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

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.

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of

Master of Science

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Civil Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

March 1986

APPROVAL

of a thesis submitted by

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 — Date

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March 7, 1986 — Date

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Signature Gerald S. Michel

Date Feb. 28, 1986

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

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

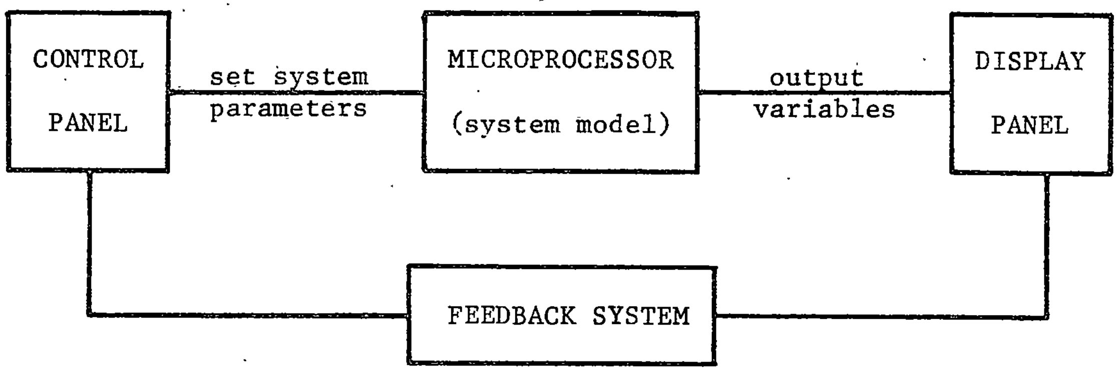

Figure 1. Interactive Simulator Components.

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.

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

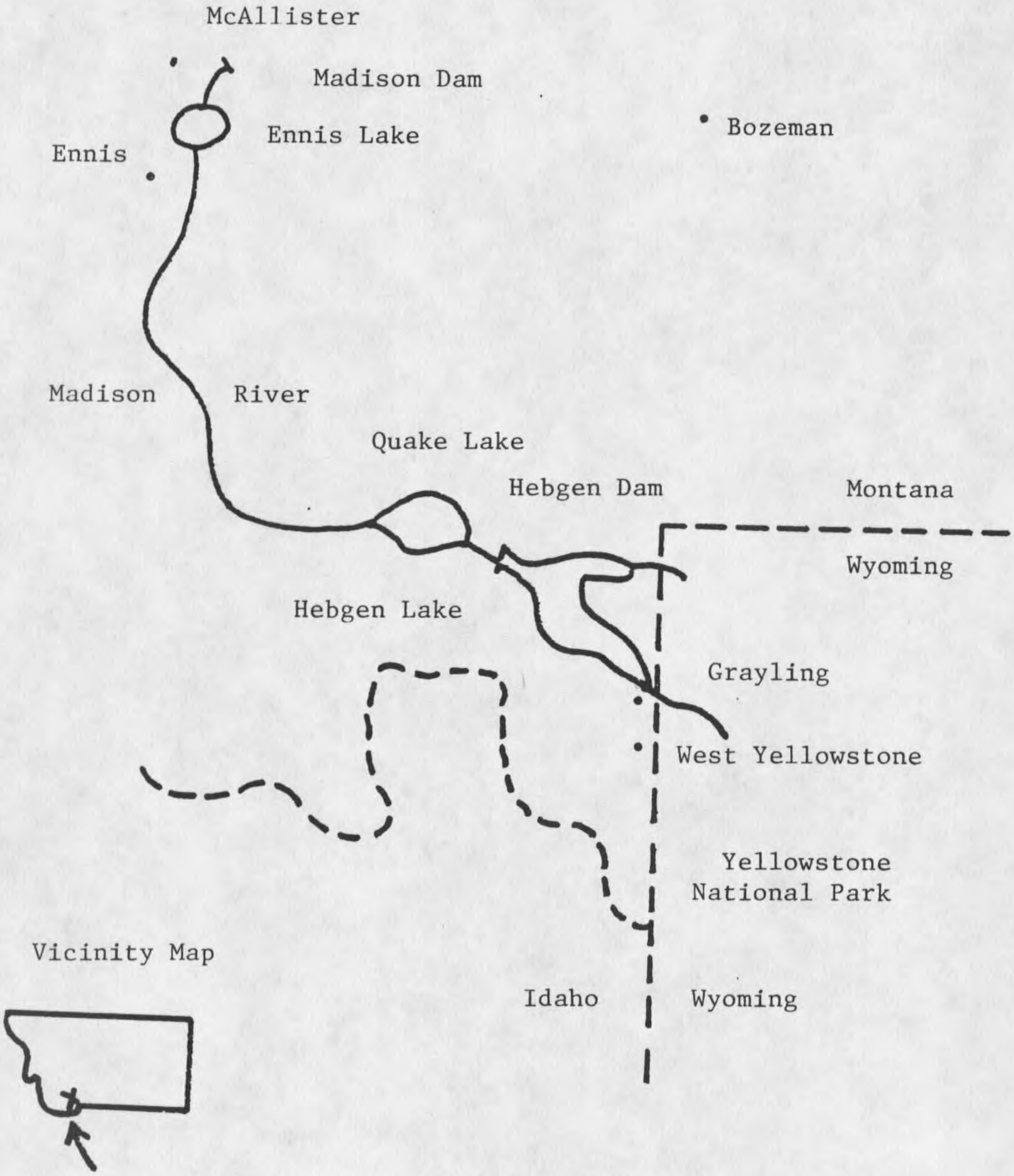

Figure 2. Schematic Map of the Madison River Basin (Not to Scale).

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

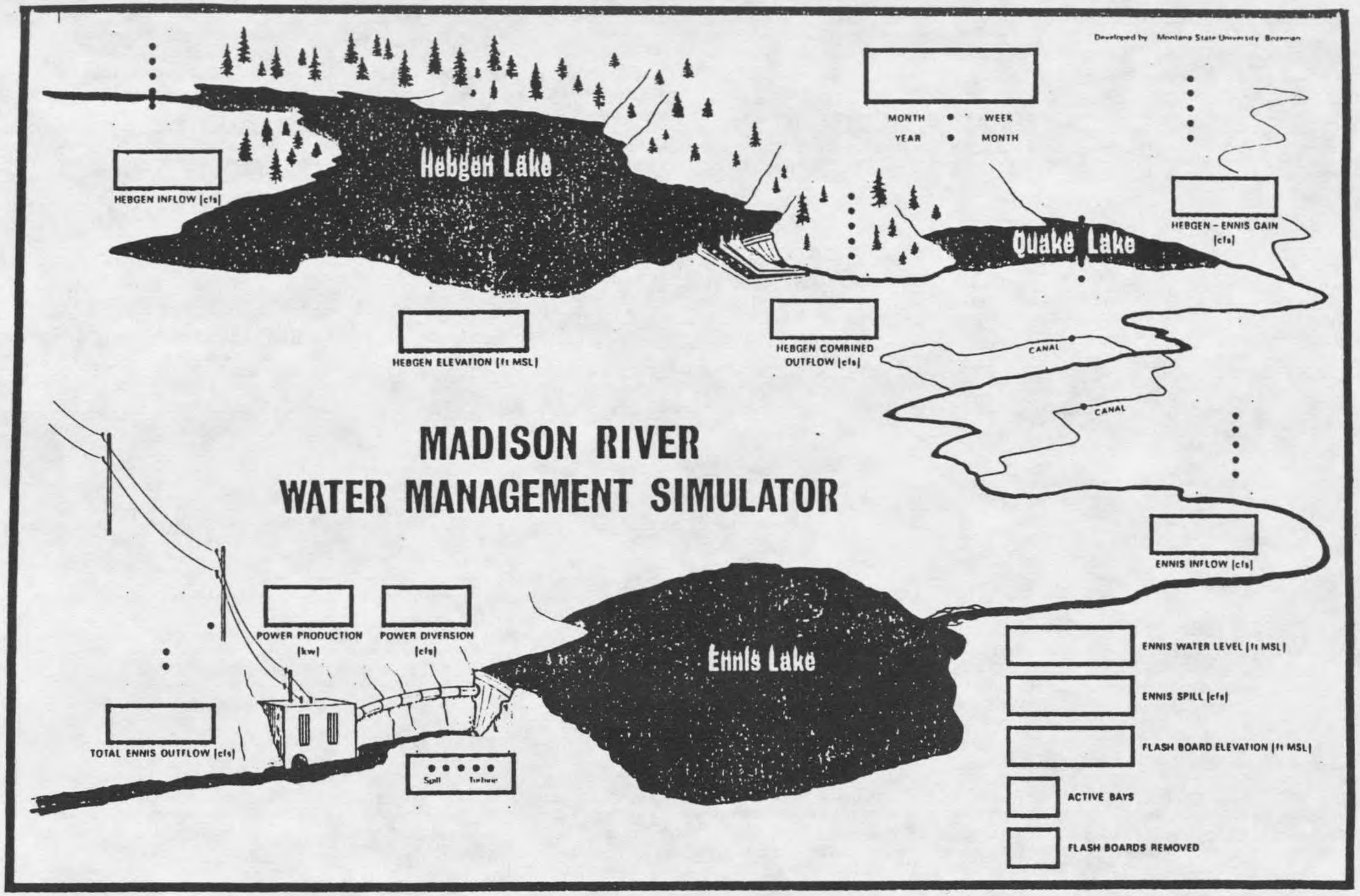

Figure 3. Simulator Schematic.

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

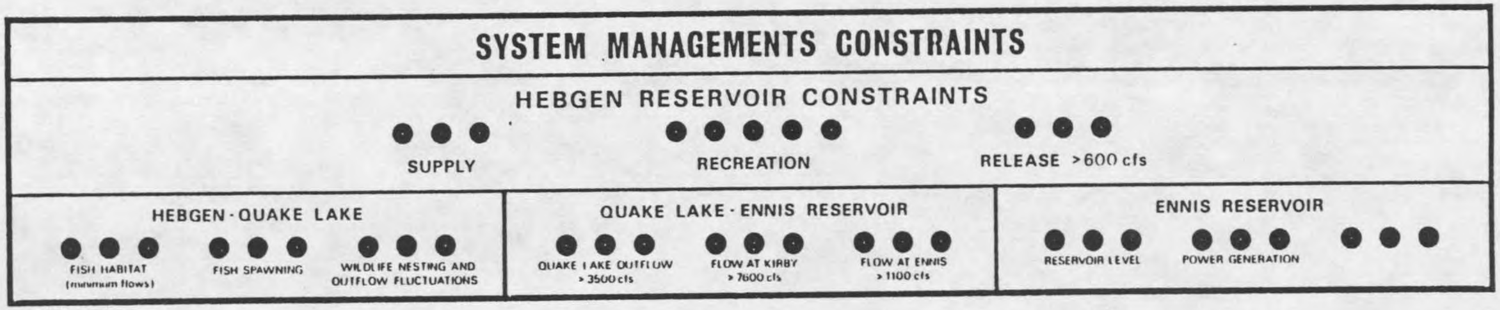

Figure 4. Madison River Constraint Panel.

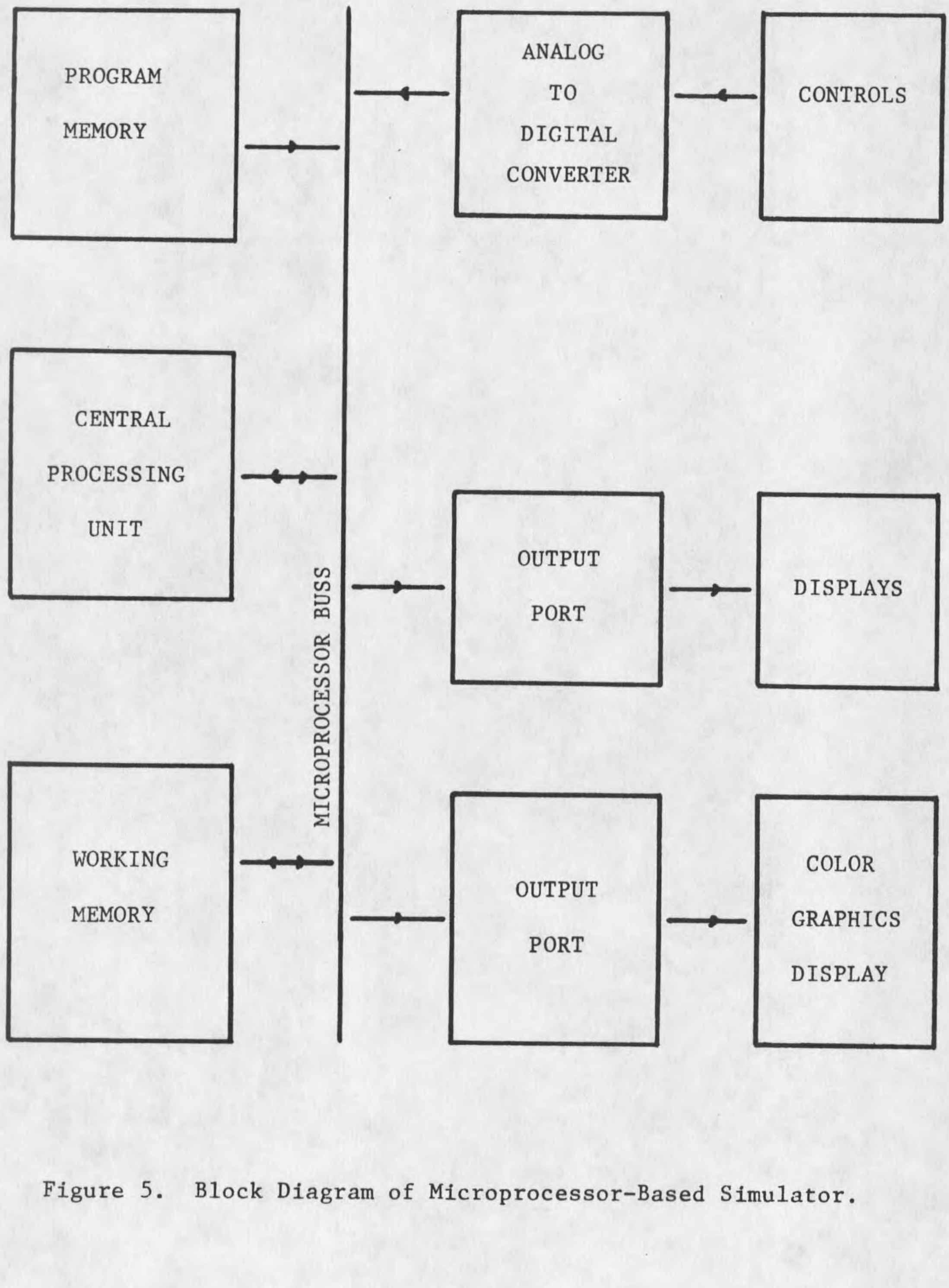

Figure 5. Block Diagram of Microprocessor-Based Simulator.

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 determined, the standard deviation S for each month of the year can be calculated by the following formula:

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

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.

	Hebgen Inflow		Hebgen to Ennis Tributary Inflow			
Month	Mean (cfs)	Standard Deviation (cfs)	Mean (cfs)	Standard Deviation (cfs)	Regression Coeff.	Serial Coeff.
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