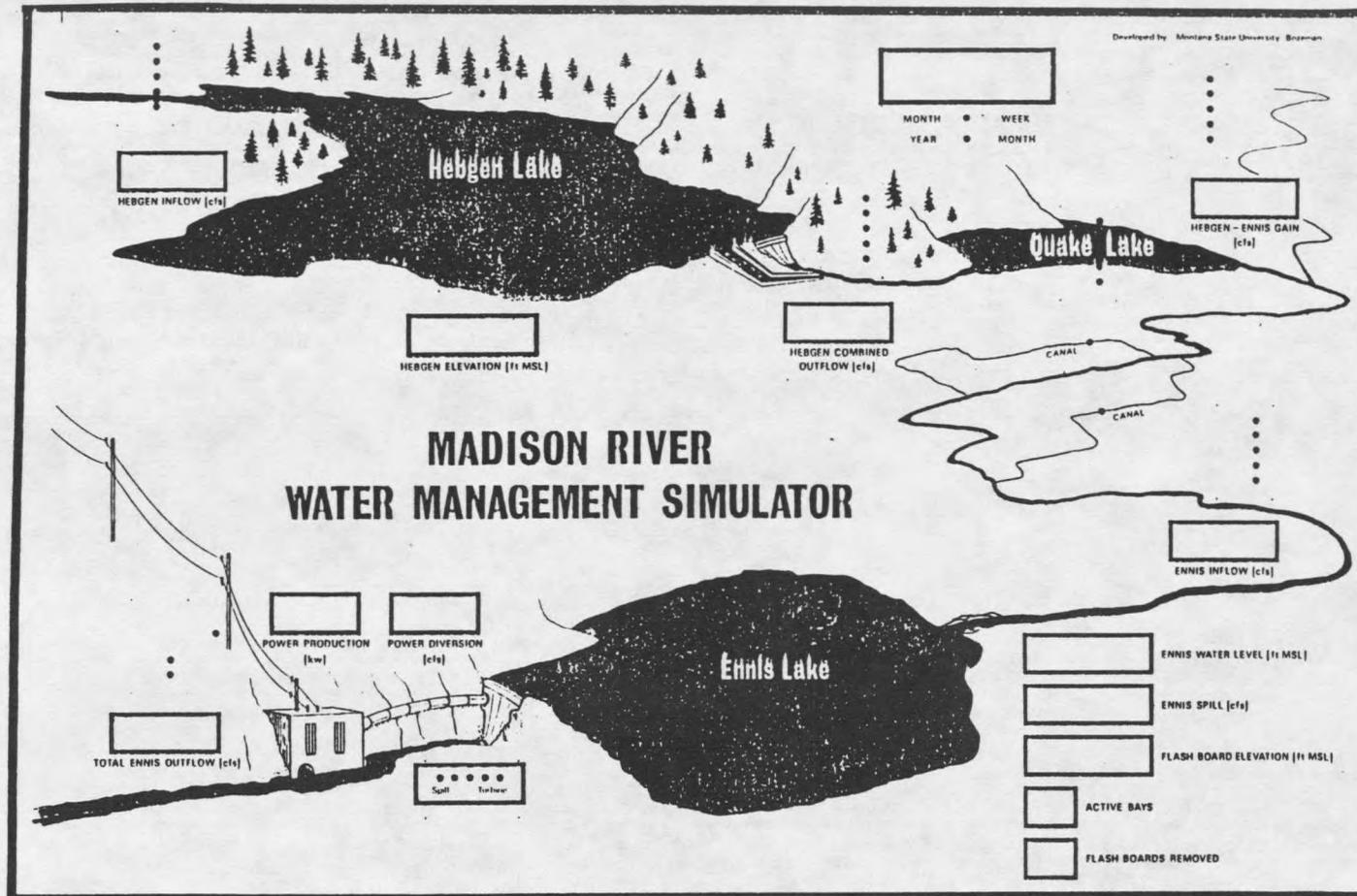
Figure 3.   Simulator Schematic.

Initializing values. Two control knobs are also located on this component, one for adjusting outflow from Hebgen Lake, and one for adjusting the flow into the powerhouse at Ennis Dam.

The third component shown in Figure 4 is the system management constraint panel. This component is a lighted display panel that indicates which system constraints are violated and which are satisfied.

The circuit design of the simulator is shown in Figure 5. The information flow is as follows. Control signals are brought into the main simulator and coverted to digital values by an analog to digital converter circuit (ADC). The central processing unit (CPU) reads instructions from the Program Memory (PROM), receives input from the ADC circuit, processes the input according to the algorithm in the PROM, and outputs results through display and color graphic output ports. The random access memory (RAM) holds intermediate computational results and is also used as a location for field-programmed information. The computer is mounted on the rear panel of the simulator, and the ADC and input and output ports are mounted on a "buss" panel inside the simulator cabinet. Sequential computer operations required to implement the algorithm are stored as machine instructions in the PROM. This allows flexibility in program updating. (4)

Synthetic Streamflow Generation

The simulator is used to generate synthetic stream inflows to Hebgen Lake as well as tributary inflows between Hebgen Lake and Ennis Lake. Ten years of historical monthly streamflow records at three

SYSTEM MANAGEMENTS CONSTRAINTS

HEBGEN RESERVOIR CONSTRAINTS

● ● ●   ● ● ● ● ●   ● ● ●

SUPPLY   RECREATION   RELEASE > 600 cfs

HEBGEN - QUAKE LAKE	QUAKE LAKE - ENNIS RESERVOIR	ENNIS RESERVOIR

● ● ●   ● ● ●   ● ● ●

FISH HABITAT   FISH SPAWNING   WILDLIFE NESTING AND
(minimum flows)   OUTFLOW FLUCTUATIONS

● ● ●   ● ● ●   ● ● ●

QUAKE LAKE OUTFLOW   FLOW AT KIRBY   FLOW AT ENNIS
> 3500 cfs   > 7600 cfs   > 1100 cfs

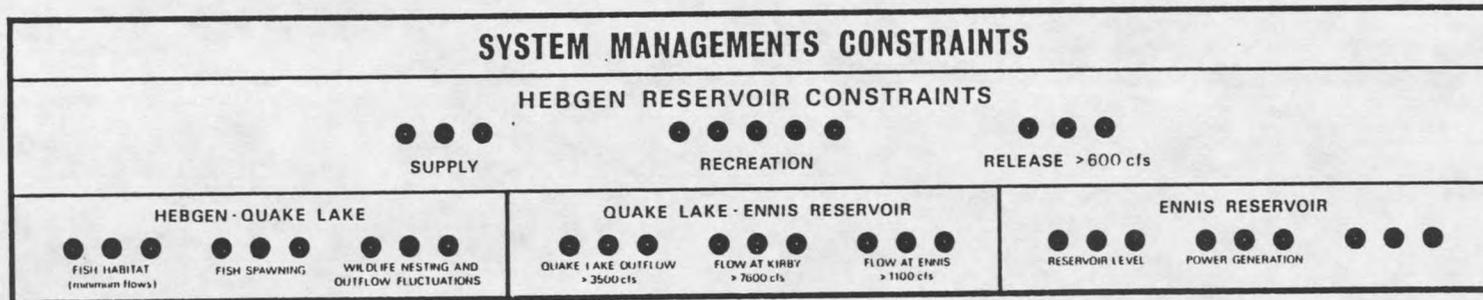● ● ●   ● ● ●   ● ● ●

RESERVOIR LEVEL   POWER GENERATION

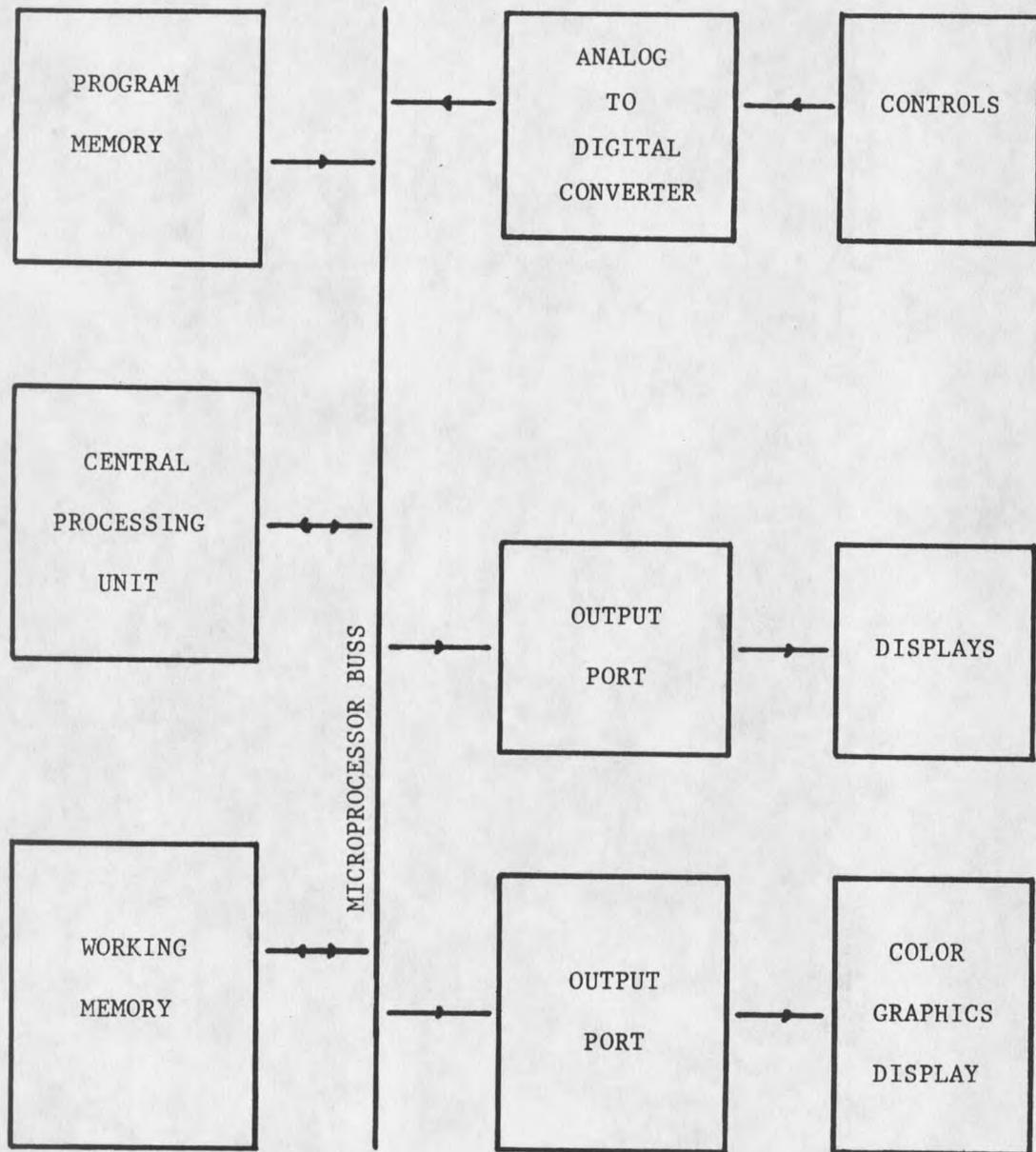Figure 4.   Madison River Constraint Panel.

Figure 5. Block Diagram of Microprocessor-Based Simulator.

Madison River locations (near Grayling Creek, above Hebgen Lake; below
Hebgen Dam; and at McAllister, Montana) provide the basis for the
synthetic streamflow generations. The streamflow record from the gage
near Grayling Creek is used to generate the synthetic Hebgen Lake
inflows. The generation is accomplished by first obtaining the
average, or mean, inflow rate for each month of the year, based on
the ten years of record. The monthly mean can be calculated by the
following equation:

$$\bar{Q}(j) \; = \; \sum_{i=1}^{N} \; Q(ij)/N$$

where $\bar{Q}(j)$ is the mean flow rate for the month j in question, $Q(ij)$ is
the streamflow rate for one month i in the series, and N is the number
of years of record. When all twelve mean flow rates have been deter-
mined, the standard deviation S for each month of the year can be
calculated by the following formula:

$$S(j) \; = \; \left\{ [1/(N-1)] \; \sum_{i=1}^{N} \; (Q(ij)-\bar{Q}(j))^2 \right\}^{\frac{1}{2}}$$

where N, $Q(ij)$, and $\bar{Q}(j)$ are as previously described. The values for
the monthly means and standard deviations for the Hebgen inflow, based
on the streamflow data obtained at the gage near Grayling Creek, are
shown in Table 1.

Table 1. Statistical Quantities for Synthetic Streamflow Computations.

Month	Hebgen Inflow		Hebgen to Ennis Tributary Inflow		Regression Coeff.	Serial Coeff.
	Mean (cfs)	Standard Deviation (cfs)	Mean (cfs)	Standard Deviation (cfs)		
Jan.	441	34.27	619	95.80	1.2	.87
Feb.	432	32.37	661	104.74	1.2	.78
Mar.	430	31.42	690	108.44	1.3	.16
Apr.	477	47.71	696	110.09	4.0	.57
May	905	143.21	1313	351.28	2.2	.44
June	1065	143.21	2171	640.14	.43	.82
July	593	113.86	1087	339.62	.61	.84
Aug.	498	70.73	601	208.66	1.0	.84
Sep.	489	70.90	657	116.22	.75	.75
Oct.	479	69.27	624	181.89	.53	.84
Nov.	465	41.38	732	101.97	.85	.74
Dec.	453	40.85	609	83.06	1.3	.79

With the monthly means, streamflows can be generated for each month on the basis of the following regression relationship:

$$Q(j) = \bar{Q}(j) + m(j) [Q(j-1) - \bar{Q}(j-1)]$$

where the subscript j refers to the month j of the year. The variable $Q(j)$ is a flow rate for a month j of the year, $\bar{Q}(j)$ is the average flow rate for a month j of the year, and $m(j)$ is a regression coefficient between the discharge differences $Q(j)-\bar{Q}(j)$ and $Q(j-1)-\bar{Q}(j-1)$. The regression coefficient is derived graphically from the linear relationship between these two successive monthly discharge differences as determined from the historic record. The slope of this line is determined by plotting a graph of $(Q(j)-\bar{Q}(j))$ vs. $(Q(j-1)-\bar{Q}(j-1)$ using the historical streamflow records and the previously calculated means. The slope of the line of best fit, by observation, through these data points is the value of the regression coefficient. With the known values of $\bar{Q}(j)$, $m(j)$, and $\bar{Q}(j-1)$, synthetic streamflows can be calculated by using a specified initial inflow for $Q(j-1)$ to successively generate a synthetic value for each month of the year. (1) The values for the regression coefficients are shown in Table 1. Each regression coefficient in the table is a value relating the flow rate from its corresponding month to the flow rate in the succeeding month.

This method of developing a synthetic series is completely deterministic. This means that with a specified initial value the entire series is fully predictable, based on past streamflow records. However, since streamflows in reality do not follow a predictable pattern, a random component can be introduced into the above synthetic

streamflow equation to simulate the unpredictability of actual streamflows as shown below:

$$Q(j) = \bar{Q}(j) + m(j)[Q(j-1)-\bar{Q}(j-1)] + t(j)S(j)(1-r(j)^2)^{\frac{1}{2}} \qquad (1)$$

where $S(j)$ is the standard deviation for month j, $r(j)$ is the serial correlation coefficient between month j and month $j-1$, and $t(j)$ is a random number generated by the simulator based on a normal distribution with a mean of zero and a standard deviation of one. The serial correlation coefficient is based on the historical streamflow records and is calculated from the following formula:

$$r(j) = \{\sum_{j=1}^{N-1} Q(j)Q(j+1) - [1/(N-1)][\sum_{j=1}^{N-1} Q(j)][\sum_{j=2}^{N} Q(j)]\}/S(j)S(j+1) \qquad (1)$$

The serial correlation coefficient is an indication of the ability of the previous monthly streamflow to predict its succeeding value. (1) The values for the serial correlation coefficients are shown in Table 1. Each serial correlation coefficient in the table is a value relating the flow rate from its corresponding month to the flow rate in the succeeding month.

By introducing the random deviate ($t(j)$), this final term in the equation imparts a random variation to the flows, but this variation is constrained by the known characteristics of the streamflow records, namely S and r. (5)

Synthetic tributary inflows between Hebgen and Ennis Lakes are calculated in a similar manner. Average monthly flows for the tributary inflow are calculated by using the streamflow records at

McAllister, Montana and at a gage downstream of Hebgen Lake. The differences of each corresponding monthly flow rate for each gage are calculated for each of the ten years of record. The effect of agricultural diversion in this reach is ignored. The above ten differences are then averaged for each month of the year. From these means, and standard deviations, synthetic streamflows can be generated in the same manner as for Hebgen inflows. The values of means, standard deviations, regression coefficients, and serial correlation coefficients for both inflows are shown in Table 1. Since streamflow characteristics are similar for both inflows, the same regression and serial correlation coefficients are used for both inflows.

Description of Physical System

The values for inflow rate, outflow rate, and storage for any section of reach in the reservoir system are related by the following equation:

$$\bar{I} - \bar{O} = \Delta s/\Delta t$$

where $\bar{I}$ is the inflow rate to the reach, $\bar{O}$ is the outflow rate from the reach, and $\Delta s/\Delta t$ is the rate of change of storage within the reach.

In Figure 2, a diagram of the three lake system and interconnecting channels is shown. The above equation is applied to Hebgen Lake. The monthly inflow rate is calculated from synthetic streamflow generation as previously described. The analyst manually adjusts the monthly outflow rate on the simulator panel. These values of inflow and outflow result in a particular change in the value of storage for Hebgen Lake for the month. The change in storage is then added to the

initial storage of the reservoir to obtain the new storage. From the new storage value, the new reservoir elevation can then be calculated. The effects of reservoir evaporation, river bank storage, and channel travel time of the water through the reservoir are ignored in all of the above computations.

In order to attempt to satisfy recreation and water supply constraints, Hebgen Lake outflows are adjusted so as to maintain a reservoir elevation between 6530 ft. and 6535 ft. for the period from June through September. Outflow releases from Hebgen Lake are maintained between 600 cfs. and 3500 cfs. for all months when possible. The analyst also attempts to limit Hebgen outflows from March through May to no more than 100 cfs. above the February Hebgen Lake outflow. This constraint minimizes damages to wildlife nesting areas. To provide for an adequate fish habitat, the analyst provides at least 500 cfs. of streamflow downstream of Hebgen Lake, when possible.

Downstream of Hebgen Lake, the Madison River flows into Quake Lake. Since no dam structure exists to regulate outflow, the inflow rate to Quake Lake is also the outflow rate, and no change in storage occurs.

Downstream from Quake Lake additional inflow from local tributaries is combined with the outflow from Quake Lake. The tributary inflow is calculated from the synthetic streamflow generation procedure previously described. From this combined flow rate, 150 cfs. of water is diverted for agricultural irrigation. Approximately 55 percent of this diverted flow is returned to the river before the river flows into

Ennis Lake. It is assumed that returned flows occur in the same month they are diverted, ignoring the effect of travel time.

In order to attempt to satisfy system constraints, the analyst must attempt to manage outflows from Hebgen Lake so that the combined Hebgen Lake outflow and tributary inflow, less the diverted irrigation flow, will result in at least 1100 cfs. flowing into Ennis Lake.

At Ennis Lake the reservoir is managed such that a constant elevation of 4841 ft. is maintained. Therefore, the inflow rate to Ennis Lake is also the outflow rate, and no change in storage occurs. Losses due to evaporation at the reservoir are ignored. The analyst attempts to allocate the outflow from Ennis Lake to allow the maximum amount of water possible through the penstock in the powerhouse, while maintaining minimum streamflow requirements.

To satisfy system constraints, the analyst must attempt to maintain a flow of at least 50 cfs. over the spillway to satisfy minimum streamflow requirements between the Madison Dam and the powerhouse. Up to 1600 cfs. can be diverted into the penstock. Flows in excess of 1650 cfs. are passed over the spillway, resulting in lost power generation.

Program Description

Outlined in Figure 6 is a flow chart of the program used by the Madison River Water Management Simulator.

Initially, all of the required data, such as streamflows, structural parameters, and system constraints, are read into the
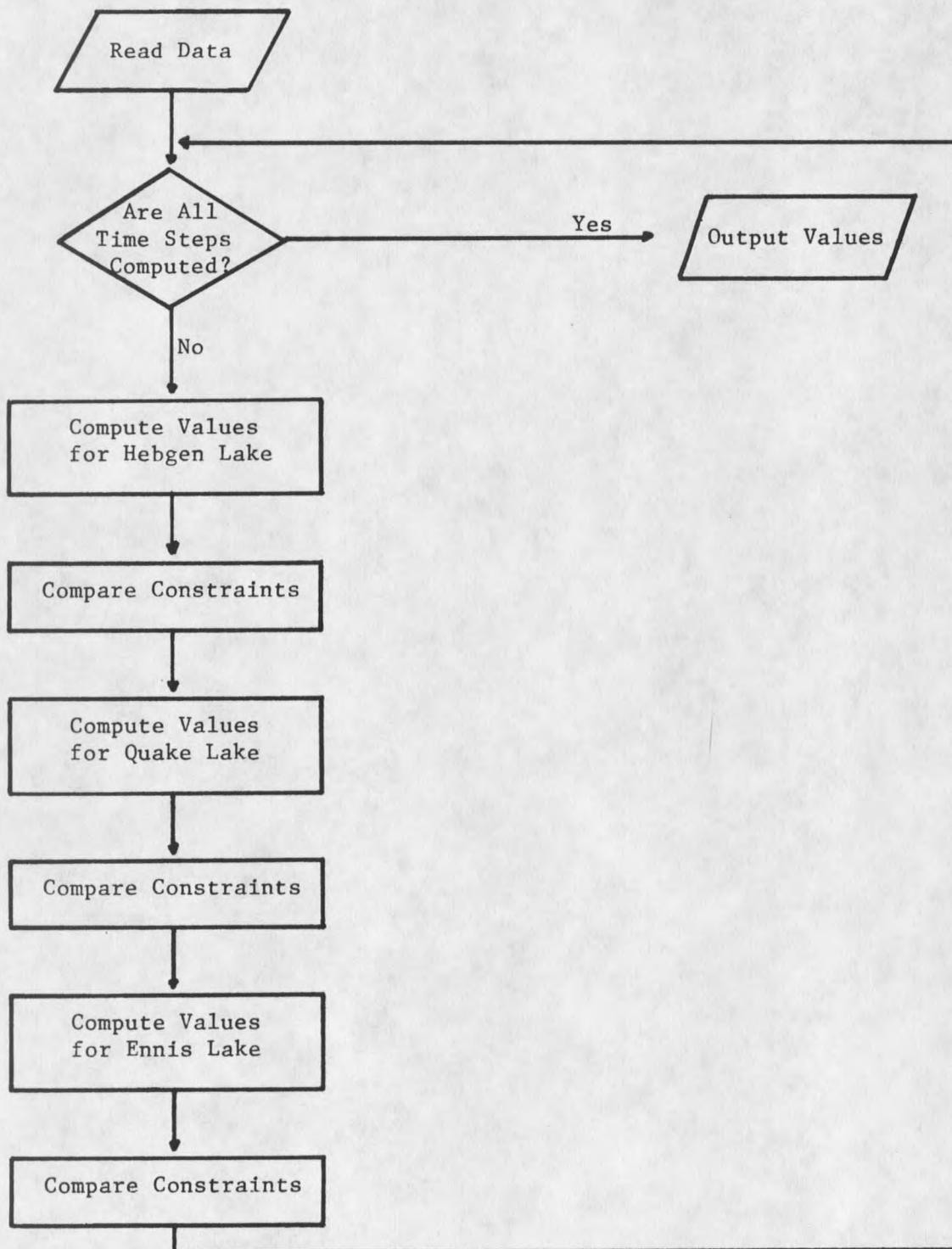
Figure 6.   Simulator Program Steps.

program. The central processing unit (CPU) of the simulator can then initiate program execution.

After data are read, the main loop of the program is executed. The main loop will calculate output for each time step for as many time steps as are desired. The time step in this program will be of one-month duration, and all values calculated for each pass through the loop will be monthly values. A 30 day monthly period will be used. Each yearly sequence of values will be analyzed independently, ignoring the effect of year-to-year dependency.

At Hebgen Lake the change in storage is computed by subtracting the Hebgen Lake outflow selected by the analyst from the inflow to the lake and multiplying by the number of days in the month (30). This result (negative or positive) is added to the initial storage. The resultant storage is converted into a corresponding Hebgen Lake elevation by a series of program steps relating reservoir storage to reservoir elevation. The program steps approximate a storage-elevation curve for Hebgen Lake by a series of small line segments each with a range of ten feet of reservoir elevation. The calculated value of storage determines the line segment from which the elevation is calculated. A corresponding equation for that line segment is then used to calculate the reservoir elevation.

If the new Hebgen Lake water surface elevation exceeds the Hebgen spillway elevation, then spillway flow occurs. The spillway flow is calculated by determining the value of reservoir storage at the spillway elevation and the value of storage corresponding to the new elevation by the procedure described above. The difference of the two

storage values is divided by the 30-day monthly flow period to obtain the average flow rate over the spillway for the month. This flow is added to the Hebgen outflow to obtain the inflow to Quake Lake.

The calculated Hebgen Lake water surface elevation and the Quake Lake inflow (which is also the combined Hebgen outflow) are compared to the system constraints. The simulator then indicates what constraints are violated, if any, and allows the analyst to correct violations before advancing to the next time step.

At Quake Lake, since no dam or spillway exists, the inflow rate is the same as the outflow rate. The outflow rate from Quake Lake is then added to the tributary inflow between Hebgen and Ennis Lakes. The simulator program subtracts the agricultural irrigation flows (150 cfs.) from this streamflow. The program then returns 55 percent of the diverted flows to the river before it enters Ennis Lake. Diverted flows are assumed to be returned to the river in the same month that they are diverted, ignoring any effects of delayed groundwater return.

At this point, the program compares the flow rate into Ennis Lake with the system constraints. Violations, if any, are indicated by the simulator, allowing the analyst to adjust Hebgen Lake outflows to correct them before advancing to the next time step.

A provision in the simulator program allows for the establishment of a target elevation for Ennis Lake. The target elevation is that elevation that the program allows the surface of the water to reach before flows exceeding minimum streamflow are passed over the spillway. The value of the target elevation is assigned by the analyst. Thus two conditions are possible. The Ennis reservoir elevation can be less

than the target elevation or it can be equal to the target elevation. In the scenarios that follow, however, the Ennis reservoir elevation will always equal the target elevation.

In Figures 7 and 8 decision charts illustrating the options available to the analyst at Ennis Lake are shown. If the Ennis reservoir elevation is less than the target elevation, and if the inflow to Ennis Lake is less than the minimum spillway flow required, then the outflow rate equals the inflow rate, and the entire flow is passed over the spillway. The Ennis Lake elevation remains unchanged.

If the Ennis reservoir elevation is less than the target elevation, and if the inflow to Ennis Lake exceeds the minimum spillway flow required, but does not exceed the maximum penstock flow, then the minimum spillway flow is passed over the spillway and the remaining flow is diverted into the penstock to produce electricity.

If the Ennis reservoir elevation is less than the target elevation, and if the inflow to Ennis Lake exceeds the sum of the minimum spillway flow and the maximum penstock flow, then the minimum spillway flow is passed over the spillway, the maximum penstock flow is diverted through the penstock for power production, and the remaining inflow is multiplied by the number of days in the monthly period (30) to obtain the additional incremental storage to be added to Ennis Lake. The additional storage is added to the original storage and converted to an elevation by the same procedure used for Hebgen Lake. If the new elevation exceeds the target elevation, then the difference of the two storage values corresponding to these two elevations is divided by the number of days in the monthly period, and the resultant flow rate is
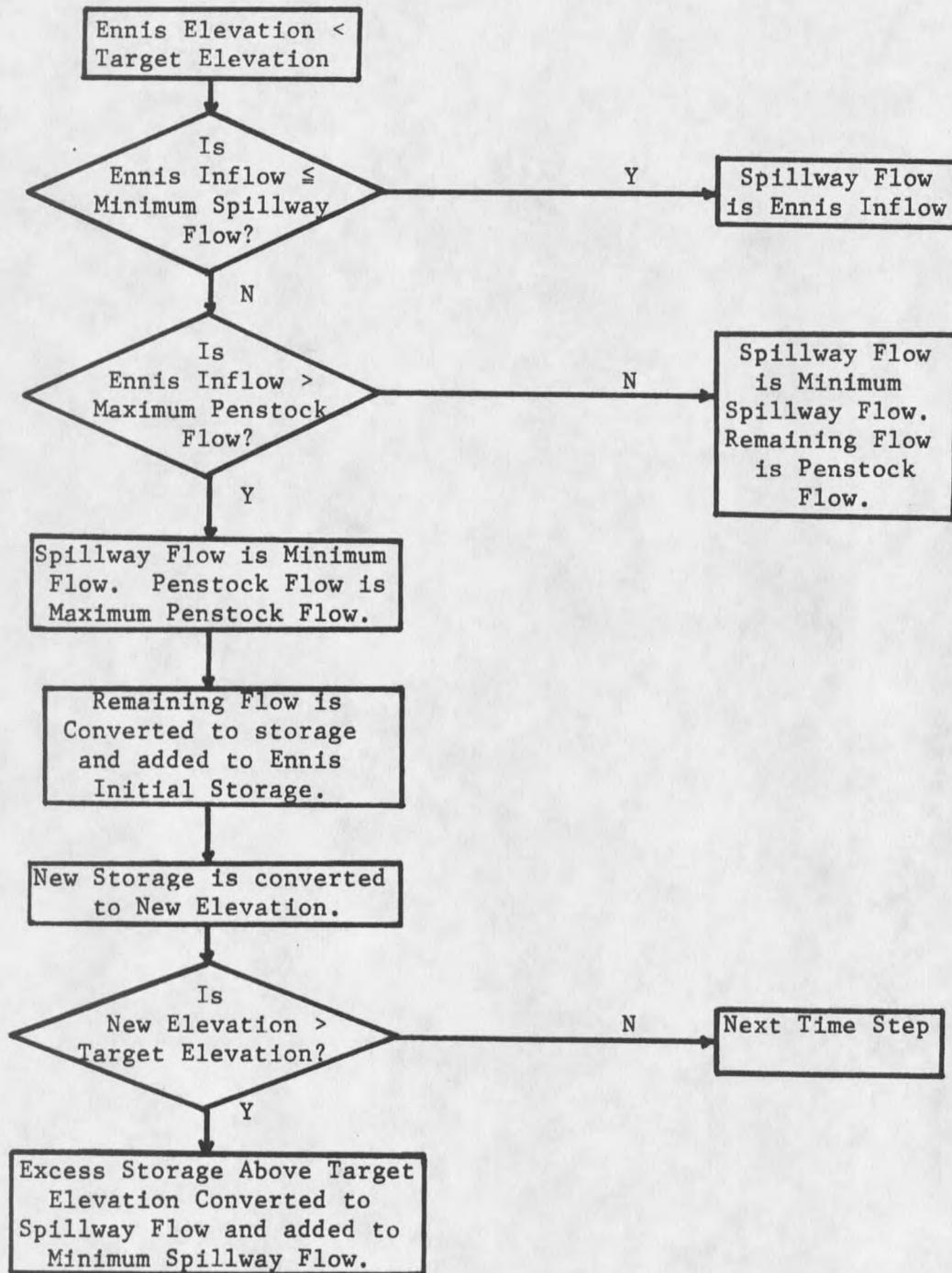
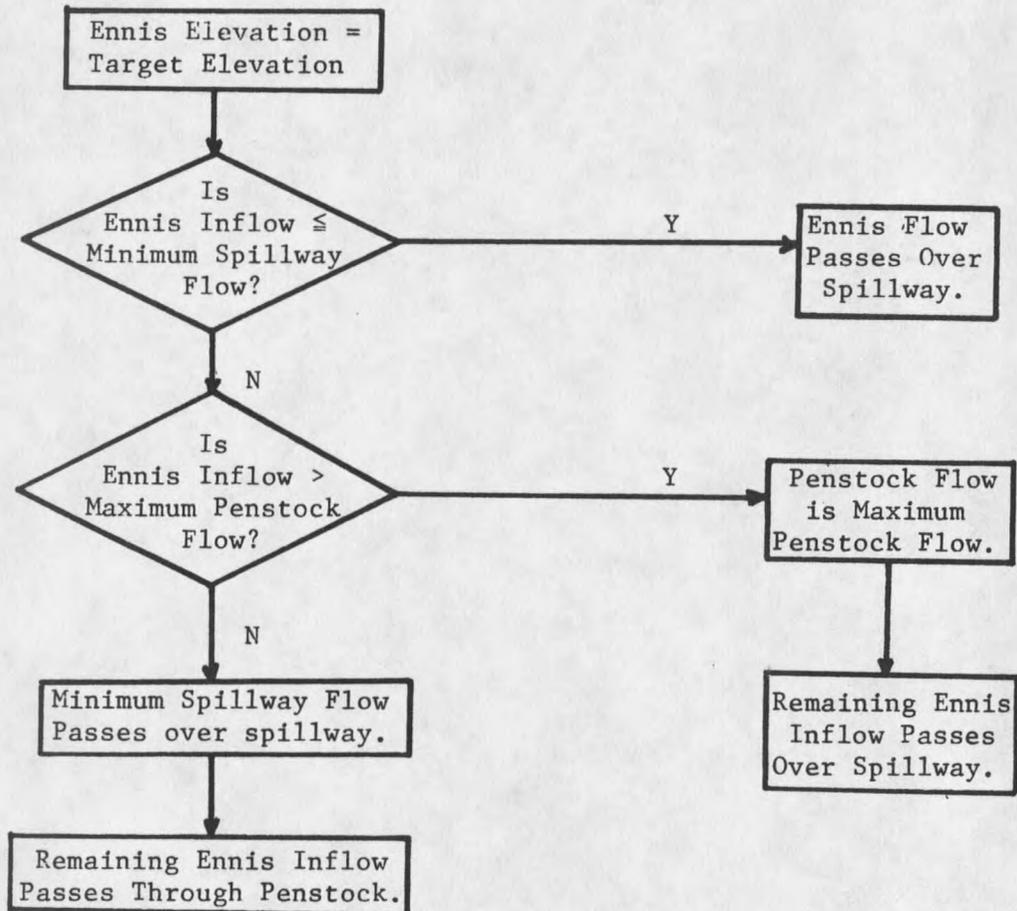Figure 7. Decision Chart for Ennis Lake Elevation Less Than Target Elevation.

Figure 8. Decision Chart for Ennis Lake Elevation Equal to Target
Elevation.

added to the minimum spillway flow. This will adjust the Ennis Lake elevation to the target elevation by passing the required amount of water over the spillway to achieve the target elevation.

If the Ennis Lake elevation equals the target elevation, and if the inflow to Ennis Lake is less than the minimum spillway flow, all of the inflow is passed over the spillway. If the Ennis elevation equals the target elevation and if the inflow to Ennis Lake exceeds the maximum spillway flow but does not exceed the maximum penstock flow, then the minimum spillway flow will pass over the spillway, and the remaining flow will pass through the penstock to produce electricity. If the Ennis elevation equals the target elevation and if the inflow to Ennis Lake exceeds the sum of the minimum spillway flow and the maximum penstock flow, then the maximum penstock flow is passed through the penstock to produce electricity, and the remaining flow is passed over the spillway.

After the spillway flow rate is calculated, the flashboard arrangement required to pass this flow is determined. The flashboard apparatus is arranged in twenty-three bays across the spillway inlet. Each bay has a series of removable flashboards, which are removed or added in response to the spillway flow and target elevation require- ments. The number of active bays, or bays through which flow passes, is determined first. The program assumes one active bay and divides the spillway flow by the number of active bays to obtain the flow rate per bay. The head on the spillway corresponding to this flow rate is then calculated. This value of head is compared to the difference between the target elevation and the spillway elevation. If the head

exceeds this difference, the number of active bays is increased by one. The flow rate per bay and the head are recalculated in the same manner until the head no longer exceeds the difference between target elevation and spillway elevation. The number of active bays is thus determined.

If the water surface elevation equals the target elevation, the flashboard elevation is the difference between the target elevation and the head. This is the elevation of the flashboards in the active bays that will pass the required spillway flow over the boards and maintain the target elevation. If the initial Ennis elevation is less than the target elevation, then the flashboard elevation is the difference between the computed water surface elevation and the head. The number of flashboards is determined by dividing the head by 0.9 feet per board.

If all 23 bays are active and all flashboards are removed, then the change in Ennis reservoir storage would be computed by subtracting the Ennis outflow from the Ennis inflow and multiplying by the number of days in the monthly period (30). The change in storage is added to the initial Ennis reservoir storage.

Power production in kilowatts at Ennis reservoir is calculated from the following equation:

$$P = QwH (0.8) / 550$$

where Q is the discharge, w is the specific weight of water, and H is the effective head, which is the difference between the Ennis water surface elevation and the turbine elevation. The downstream flow

leaving the reservoir system is the sum of the spillway flow and the penstock flow.

At this point the program compares the spillway flow and the Ennis lake elevation with system constraints. This allows the analyst to correct violations of constraints before advancing to the next time step. This is the final step in the main loop of the program.

The main loop of the program is repeated for each time step. Each time step will be one month in duration. At the end of each time step, values for Hebgen Lake inflow, Hebgen Lake water surface elevation, Hebgen Lake outflow, tributary inflow (or Hebgen-Ennis gain), Ennis Lake inflow, Ennis Lake water surface elevation, Ennis spillway flow, flashboard elevation, number of active bays, flashboards removed, penstock flow, power production, and total outflow from Ennis Lake are output and displayed on the main simulator panel.

Description of Input and Output

Input for the program consists of initial reservoir elevations, dam elevations, spillway elevations, the values for the constraints on the reservoir system, and other fixed basin parameters. Input which is not fixed consists of the synthetically generated streamflows for the Hebgen inflow and the Hebgen-Ennis gain. A summary of the fixed input values for the simulator is shown in Table 2.

Output for the program consists of streamflows, water surface elevations at each reservoir, spillway flows, and power production. A summary of the variables which are output is shown in Table 3.

Table 2. Input Variables.

Variable Name	Variable Abbr.	Value
Hebgen Lake Initial Elevation	HIEL	6530.0 ft.
Irrigation Diversion West	QDVWST	100 cfs.
Irrigation Diversion East	QDVEST	50 cfs.
Ennis Initial Elevation	EIEL	4841.0 ft.
Ennis Minimum Spillway Flow	IESPMF	50 cfs.
Maximum Penstock Flow	IQPMAX	1600 cfs.
Ennis Target Storage	ETARST	19800 A-FT.
Recreation Constraint (Red)+	RECRP	>6534.87 ft.
Recreation Constraint (Amber)+	RECAP	>=6534.00 ft.
Recreation Constraint (Green)	RECGR	>6531.00 ft.
Recreation Constraint (Amber)-	RECAN	>=6530.26 ft.
Recreation Constraint (Red)-	RECRN	<6530.26 ft.
Supply Constraint (Amber)	SUPA	<=6531.00 ft.
Supply Constraint (Red)	SUPR	<=6529.00 ft.
Hebgen Outflow Constraint (Red)	IHFLOR	<600 cfs.
Hebgen Spillway Elevation	HSPLEL	6535.00 ft.
Hebgen Allowable Elevation	HALLEL	6540.40 ft.
Hebgen Spillway Storage	HSPILS	179875 A-FT.
Ennis Spillway Elevation	ESPLEL	4833 ft.
Turbine Elevation	ELTURB	4754 ft.
Initial Quake Elevation	QIEL	6388 ft.
Turbine Efficiency	EFF	0.80

Table 2. Continued.

Variable Name	Variable Abbr.	Value
Irrigation Constant West	CW	0.45
Irrigation Constant East	CE	0.45
Initial Quake Initial Storage	QIS	30000 A-FT.
Ennis Reservoir Level Constraint (Red)	ERESR	4839 ft.
Ennis Reservoir Level Constraint (Amber)	ERESA	4840 ft.
Hebgen Release Constraint (Amber)	INFOLA	<=800 cfs.
Fish Habitat Constraint (Red)	IHABR	<500 cfs
Fish Habitat Constraint (Amber)	IHABA	<700 cfs.
Spawning Constraint (Red)	ISPAWR	>200 cfs.
Spawning Constraint (Amber)	ISPAWA	>100 cfs.
Nesting Constraint (Red)	INESTR	>200 cfs.
Nesting Constraint (Amber)	INESTA	>100 cfs.
Quake Outflow Constraint (Red)	IQFLOR	>3500 cfs.
Quake Outflow Constraint (Amber)	IQFLOA	>3300 cfs.
Kirby Flow Constraint (Red)	IKFLOR	<600 cfs.
Kirby Flow Constraint (Amber)	IKFLOA	<800 cfs.
Ennis Flow Constraint (Red)	IEFLOR	<1100 cfs.
Ennis Flow Constraint (Amber)	IEFLOA	<1300 cfs.
Maximum Power Production	IPMAX	9400 KW
Power Generation Constraint (Red)	IGENR	<8000 KW
Power Generation Constraint (Amber)	IGENA	<9000 KW

Table 3. Output Variables.

Variable Name	Variable Abbreviation
Hebgen Inflow	QHIN
Hebgen-Ennis Gain	HEGAIN
Hebgen Elevation	NNEWEL
Hebgen Outflow	QHOUT
Ennis Inflow	QIEN
Ennis Elevation	EIEL
Ennis Spillway Flow	ESPILL
Flashboard Elevation	FLSHEL
Active Bays	NBAY
Flashboards Removed	IBOARD
Power Diversion	QPOWER
Ennis Outflow	QFINAL

Description of Simulator Operation

The simulator control panel contains all of the switches and buttons necessary to operate the simulator. After the simulator power switch is turned on, a red button is pushed to initialize all displays to zero. To operate the simulator in the random mode for synthetic streamflow generation, a toggle switch on the right hand side of the panel is flipped to "operate" and the button marked "enter" is depressed. This initiates the synthetic streamflow generation by seeding the random number. Utilizing the values from Table 2 stored in the program memory (PROM) and the synthetic streamflow generated from the random number, the button marked "step" is pressed, and output values for the first time step are displayed on the main simulator panel. To advance to succeeding time steps, the step button is depressed for as many time steps as are desired. For each time step, values are output and displayed on the main simulator panel.

To input programmed flows or to change input from the program memory (PROM), the operate/standby toggle switch is flipped to "standby." After displays are initialized, a button labeled "down" is depressed, allowing the analyst to select the desired variable to be changed. When this is determined, the new value can be input by means of a thumbwheel switch located on the left side of the simulator control panel. When the thumbwheels register the desired value, the button marked "enter" is depressed, and the new value is entered into the program. When all desired values are input, the analyst flips the

toggle switch back to "operate," pushes "step," and proceeds with the simulation.

During simulation, outflows from Hebgen Lake and diverted flows into the Ennis powerhouse can be regulated by knobs located on the simulator control panel.

The output of the numerical results are accomplished by the use of lighted digital displays. Other output which indicates relative magnitudes of water surface elevations and streamflows are displayed by using vertical L.E.D. strings.

On the simulator constraint panel each system constraint condition is indicated by a red-amber-green light sequence. A red light indicates a constraint violation, an amber light indicates a condition approaching but not exceeding a violation, and a green light indicates no violation.

MANAGEMENT SCENARIOS

In order to illustrate the capability of interactive simulation in the development of the planning and management alternatives for a particular site, the Madison River Water Management Simulator will be utilized to determine how the Madison River system from Hebgen Lake to Ennis Lake will behave under certain operating conditions. In the first illustration, it will be shown that a realistic water management policy can be formulated for Hebgen Lake by determining a range of possible reservoir release flows from Hebgen Lake for each month of the year. These will serve as system operation guidelines for each month in the water management process. In the second illustration, physical characteristics of the reservoir system will be altered to illustrate system sensitivity to proposed design changes. In both illustrations, it will be shown that the reservoir system analysis utilizes subjective input in the system analysis procedure.

Development of System Operation Guidelines

In this illustration interactive simulation was used to develop system operation guidelines for Hebgen Lake. System operation guidelines were values of Hebgen reservoir releases for which adverse effects on the system downstream are minimized. Adverse effects could include excessive flooding or insufficient water supply downstream of Hebgen Lake. Synthetically generated streamflows allowed the simulator

to analyze reservoir system behavior under a variety of operating conditions. Adjustments were made to reservoir releases when system constraints were violated. In cases where not all constraints could be satisfied, the analyst had to evaluate constraint trade-offs, subjectively determining which constraints would be violated and which would be satisfied. Indications of system constraint violation limited the possible water release criteria from Hebgen Lake and thus defined the sensitivity and tolerance of release practices for each month. When the reservoir release from Hebgen lake was determined to be an acceptable value, it was noted and the simulation process was advanced to the next month. This continued for the entire twelve-month period of the year. Each year was analyzed independently from each other, with no allowances made for year-to-year dependency. When a situation was reached whereby an acceptable condition for a particular month could not be reached by regulating the Hebgen Lake outflow, then the flows from the previous months were re-analyzed to determine if they should have been altered to avoid the present problem. For example, one problem in managing the Hebgen reservoir releases occurred if too much water was released in the first three to four months of the calendar year. If this occurred, then required reservoir levels for June through September were impossible to meet by the month of June. (2)

After sufficient repetition of the procedure described above, system operation guidelines for each month were developed. Utilizing this procedure and the input shown in Table 2, the Madison River Water Management Simulator can develop system guidelines as shown in Figure 9. The extremes of the values of Hebgen reservoir elevations
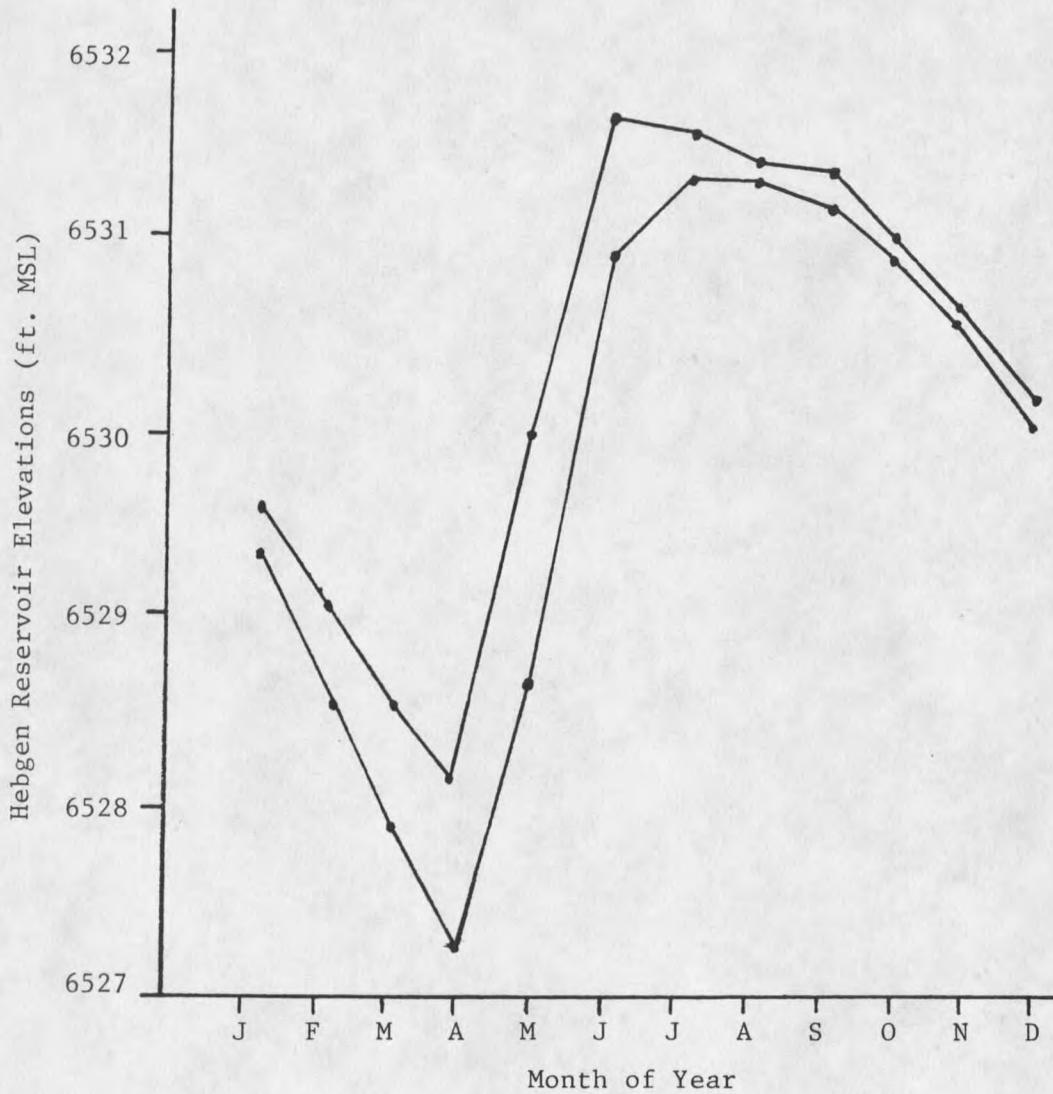
Figure 9. Hypothetical Operation Guidelines Determined for Hebgen Reservoir Using Interactive Simulation.

for each month describe the maximum and minimum desirable monthly water surface elevations. In other words, the interactive simulation technique has shown that if Hebgen reservoir levels are maintained between the two tolerance limits of the bandwidth, then the risk of any adverse effects on the basin downstream of Hebgen is kept within acceptable limits. (3)

It should be emphasized that the limits for the bandwidth do not imply absolute safety from adverse effects if system operation is constantly between these limits. Safe system operation is more likely when system operation is followed as close to the middle of the bandwidth as possible. Sustained operation of the system at or near the higher or the lower limits of the bandwidth can also result in unacceptable system conditions.

These guidelines serve to illustrate the great uncertainty in many water resource management situations. Variation in inflows into the reservoir system and fluctuation in water demands contribute to the system uncertainty. During months with a narrow bandwidth or tolerance, the level of uncertainty is high. Fewer reservoir release values are acceptable during these particular months. (3)

In this illustration it was possible to illustrate the formulation of system operation guidelines in a straightforward manner. In other more complex reservoir systems, with more variables and complications, interactive simulation can also be useful because of the ability to introduce subjectivity into the analysis procedure.

In Figure 10 the actual reservoir system operation policy for Hebgen Lake, based on Hebgen Lake storage data obtained from Montana
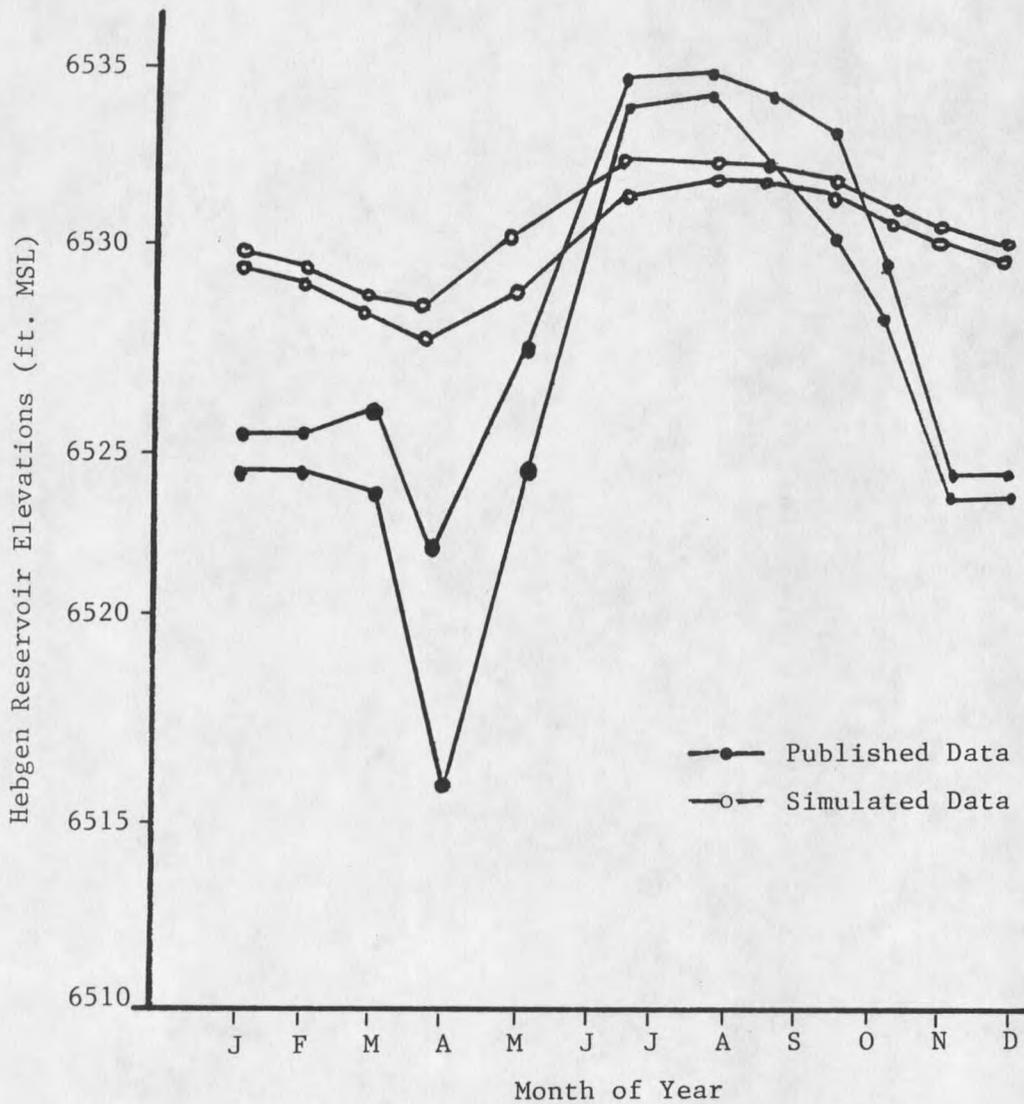
Figure 10. Reservoir Elevations from Published Data and Simulated Data.

streamflow records, is superimposed on the simulator operation guide-
lines from Figure 9. The limits of the guidelines in this figure are
based on the extremes of actual recorded reservoir elevations. These
elevations are based on actual reservoir release policies performed by
the system operators. It is apparent from the figure that reservoir
operation follows a more variable pattern than that which is described
by the simulator. This is due to the fact that, under the simulator
operation, no allowance is made for the effect of snowmelt runoff on
actual system operation. Additionally, no allowance is made by the
simulator for the effect of additional inflow to Hebgen Lake resulting
from sources other than the Madison River inflow. But it is important
to note that in either operation policy, the relative levels of uncer-
tainty from month to month are consistent. Uncertainty and relative
tolerances are still predictable by interactive simulation.

Analyses of Physical Changes

In the following scenarios interactive simulation was used to
illustrate the effect on the reservoir system operation when physical
changes were made to the system. Three separate physical changes were
varied, one in each of three scenarios. As in the development of
system operation guidelines, subjective input was utilized in the
reservoir system analysis procedure by allowing the analyst to correct
system constraints when violations occurred.

Physical Change (Increased Ennis Power Diversion)

In the first scenario a physical change was assumed for the allowable penstock flow at the Ennis Lake powerhouse by increasing the allowable flow from 1600 cfs. to a flow of 10000 cfs. The simulator then executed the program and output values of the reservoir system for each month in the flow sequence. Reservoir release policies from Hebgen Lake were governed such that violations of constraints were eliminated or minimized. Constraint trade-offs were determined by using subjective judgment. For example, required Hebgen reservoir levels were strictly adhered to in all instances. However, satisfaction of constraints such as wildlife nesting, fish spawning, and minimum releases from Hebgen Lake were not strictly adhered to if, in satisfying these constraints, required Hebgen reservoir levels could not be maintained.

The results of the system operation for each allowable penstock flow are shown in Table 4. It is apparent from this table that an increase in average monthly power production can be realized for the three-month period of May through July if the physical change is made. System operation is not greatly affected by this particular physical change. Releases from Hebgen Lake would be essentially unchanged. However, more of the increased flows from spring runoff can be diverted into the higher capacity penstock for increased power production.

Table 4. Average Monthly Flow Diversions and Average Monthly Power
Produced for Power Diversions.

Month	Maximum Q(Power)=1600 cfs.		Maximum Q(Power)=10000 cfs.	
	Q(Power)(cfs.)	Power(KW)	Q(Power)(cfs.)	Power(KW)
Jan.	820	4833	779	4571
Feb.	902	5316	820	4833
Mar.	1025	6041	1025	6041
Apr.	902	5316	1189	7008
May	1230	7250	2010	11841
June	1600	9425	2830	16675
July	1517	8941	1641	9666
Aug.	1107	6525	1107	6525
Sep.	1230	7250	1107	6525
Oct.	1025	6041	984	5800
Nov.	1148	6766	1107	6525
Dec.	984	5800	1066	6283

Physical Change (Increased Head for Ennis Power Generation)

In the second scenario a physical change was assumed for the turbine elevation at the Ennis Dam powerhouse by lowering the turbine elevation from 6754 feet to 6744 feet. The simulator calculated values for all twelve months, as in the previous physical change. Reservoir release policies were also governed, as before, to eliminate or minimize constraint violations, subjective judgment being utilized to determine constraint trade-offs, if necessary.

It is apparent that an increase in average monthly power can be realized for every month of the year due to the increased available head. The total amount of power produced for the entire year is also increased under this physical change. As in the first physical change, system operation of Hebgen Lake is not appreciably affected.

Physical Change (Increased Elevation of Hebgen Spillway)

In the third scenario, a physical change was assumed for the Hebgen spillway elevation by raising the bottom of the spillway from an elevation of 6535 feet to 6540 feet. The simulator operation procedures were the same as for the other two physical changes. The results are shown in Table 5. It can be seen that no appreciable changes occurred in reservoir system operation since inflows are insufficient to affect the upper limit of the allowable Hebgen reservoir level. Even though no changes in system operation were obvious, the interactive simulation technique was still useful, since sometimes

Table 5. Average Monthly Flow Diversions and Average Monthly Power Produced for Spillway Elevations.

Month	Hebgen Spillway Elevation = 6535.26 ft.		Hebgen Spillway Elevation = 6541.26 ft.	
	Q(Power)(cfs.)	Power(KW)	Q(Power)(cfs.)	Power(KW)
Jan.	820	4833	697	4108
Feb.	902	5316	820	4833
Mar.	1025	6041	943	5558
Apr.	902	5316	984	5800
May	1230	7250	1600	9425
June	1600	9425	1600	9425
July	1517	8941	1600	9425
Aug.	1107	6525	943	5558
Sep.	1230	7250	943	5558
Oct.	1025	6041	943	5558
Nov.	1148	6766	1066	6283
Dec.	984	5800	943	5558

structural modifications may result in no appreciable change in system operation.

Conclusions

Based on this investigation, interactive simulation appears to be a viable tool for the analysis, investigation, and screening of water resource system management alternatives. Specifically, this study has demonstrated how interactive simulation can be used to analyze numerous alternatives in order to develop system operation guidelines for a complex, multipurpose reservoir system. These operation guidelines were based in part on subjective judgment of past and anticipated reservoir system behavior. Subjective judgment was also used to evaluate constraint trade-offs for the reservoir system.

It has also been shown that subjective judgment and the consideration of constraint trade-offs can be used by the interactive simulator to evaluate the effects of physical changes on the reservoir system operation. In analyzing the effect of physical changes, the interactive simulator provided an efficient means for determining how the reservoir system would react to each type of change.

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REFERENCES CITED

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APPENDIX

Table 6. Values for Figures 9 and 10.

Month	Elevation (Simulated)		Elevation (Recorded Data)	
	Lower Limit (ft.)	Higher Limit (ft.)	Lower Limit (ft.)	Higher Limit (ft.)
Jan.	6529.32	6529.51	6524.30	6525.00
Feb.	6528.64	6529.10	6524.30	6525.00
Mar.	6527.93	6528.58	6523.30	6525.80
Apr.	6527.28	6528.15	6515.70	6522.00
May	6528.60	6530.01	6523.70	6527.00
June	6530.98	6531.59	6533.50	6534.00
July	6531.26	6531.41	6533.60	6534.10
Aug.	6531.26	6531.29	6531.20	6533.80
Sep.	6531.17	6531.27	6529.70	6532.50
Oct.	6530.89	6530.91	6527.10	6528.00
Nov.	6530.43	6530.47	6523.00	6523.80
Dec.	6529.90	6530.09	6523.20	6523.80

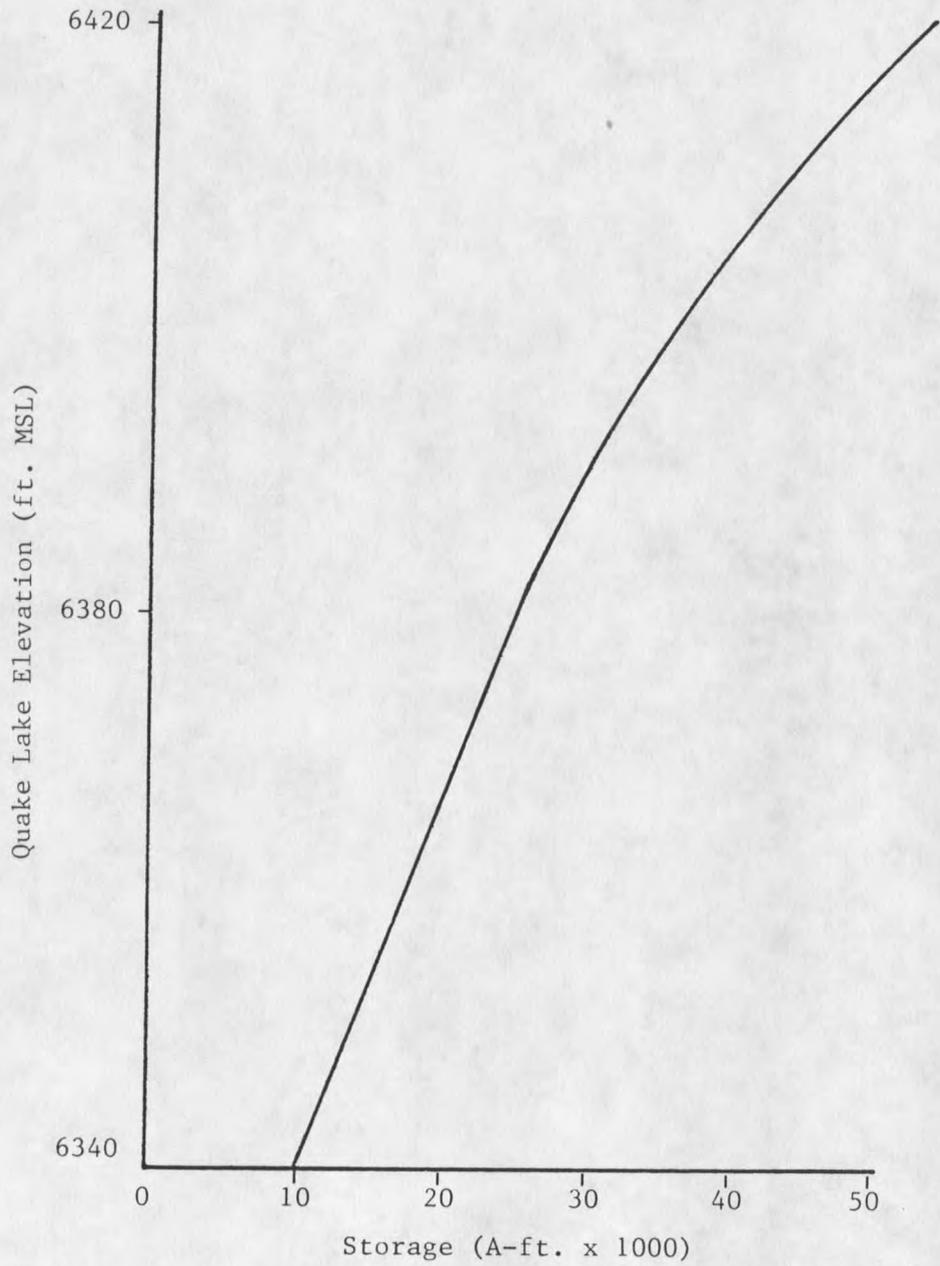Figure 11.   Hebgen Reservoir Elevation vs. Storage.

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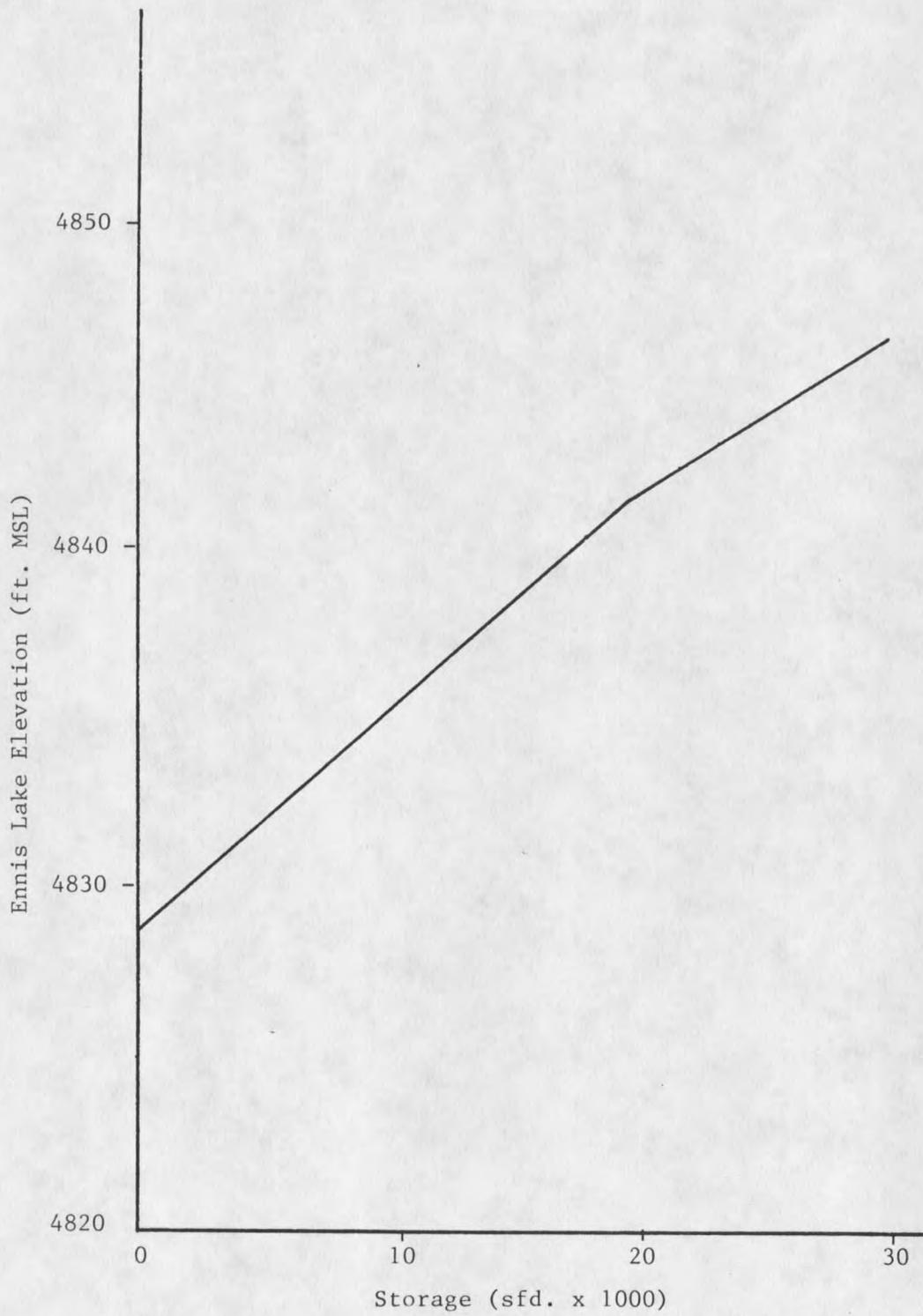Figure 12.   Quake Lake Elevation vs. Storage.

Figure 13.   Ennis Lake Elevation vs. Storage.
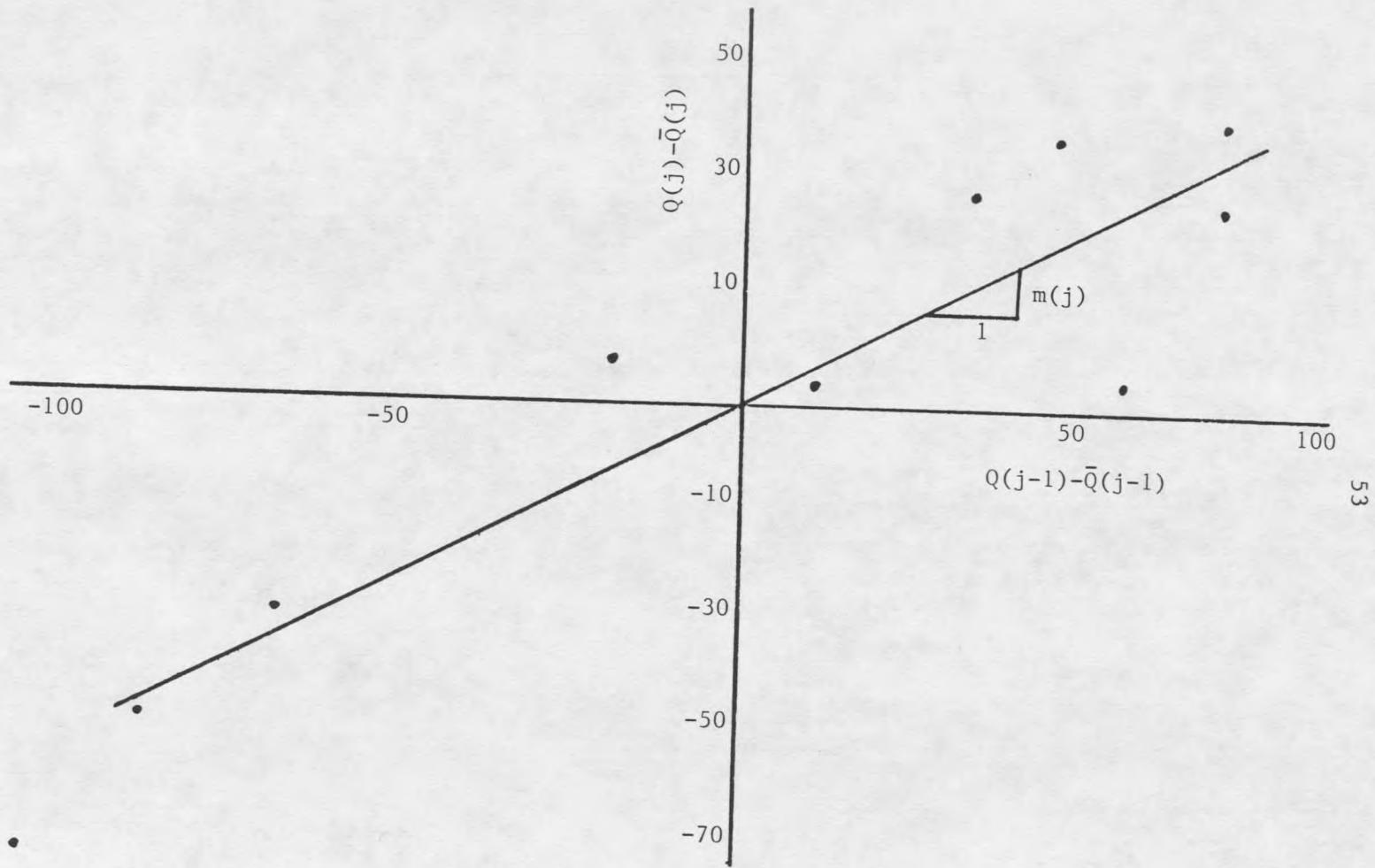
Figure 14. Typical Linear Regression.