DEVELOPMENT OF METHODOLOGIES FOR DETERMINING OPTIMAL WATER STORAGE STRATEGIES

PRELIMINARY REPORT

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ABSTRACT

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Demands for water are rapidly increasing within the State of Colorado. The potential for coal and oil shale energy development could add intense pressure to currently developed water resource systems. To satisfy the growing demands for water, the water resources of the State must be developed. It is clear that additional reservoir storage will be required. Due to a variety of constraints it appears that the number of future reservoir projects may be limited and therefore those reservoirs which are constructed should be designed in an *integrated* fashion to maximize their benefit to the State. It is also apparent that not all demands for water can be satisfied since many demands represent conflicting objectives. The *tradeoffs* between various objectives need to be identified and displayed in such a manner as to facilitate the selection of rational development plans by the appropriate decision makers.

This report presents the initial development of a methodology for determining optimal reservoir storage strategies within a river basin. The methodology employs a computer model OPTRES developed by linking an existing simulation model and an optimization technique. The simulation model describes the operation of a river-reservoir system to satisfy various demand scenarios. The optimization technique determines appropriate sizes of reservoirs to be evaluated by the simulation model. Given a number of possible reservoir locations, the combined simulation-optimization model determines which locations should be developed and the appropriate sizes of the reservoirs at each of the locations, based upon minimizing or maximizing a user specified objective function.

The Yampa River Basin in northwest Colorado was selected as a case study for initial testing of the OPTRES model. The Yampa River Basin is relatively

undeveloped at present; however, over 30 reservoirs have been proposed for the basin. The basin also contains the potential for coal energy development. Information on nineteen proposed reservoir projects for the Yampa Basin were obtained from the U.S. Geological Survey.

Initial tests of the OPTRES model were made using a limited number of proposed reservoirs for the Yampa River Basin and the objective of minimizing total construction costs of the reservoirs and flow shortages at critical demand locations. The results of these tests demonstrate the ability of the model to converge to optimal (not necessarily global) solutions. The results also indicate that the availability of a screening procedure to give good initial estimates for reservoirs sizes for use in the OPTRES model would be a valuable component of the methodology being developed.

Based on the results of these initial tests, further development of the OPTRES model will be continued and is described in the report. Emphasis will be placed on developing interactive conversational coding to facilitate use of the model by persons without computer programming experience. Techniques will be developed to extract and display tradeoff information relative to multiple objectives for water use. To compliment the OPTRES model a screening model based upon a dynamic programming optimization technique will be developed. A description of the proposed screening model is presented.

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CHAPTER I

INTRODUCTION

A. PROBLEM STATEMENT

Planners and managers are facing an increasingly complex task of allocating and managing water resources. This is particularly true in the State of Colorado, where there are rapidly increasing in-state water demands, as well as a substantial dependency by several other States on water originating in Colorado. Demands for water within Colorado are diverse, including irrigation, municipal and industrial water supply, recreation, fish and wildlife maintenance, salinity control, hydropower, and more recently, coal and oil shale energy development. These demands originate from a variety of groups such as federal, state, and local governments, irrigation and water conservancy districts, development organizations and power associations. Additionally, Colorado is regulated to a degree on use of its water by interstate compacts, U.S. Supreme Court Decisions, and an international treaty.

With intensifying pressures on currently developed water resources, it is imperative that water legally available for Colorado be developed and used in the most efficient and beneficial manner possible; otherwise, new demands for water such as energy development can only be satisfied at the expense of existing demands. Since the demands for water vary over time and space, it is often difficult to meet all requirements, especially under constraints of variable hydrology. Reservoir storage is an effective means of reducing the impacts of hydrologic variability and providing a consistent supply of water to meet varying demands. However, the construction of reservoir storage has become increasingly difficult for a variety of institutional, political, financial, and environmental reasons. Since it appears that the number of future reservoir projects may be limited, those reservoirs that are constructed should be designed in an *integrated* fashion to maximize their benefit to the State.

Objectives for reservoir storage are generally site-specific from the perspective of the potential reservoir builder, with little emphasis on the overall impacts of the project. A water resources planner or manager at the State level may be interested in broader objectives than the potential reservoir builder. To accomplish long range planning and assessment of the water resources of the State, the planner or manager needs the ability to evaluate the impacts of a variety of development scenarios on the environment of the basin. In terms of reservoir development, the types of questions the planner may want to evaluate are: a) what is the optimal amount of reservoir storage in a basin for a given set of demands?; b) what is the optimal storage configuration; that is, which sites should be selected and how large a reservoir should be built at each site?; c) how is this optimal storage configuration influenced by type, magnitude, and location of demands?; and d) what are the tradeoffs between various storage and demand strategies?

It should be pointed out that the development of the water resources in a basin involves multiple purposes and therefore multiple and often conflicting objectives that are difficult to place in commensurate terms (e.g., economic benefit of energy development (in $) vs. increases in total dissolved solids (in mg/l)). There are other objectives which are extremely difficult to quantify, such as instream uses and recreation. In this context, there is really no such thing as one overall optimal storage strategy. The term *optimal storage strategy*, as used throughout this report, refers to the best storage strategy for a given limited set of objectives. The process of planning involves determining these storage strategies for a range of target objectives of interest. Tradeoffs between these objectives are then analyzed to find the overall storage strategy which will best serve the needs of the State.

As the demand for water for a wide diversity of uses grows, the potential for serious conflict grows also. An integrated approach to water planning and management will be required to most effectively use our water resources as has been documented by various authors [1,2,3].

One of the tools that water resources planners can use to evaluate effects of various alternatives upon a basin are computer models. Computer models are valuable devices for storing, analyzing, and displaying large quantities of information. They can be designed in order to evaluate a wide range of alternatives. Although the use of computer models is increasing, there still exists a large number of planners and managers who are reluctant to use them. These computer models are often intimidating to a person with little experience in computer programming. Many planners, additionally, lack the time in the context of a given study period to learn the necessary amount of computer programming needed to effectively use a given program. Of course, the planner may have someone familiar with computer programming to actually run the model for him. However, unless there is a high degree of communication between the planner and the programmer, the program will probably not be used as effectively as it could be.

Often, the planner cannot find a computer model completely suited to his needs. There are, for example, two basic approaches to river basin modeling: simulation and optimization. Simulation models can yield a detailed representation of the physical and operational characteristics of a river basin for a specific storage configuration. If the planner wishes to compare various storage configurations, he must simulate each configuration separately and then compare the results. There is unfortunately, no guarantee that the configuration selected is indeed optimal due to the limited number of alternatives considered. Optimization models can be used to select the optimum storage configuration, but generally require simplification of the physical and operational characteristics of the system. The results, however, can be checked using a simulation model. If discrepancies occur, the optimization model may have to be modified and the process repeated until compatibility is achieved.

Attempts in the past to overcome these difficulties in model usage, model type, etc., have often led to the development of new models, with the unfortunate consequence that the planner or manager is more confused than ever. There are techniques available that can be used with new or existing models to overcome most of the difficulties previously mentioned.

B. STUDY OBJECTIVES

The primary objective of this study was to develop a methodology to be used by water resources planners and managers to evaluate optimal water storage strategies for Colorado. The methodology is based on a computer model linking an existing river basin simulation model and an existing optimization model. By linking simulation and optimization, the best advantages of both models are preserved, while retaining the integrity of the existing models. Interfacing is accomplished by developing a main program to link the models; with various subroutines to provide the required input and output conversions. This modular concept is employed so that the general model structure can be retained even if different simulation or optimization models are used.

The overall model is written such that a maximum amount of interfacing can be accomplished in the interactive mode. The use of interactive conversational coding greatly expands the ability of the non-computer oriented planner or manager to use computer models. In concept, the computer program questions the user to determine the input needed for the model. It then produces a summary of the output as desired by the user. Detailed output can be written on a file and routed to a high speed line printer if desired. This type of overall model allows a planner to look at a variety of alternatives and compare results simply by responding to a series of questions about the project. An understanding of computer programming language, such as FORTRAN, is not required. It also facilitates his ability to go back and change certain aspects of the system he is analyzing and note the effects.

This report documents the development of the combined optimization-simulation model and recommends future efforts. The components of the model are described as well as the initial testing of the model in a demonstration study of a river basin in Colorado. Although the initial model testing was based on an economic objective of minimizing cost, it should be emphasized that the model was developed to analyze tradeoffs between a variety of objectives. It is hoped that future research will demonstrate more fully the capabilities of the developed model.

CHAPTER II

RIVER BASIN SIMULATION MODEL

A. MODEL SELECTION

An existing river basin simulation computer model was desired for this study. It was required that the selected simulation model be able to realistically represent the physical and operational characteristics of river basins in Colorado. Therefore, only river basin simulation models that had previously been applied to Colorado river basins were considered. Three existing simulation models (i.e., Longenbaugh and Wymore, 1977; U.S. Army Corps of Engineers, HEC-3, 1974; Ribbens, 1973) were identified and reviewed. These models had been applied to the White and Yampa River Basins. Other models, such as CORSIM, [4] have been applied, but were inaccessible to these authors due to their proprietary status.

The first of these models is actually a group of models which form the "Integrated Program for Analysis of Water for Energy Development" (IPAWED) Package. The development of the IPAWED Package and its demonstration application to the White River Basin is described in detail by Longenbaugh and Wymore [5]. In summary, a methodology was developed to combine various computer models (hydrologic, water rights, and economic) with the Colorado Water Data Bank. The developed "package" could be used to assist planners in making decisions about water project development, particularly with regard to energy development. The IPAWED Package consists of four main groups of programs: data retrieval, data analysis, hydrologic and economic analysis, and output display. Within the hydrologic and economic group, the reservoir-river basin simulation was handled by a model named RESERV. The RESERV Model is an adaptation of the U.S. Army Corps of Engineers HEC-3 Model, to interface with the other components of the IPAWED Package. The HEC-3 Model will be described later in this report.

The final two models were obtained from the U.S. Geological Survey in Denver, Colorado. Through meetings between the authors and personnel of the Water and Power Resources Service and the U.S. Geological Survey, Denver, Colorado, it was learned that both the HEC-3 Model and a River Network Program developed by the Water and Power Resources Service had been applied to the Yampa River Basin [6]. These models were used in various studies conducted by the U.S. Geological Survey to determine the effect of proposed energy development upon the water quality of the Yampa River.

The HEC-3 Model [7] was developed by the Hydrologic Engineering Center, U.S. Army Corps of Engineers to simulate the operation of a reservoir-river basin system for such conservation purposes as water supply, irrigation, recreation and hydroelectric power. The model represents the river basin by a node-link network. The nodes or control points represent either reservoirs or non-storage points where flow constraints or targets can be defined. The links represent the flow conveyance between nodes. Operating criteria can be established for each reservoir and the model will simulate the operation of the reservoir system to meet specified targets or constraints. An illustration of the representations of a river basin system by the HEC-3 Model is shown in Figure 1.

The final model considered was the River Network Program [8] written by Richard W. Ribbens of the U.S. Water and Power Resources Service. The Ribbens Model is capable of routing flows and salts (total dissolved solids) through the reservoir system. Salt is treated as a conservative substance and precipitation and dissolution of salts are not explicitly simulated. This model also employs a node-link basin representation; however, the links between geographically adjacent nodes define the physical elements of the system. The links or elements define the upstream and downstream boundaries, river reaches, junctions and reservoirs. The nodes delineate elements and provide points for desired model output. Like the HEC-3 Model, operating criteria can be established for each reservoir.

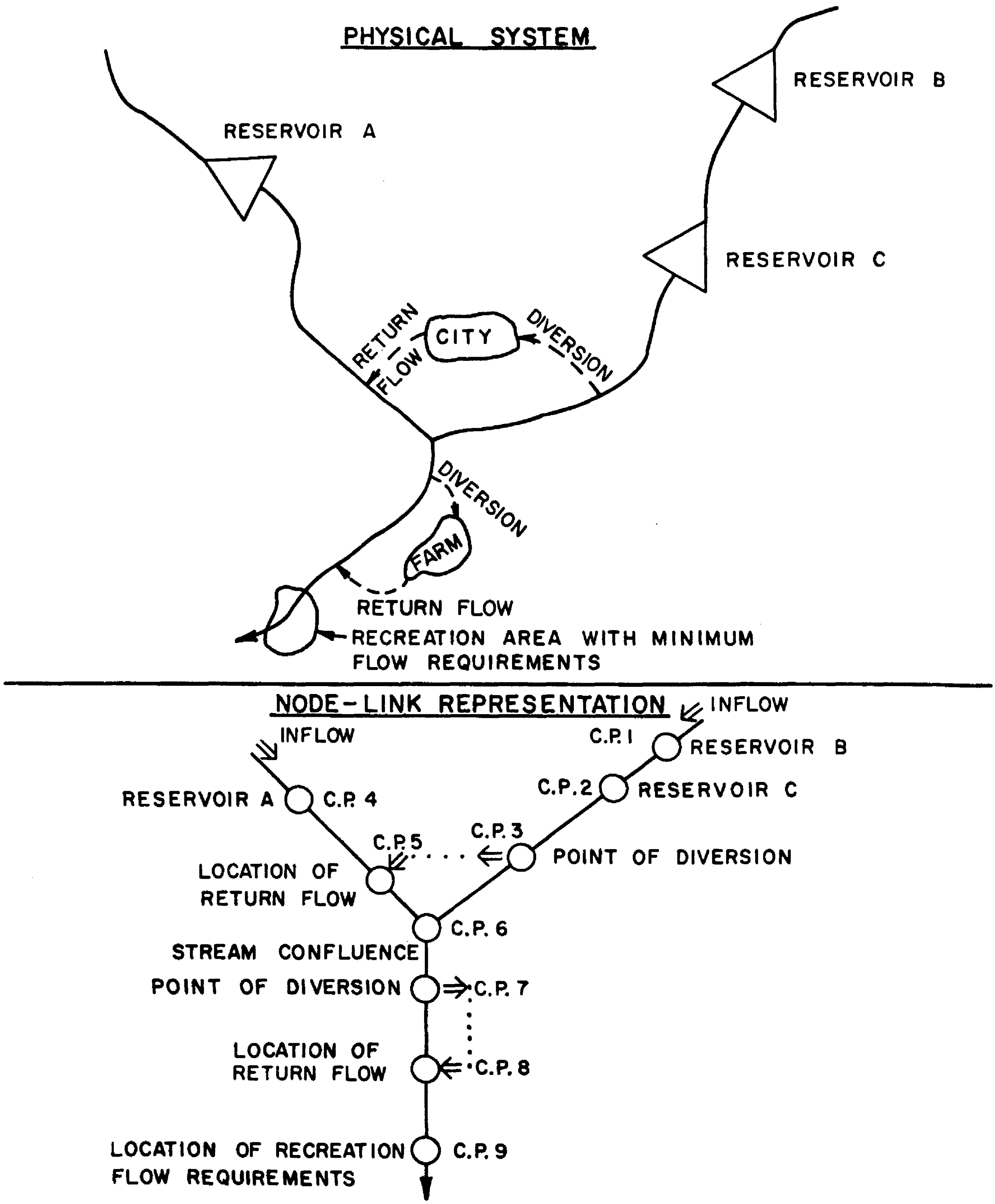

Figure 1. Example of the HEC-3 node-link representation of a hypothetical hydrologic system.

Both the HEC-3 and Ribbens Models were placed on the Colorado State University computer system so that comparison runs could be made. The RESERV Model was not tested since the computations are identical to the HEC-3 Model. Although the U.S. Geological Survey had applied both models to the Yampa Basin, the data input was significantly different. The HEC-3 Model was dimensioned to handle up to 30 reservoirs while the Ribbens Model was dimensioned for a maximum of five. The Geological Survey had used the HEC-3 Model with 50 years of monthly input data for their calibration runs and analysis of various storage scenarios. The model included approximately 20 reservoirs, although not all of these had specified active storage for any given run. The application of the Ribbens Model was primarily to evaluate the effect of reservoir storage on the salinity of the Yampa River. For these runs, they used 20 years of monthly input data and combined various reservoirs to meet the current dimension limitation of a maximum of five reservoirs. Since direct comparisons of computational requirements of the two models could not be ascertained from the studies by the U.S. Geological Survey, a set of test data was developed for comparison purposes. The test data set was based on a data set for the Yampa Basin used in the Ribbens Model and consisted of two years of monthly input data and a five reservoir system, with some of the reservoirs actually representing aggregations of several reservoirs.

Comparison of required execution times for the test data set showed that the HEC-3 and Ribbens Model had essentially the same computer requirements. The HEC-3 Model was selected as the simulation model to use for this study, and was chosen for the following reasons:

1. As will be discussed later in this report, the Yampa River Basin was used as the case study for this work. Of the models reviewed, the HEC-3 Model had the most complete data set for the Yampa.

2. The HEC-3 Model had been calibrated for the Yampa Basin by the U.S. Geological Survey. This would facilitate comparison of results from this study with results from the studies of the Geological Survey.

3. If it were decided later in this research effort to apply the developed programs to the White River Basin or some other basin, the transfer from the RESERV Model to the HEC-3 Model should be straightforward.

Although an updated reservoir river basin simulation model HEC-5C [9] has been developed by the Hydrologic Engineering Center to replace the HEC-3 Model, it was decided that the HEC-5C Model was too large and complex for the objectives of this study.

B. HEC-3 PROGRAM DESCRIPTION

The HEC-3 Model is fully documented in the user manual [7] for the program. Some of the salient features of the code of importance to this study are described in this section.

The basic components of the river basin system which are modeled are the system hydrology, reservoirs, control points, power plants and diversions. The system hydrology is accounted for by specifying inflows, local flows and evaporation by location (node or control points), magnitude and time period of occurrence. Physical reservoir characteristics are described by elevation, storage, surface area and outlet capacity data.

The operating criteria for the reservoirs are provided by dividing the reservoirs into between four and eight imaginary levels as shown in Figure 2. The lowest level corresponds to the top of the inactive pool and the highest level to the top of the flood control pool. Reservoirs are operated to meet flow targets at specified control points in the systems. Water is withdrawn from the upper storage zone first (the zone between the two highest levels). The program attempts to keep all reservoirs in the system at the same level. If multiple reservoirs are providing flow to a common control point, proper choice of

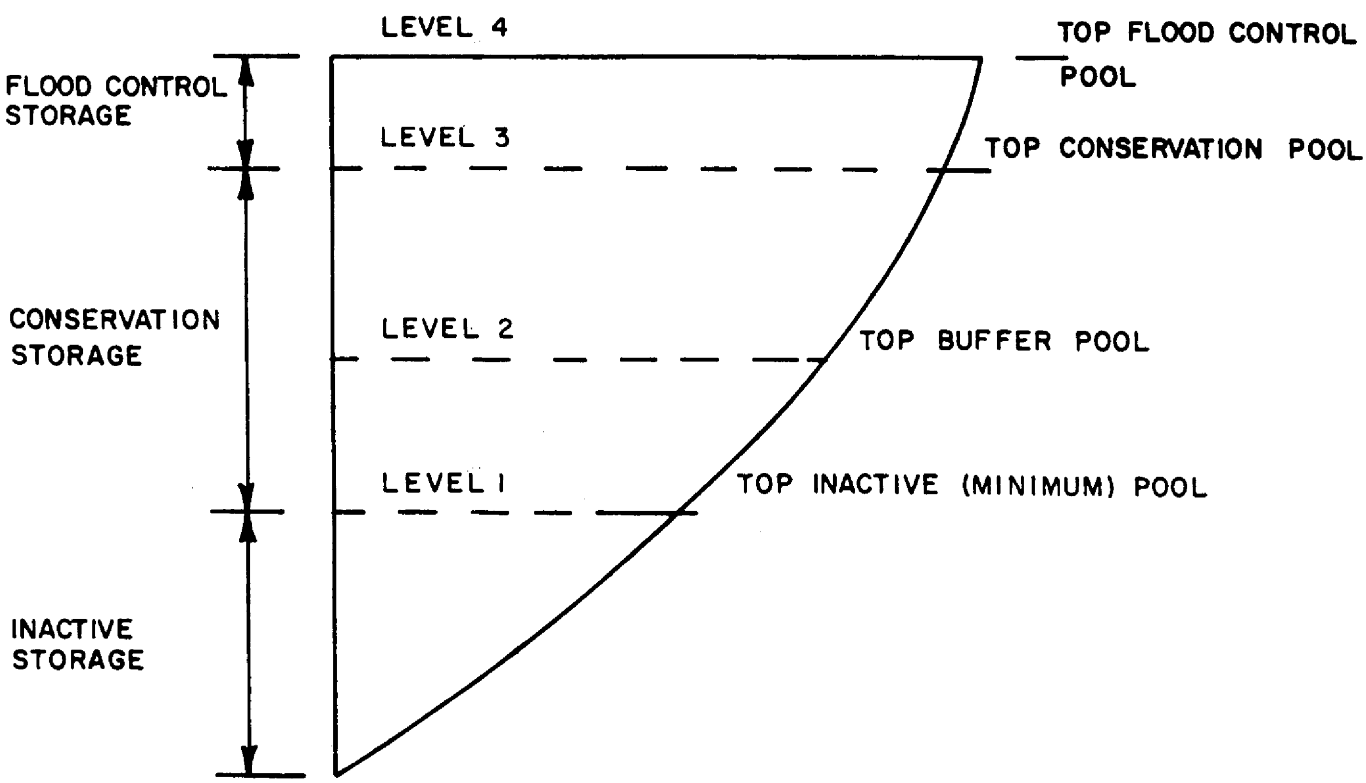

Figure 2. Basic reservoir levels used by the HEC-3 Model for specifying reservoir operating rules.

reservoir levels can be used to establish release priorities among the various reservoirs.

Non-storage control points are used to set constraints and targets for flows in the system. Maximum permissible flows, minimum desired flows, and minimum required flows can be specified at control points. The flows may be constant over the entire simulation period or vary by individual time period. Flows are constrained to the maximum permissible unless spill is occurring. Target flows are set to the minimum desired unless the reservoir goes into the buffer zone. If reservoirs are in the buffer zone, target flows become the minimum required flows. Hydropower calculations are based upon average flow, average effective head and generation efficiency for each period.

Diversions or return flows are specified at control points and only one diversion or return flow can be specified at a given control point. The diversion may be specified by an actual magnitude or as a function of flow or reservoir storage. Return flows are specified only as a function of a diversion at one upstream point. The HEC-3 program can also provide an economic analysis (based upon user supplied economic functions) of meeting desired flow, storage or power generation targets at specified control points.

The period of computation for the model is variable, although a monthly time period is commonly used. Since hydrologic computations are based upon the principle of continuity, time periods selected should equal or exceed travel time between nodes and within reservoirs. The HEC-3 Model initiates computation at the upstream control points and proceeds downstream; attempting to satisfy flow targets at all control points in a sequential fashion. If additional releases are required to meet system power requirements, the model goes back through the system and allocates additional water if it is available. This procedure is accomplished for each time period with the ending storage for one period becoming the initial storage for the next. Results from the computations including flows, storages, and power generation are stored for all control points for each time period. Output of this information can be accomplished through various options available to the user.

The version of the HEC-3 Model obtained from the U.S. Geological Survey had two modifications from the original code. The original code was dimensioned for a total of 40 control points, while the Geological Survey version is dimensioned for a total of 50. Additionally, the Geological Survey modified the model to compute maximum and minimum flows, median flows and 80 percent exceedance flows. The HEC-3 code was also modified by the authors in the development of the linked optimization-simulation model. These modifications are discussed in Chapter III.

CHAPTER III

COMBINED OPTIMIZATION - SIMULATION MODEL

A. MODEL FORMULATION

The combined optimization - simulation model presented herein, OPTRES, is based substantially on the work of Wurbs [10]. Wurbs linked a search algorithm with a hydrologic and economic simulation model to determine the optimum configuration of structural and non-structural measures for reducing flood damages. His objective was to minimize the total system costs, defined as the sum of the costs of the structural and non-structural measures and the expected annual flood damages for a given system configuration.

The hydrologic portion of the Wurbs simulation model divides the stream system into a series of stations. The stations represent points of interest such as tributary confluences or specific damage areas. Inflow hydrographs of varying frequencies are routed through the system and peak discharge-frequency functions are developed for each station. From these functions and stage-discharge functions, frequency-stage relations are also developed for each station. The inclusion of structural measures affects the frequency-stage relations for the stations in the system.

The economic and non-structural optimization portion of the simulation model consider the effect of a non-structural measure by defining a stage-damage function and an implementation cost associated with each non-structural measure. For each station, the frequency-stage function developed in the hydrologic portion of the model is combined with the stage-damage function for each non-structural measure, which yields a frequency-damage function. The integral of the frequency-damage function yields the expected flood damages. By combining the expected flood damages and implementation cost for each non-structural measure, the optimum non-structural measure for that station is selected as the one with the minimum value of that sum. After the costs of the non-structural measures and associated expected flood damages are assessed for all stations, the costs of the structural measures are added; yielding the total system cost.

The search technique is used to size the structural measures. For a selected set of structural measures, the hydrologic simulation is run to determine the frequency-stage functions and then the economic and non-structural optimization computations are performed to find the optimum non-structural measures and the total system costs. The search technique then selects a new set of sizes for the structural measures and the process is repeated. The search technique continues to select structural sizes until the set of structural sizes that minimizes the total system cost are found. Wurb's procedure is illustrated in Figure 3. It should be noted that the minimum found by the search technique is not necessarily the global minimum since this problem is nonconvex.

Wurbs evaluated two search techniques for use in his combined optimization-simulation model; the cyclic search and Powell's method of conjugate directions. The cyclic coordinate search technique minimizes along coordinate directions only. For example, if the problem to be minimized has two decision variables, then the second variable is held at a constant value and the problem is minimized with respect to the first variable. The first variable is then held constant at that minimum value and the problem is minimized with respect to the second variable. The process is then repeated until the values of the variables converge to a solution. The Powell method is not limited to only searching along the coordinate directions, but can generate a search direction termed a conjugate direction. The use of conjugate directions results in an increased efficiency of convergence. Wurbs compared the two search techniques from the standpoint of run time and number of iterations required to reach convergence. Also, he found his objective function

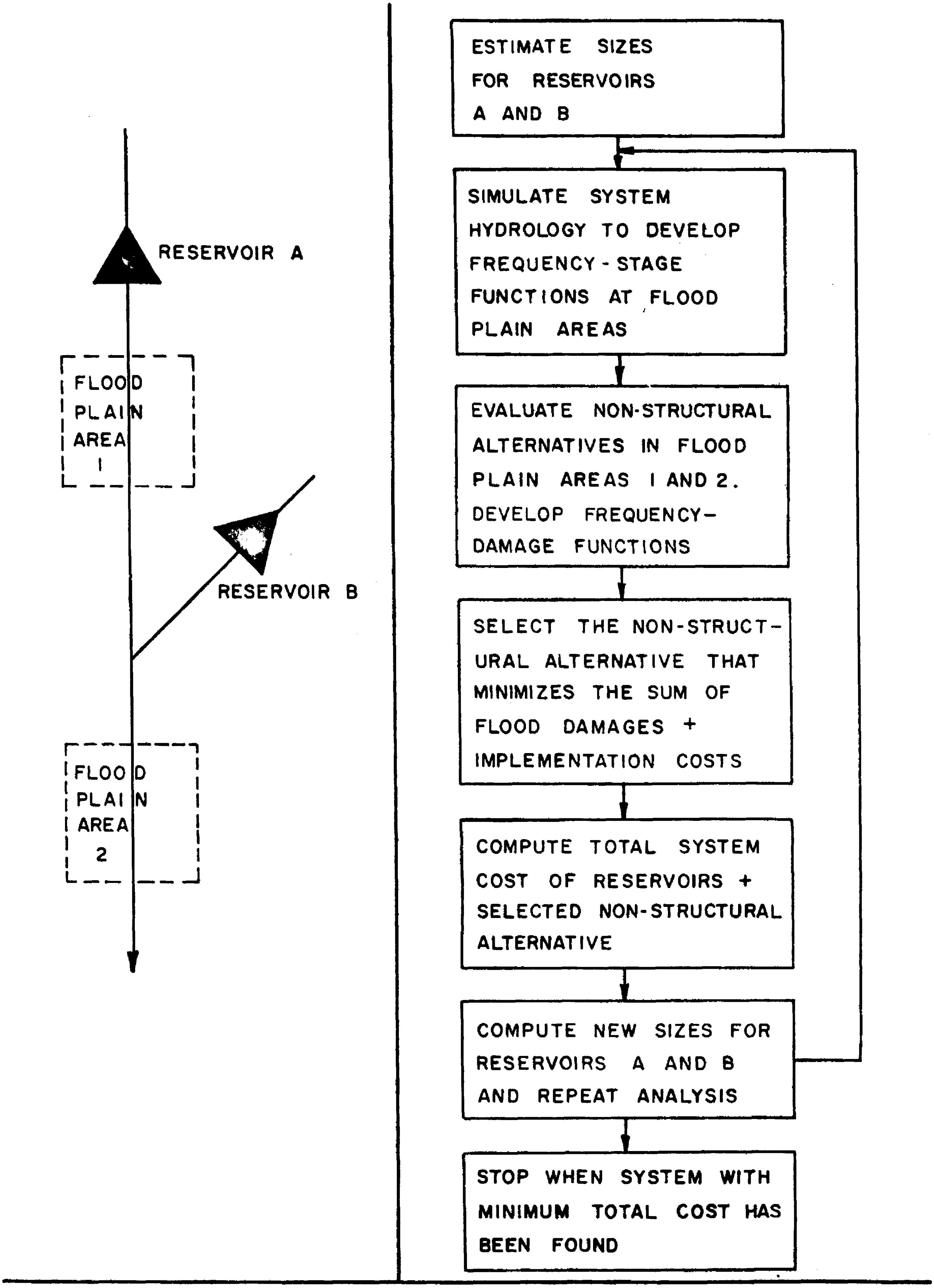

Figure 3. Application of Wurb's procedure to a hypothetical flood damage reduction system.

(total systems cost) to be multi-modal and by starting the model at various initial values for the structural measure sizes, the ability of the two search techniques to converge to the same minimum value was evaluated.

Based upon the evaluation of the two search techniques, Wurbs concluded that the Powell method was more efficient (i.e., required less computer run time) than the cyclic coordinate search in finding the optimal structural sizes. He also found the Powell method to be considerably more reliable in finding the same minimum value from various initial starting points.

As a result of the experience of Wurbs, it was decided that the initial formulation of the OPTRES model would be made by linking the HEC-3 simulation model with the Powell conjugate direction algorithm. The feasibility of using the HEC-3 simulation model in a linked model concept had been demonstrated by Claure-Pereira at the University of Texas [11]. Claure-Pereira developed a linked model to maximize the average annual economic returns for the Arkansas-White-Red-Osage River System. He used the HEC-3 model as the simulation model and developed a generalized heuristic procedure to automatically adjust operational policies of the HEC-3 model so that improved operation of the system would result. The technique basically involved adjusting target demands to maximize firm hydropower generation and firm water supply. While this heuristic procedure was not an optimizing search technique in the sense that it did not necessarily find a maximizing value, the procedure performed much like a search technique by continuing to adjust variables (in this case operational policies) so that the performance of the system was improved. His work demonstrated that the HEC-3 simulation model could function as a part of an overall linked model.

B. DESCRIPTION OF THE POWELL ALGORITHM

The Powell algorithm was developed by M. J. D. Powell [12] to find the minimum of an unconstrained, multivariable nonlinear function, without the need for calculating derivatives. The computer code of the Powell algorithm was obtained from Kuester and Mize [13]. The procedure begins by searching along the coordinate directions (i.e., it minimizes the function with respect to one variable at a time) from an initial starting point. The search along any direction (single variable searches) is made using quadratic approximation. Three function values are determined which fall on either side of the minimum. The minimum is then approximated by a quadratic interpolation routine.

Once the sequence of searches along the coordinate directions is completed, the final point from that sequence is retained. An expanded point is then located along the direction between the initial point and the final point. It can be shown that this direction is a conjugate direction. Two tests are conducted to determine if the conjugate direction is an improvement over the coordinate directions. If it is not, then the final point from the previous sequence of searches is redefined as the new initial point and a new sequence of searches along the coordinate directions is performed. If the conjugate direction is found to be an improved direction, then a search is performed along that conjugate direction to find the minimum point. That minimum point then becomes the new initial point and a new sequence of searches is then conducted. For this sequence of searches, however, one coordinate direction is discarded in favor of the conjugate direction so that the search directions are along the conjugate direction and the remaining coordinate directions. This process of discarding coordinate directions in favor of conjugate directions is continued until the minimum point is found. That minimum point is achieved when the difference between points generated by successive iterations is less than some specified tolerance. The procedure of Powell's algorithm for a two variable function is illustrated in Figure 4.

Conjugate direction methods were developed to minimize quadratic functions.

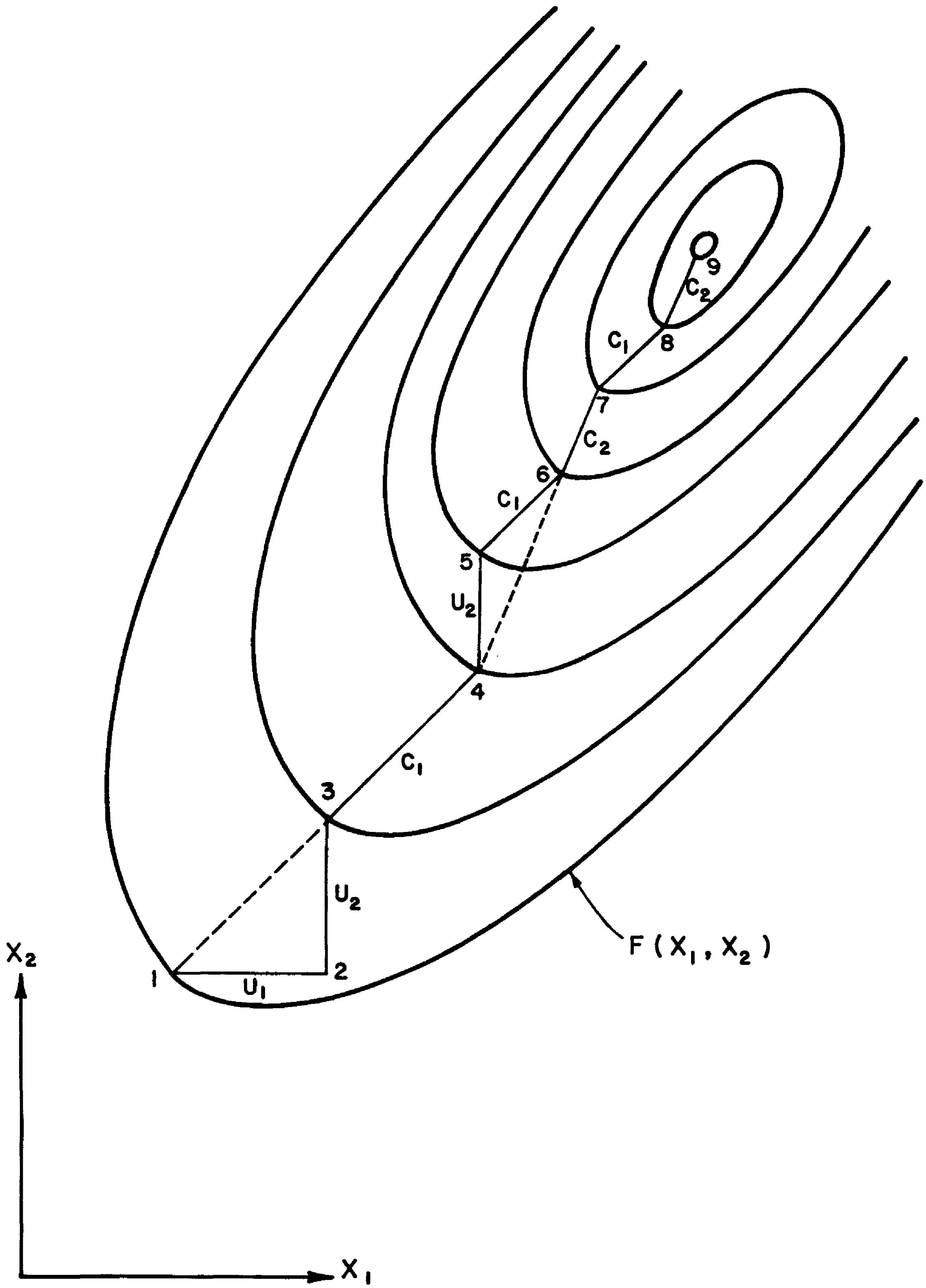

Figure 4. Progress of Powell's algorithm for a two-variable function.

If the function to be minimized is a quadratic function, then it can be shown that the function can be minimized in n sequences of searches, where n is the number of variables. While this convergence (termed quadratic convergence) can not be asserted for problems with other than quadratic objective functions, such as used in this study, the method is still quite powerful. This fact was demonstrated by the work of Wurbs [10].

C. MODEL DESCRIPTION

The general manner in which optimization and simulation models are linked is shown schematically in Figure 5. An interfacing program is used to control the interaction between the models. The simulation model is used to simulate the system for a given set of values of the decision variables and then the performance of the system is evaluated. The optimization model determines a new set of values for the decision variables and these values are then simulated. This general linkage scheme was used in the development of the OPTRES model. Emphasis was placed on retaining, to the maximum degree possible, the integrity of the HEC-3 model and the Powell algorithm. Integrity primarily refers to the input required for these models. For example, the input required for the simulation portion of the OPTRES model is *identical* to the input required for HEC-3.

The combination of the HEC-3 model and the Powell algorithm have been developed to incorporate two features not available in the model developed by Wurbs. As mentioned previously, the OPTRES model is designed such that as much input and output as practical could be accomplished in the interactive mode. The use of interactive conversational coding can greatly expand the ability of the non-computer oriented planner or manager to use computer models. The second feature of the OPTRES model is that the performance evaluation or objective function is not limited to minimizing cost. Even though initial testing of the OPTRES model used cost minimization

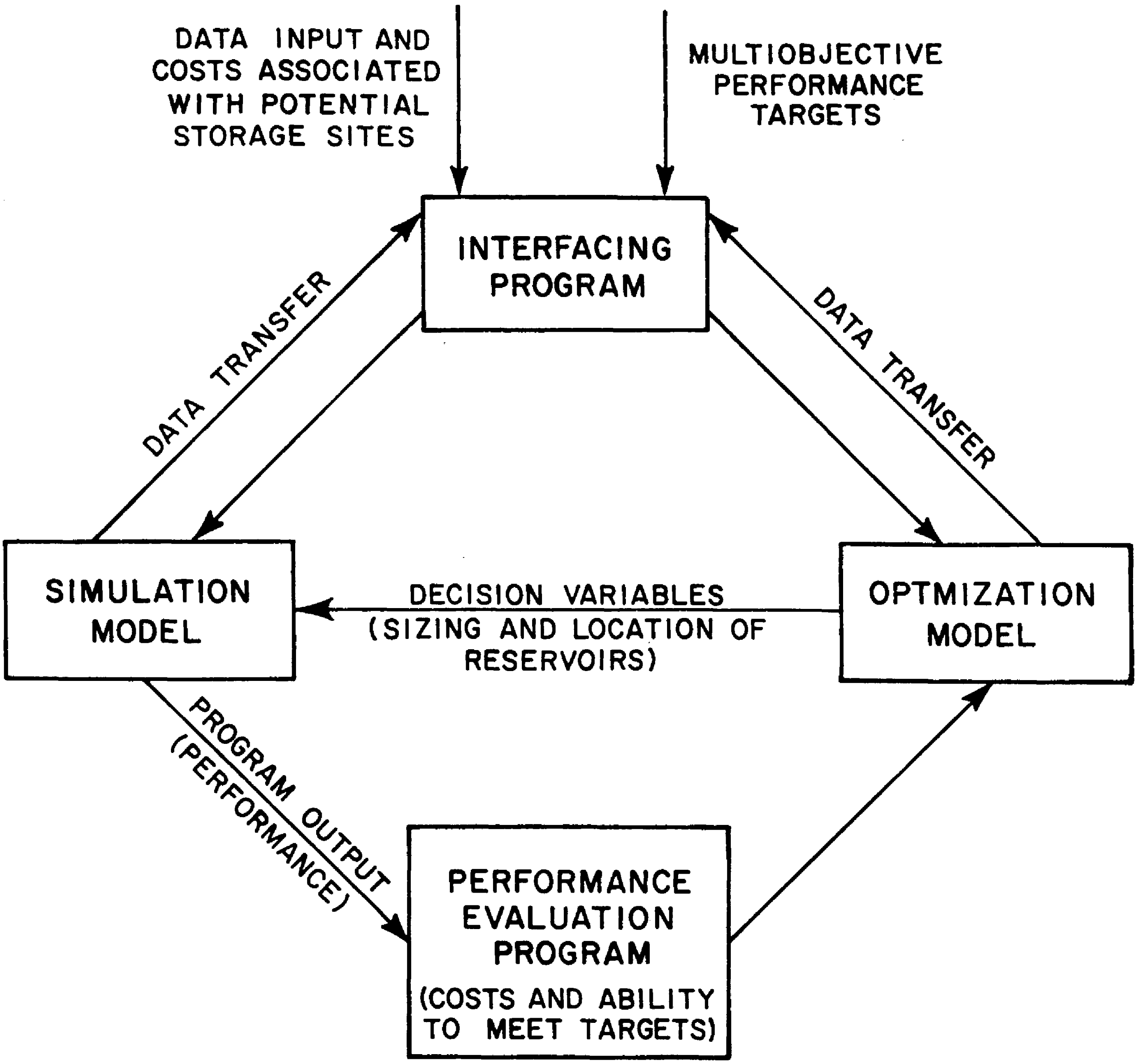

Figure 5. Linkage of simulation and optimization models.

as the objective function, the objective function can be user supplied. This feature was added for multiple objective analysis.

The OPTRES model also differs with respect to its linkage, as compared to the work of Claure-Pereira which is linked by manipulation of input and output files. The HEC-3 model output is written on an output file which was analyzed by his heuristic procedure. A new input file is then created and used to drive the next iteration of the HEC-3 model. For the OPTRES model, the HEC-3 model and Powell Algorithm are directly linked by sharing COMMON core memory in the computer. While this type of linkage required some modification of the HEC-3 model, it minimizes file manipulation and increases the computational efficiency of the combined model.

The linkage of the HEC-3 model and Powell algorithm is illustrated in Figure 6. The overall model was initially tested using data for the Yampa River Basin, which contains information on 19 proposed reservoir projects. The data on all of these projects is available to the HEC-3 model (now a subroutine of the overall model). Initially, all reservoirs have zero active storage. The user furnishes the main program with the number and location of reservoirs he wishes to consider (from the 19 available) and information on initial reservoir size and convergence criteria for the Powell algorithm. The main program then initializes the HEC-3 model and calls the Powell algorithm (subroutine SEARCH) to determine reservoir sizes for the reservoirs of interest. The Powell algorithm calls the HEC-3 model, which in turn calls subroutine STORSET. This subroutine makes the selected reservoirs active and sets reservoir levels of active storage to correspond to the reservoir size. The HEC-3 model then simulates the system for a selected period of time. The performance of the system was initially evaluated based upon minimizing reservoir costs subject to meeting a desired flow constraint at a specific point of interest in the basin. A penalty

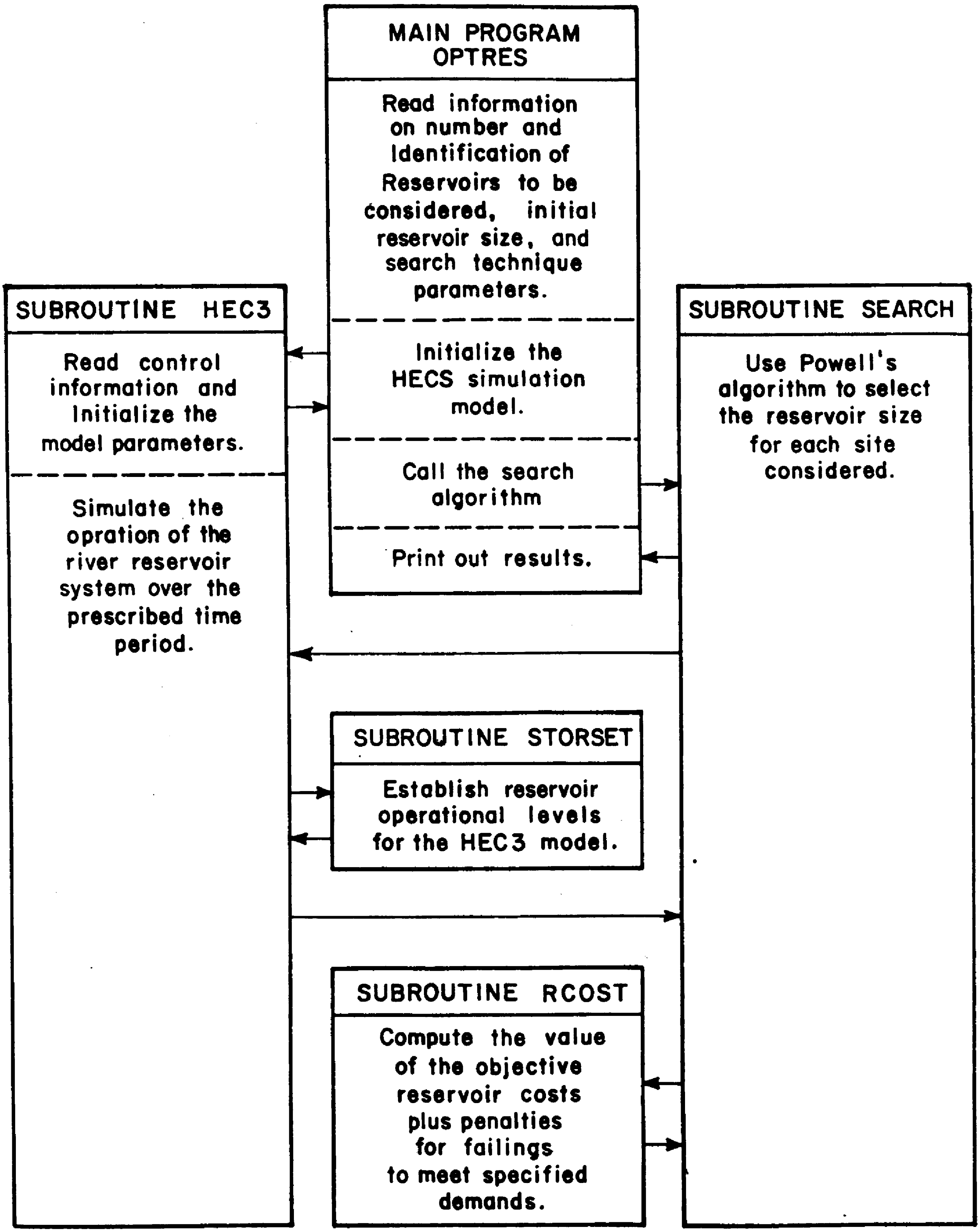

Figure 6. Linkage of the OPTRES Model.

function was used if the flow did not meet requirements. Based upon the value of the objective function, the Powell algorithm will select a new set of reservoir sizes and continue to cycle until a solution is achieved.

Two modifications were made to the HEC-3 model (now called Subroutine HEC3) for incorporation into the overall OPTRES model. It should be noted that the HEC-3 model was developed for use as a one-time through simulation model. This means the model was designed to read control information about the reservoirs, then read annual hydrologic information, simulate the system, and print out summary results for all control points on an annual and total simulation period basis. The OPTRES model, however, requires that the HEC-3 model be used in an iterative fashion. The two major problems that existed in using the HEC-3 model in an iterative manner were: how to avoid reading all of the control information on all reservoirs if information on only one reservoir was changed from one iteration to the next; and how to reduce the volume of the output? The approach of Claure-Pereira did not consider these problems since the number of iterations performed was generally on the order of three or less. For this work, it was realized that the number of iterations required could be large (perhaps on the order of 100) and the problems of unnecessarily redefining input information and generation of unnecessary output information must be solved.

The first modification to the HEC-3 model was the addition of logic that allowed HEC-3 to read control information about the reservoirs only on the first iteration. For all subsequent iterations, only the annual hydrologic data are read. Whenever a change in the size of a reservoir is made by the search algorithm, Subroutine STORSET is used to change the information about the reservoir(s) of interest and eliminates the need to read control information and reinitialize the model for each iteration.

The second modification to the HEC-3 model was the capability to output results only for control points of interest. Additionally, the option is available for only selected summary information for the control points of interest to be output. This modification significantly reduces the volume of the output.

CHAPTER IV

DEMONSTRATION STUDY: YAMPA RIVER BASIN

A. DESCRIPTION

As mentioned in Chapter I, the Yampa River Basin was selected as the case study area for development of the methodologies to determine optimal reservoir storage strategies. The Yampa River Basin, encompassing approximately 8000 sq. mi., lies in the northwest corner of Colorado, with one of its subbasins (the Little Snake) extending into southern Wyoming (see Figure 7). The Yampa River runs south of Steamboat Springs, Colorado, to Dinosaur National Monument, where it becomes a tributary of the Green River. A number of characteristics of the Yampa River Basin make it well suited for use as a case study in this effort.

At present, the Yampa River Basin is relatively undeveloped, both in terms of its population and its water resources. The mean annual flow of the Yampa River is approximately 1.5 maf. Currently only 54,000 ac-ft of storage have been developed in the basin. However, the Yampa Basin has potential for future development. In a report by the U. S. Geological Survey [6], 34 proposed reservoirs (some of these competing for the same sites) have been identified in the Yampa Basin. If all of the non-competing reservoirs were constructed, their total storage would equal approximately 2.2 maf or 1.5 times the mean annual flow. While this set of proposed reservoirs does not necessarily represent all potential sites or the best potential sites in the basin, it does provide a good set of potential sites with which to test the developed methodologies.

There is a potential for economic development in the Yampa Basin primarily due to the availability of coal resources. The nature of the coal resources in the basin, the types of potential energy development, and the

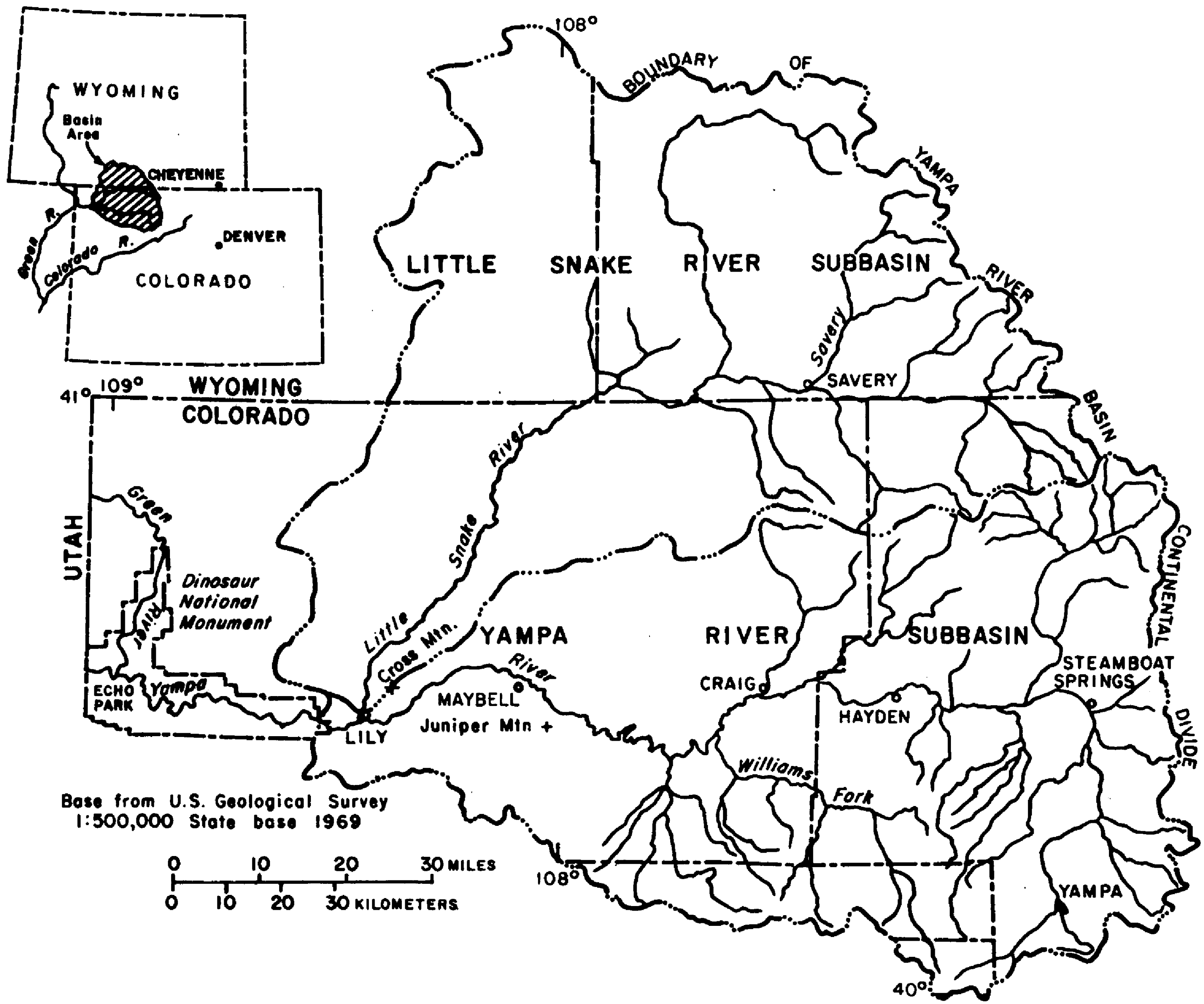

Figure 7. Location of the Yampa River Basin

impacts of this development upon the water resources of the basin have been addressed in recent studies by the U.S. Geological Survey [6] and the Colorado Department of Natural Resources [14]. It appears that the majority of the potential energy development will be in the area between Craig and Hayden, Colorado. It is currently anticipated that the bulk of the coal development will be in the form of strip mining and hence the largest part of the water requirement for energy development will be for rehabilitation of the mined lands. There is also potential for water requirements for coal slurry pipelines and for possible diversion to the White River Basin for oil-shale development in that basin.

Associated with energy development, it can be anticipated that the population of the basin will increase. People will be required not only for the developing energy industry but also to provide the necessary support services. The increased population and the associated development in the Craig-Hayden area will also create additional demands for water in the basin.

While the potential energy development will create additional demands for water, other factors could serve to place restrictions on the development and use of the water resources of the basin. As part of the upper Colorado river basin compact, it is stated [15] that:

> "Colorado will not cause the flow of the Yampa River at the Maybell gauging station to be depleted below an aggregate of 5 maf for any period of ten consecutive years reckoned in a continuing progressive series."

Additionally there are two rare and endangered fish species (the Colorado River squawfish and the humpback chub) in the basin and two areas of the basin (the Elk River upstream from Clark and the main stem of the Yampa within Dinosaur National Monument) are currently under study for designation as wild and scenic rivers.

In summary, the Yampa was selected as the case study for this research since it represents an area which is currently undeveloped but has the potential for major development of its water resources. The development of the water resources will potentially have to satisfy current water demands, additional demands from a developing energy industry and demands for instream uses. Since multiple objectives for water use exist, tradeoffs between these objectives will have to be evaluated. Finally, the Yampa Basin has been the subject of two recent studies and therefore much of the data required for this study were readily available.

B. PROPOSED RESERVOIR PROJECTS

The data for proposed reservoir projects in the Yampa Basin were obtained from the U.S. Geological Survey, Denver, Colorado. Although the report by the Geological Survey [6] lists 34 proposed reservoirs, the data set obtained from the U.S.G.S. contained only 19 proposed reservoirs. A list of these reservoirs is given in Table 1 and a schematic diagram of the projects is shown in Figure 8. The data for the proposed reservoir projects were furnished as a data set prepared for use in the HEC-3 model and therefore provided the required hydrologic and physical description of the projects. Information such as storage-elevation, area-elevation, minimum storages, outlet capacities, and desired flows were provided in the HEC-3 data set.

Information on the costs of the proposed reservoirs were not available. Since cost information was required for this work, the cost of the various reservoirs was estimated by consideration of general site characteristics and similarity to other reservoirs. It should be emphasized that the estimated costs of the reservoirs *do not* represent the actual costs at the sites although it is hoped that the estimates are at least reasonable. It is not the intent of this study to select the best projects among those proposed for the Yampa, but rather to use the Yampa as a demonstration of a general methodology for optimal selection of projects. As accurate cost data become available, they can be easily included.

TABLE 1

YAMPA RIVER BASIN CASE STUDY PROPOSED RESERVOIR PROJECTS

NUMBER	PROJECT NAME	TOTAL CAPACITY (1000 AC-FT)
1	Yamcola	9
2	Blacktail	229
3	Morrison	12
4	Lower Green	100
5	Pleasant Valley	43
6	Hinman Park	44
7	Grouse Mountain	79
8	Childress	24
9	Upper Middle	127
10	Dunckley	57
11	California Park	37
12	Rampart	12
13	Craig	44
14	ColoWyo	70
15	Thornburg	36
16	Juniper	1080
17	Cross Mountain	142
18	Sandstone	15
19	Pothook	60

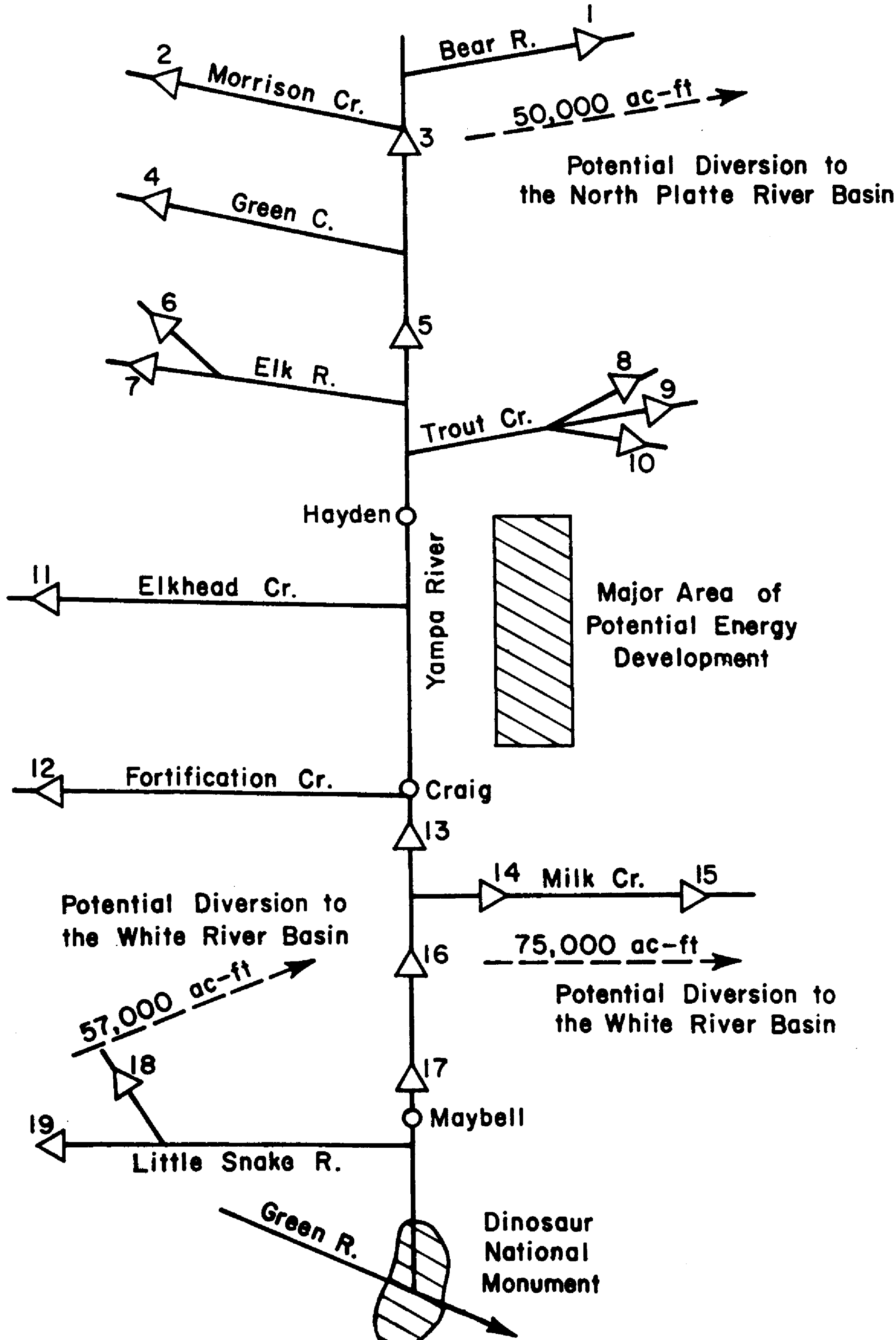

Figure 8. Schematic of Yampa River Basin proposed projects

Projects selected as part of an optimal storage configuration are selected based upon their assumed cost functions. Two cost functions (i.e., for Pleasant Valley and Juniper Reservoirs) used in the initial testing of the OPTRES model are shown in Figures 9 and 10. Quadratic functions were used to describe the cost functions within the computer program.

C. RESULTS OF INITIAL MODEL TESTING

Initial testing of the OPTRES model was conducted to determine its ability to find acceptable solutions to the optimal storage configuration problem. The performance of any given system configuration was measured in terms of its cost and its ability to satisfy various target objectives, such as satisfying demands at various locations in the system. The latter were introduced into the total system objective via terms which penalize deviations from the demand targets. Thus, the performance of the system was measured by:

$$\min \sum_{i=1}^{M} f_i(S_i) + \sum_{j=1}^{N} P_j(\underline{Q}_j, \underline{D}_j) \qquad (1)$$

where $f_i(S_i)$ = cost of storage S_i at reservoir i

M = number of reservoirs

$P_j(\underline{Q}_j, \underline{D}_j)$ = penalty cost for failing to satisfy demand $\underline{D}_j$ at demand location j with flow $\underline{Q}_j$ over the selected time horizon.

N = number of demand locations

Although various combinations of reservoirs were tried, the majority of the initial tests were conducted with two proposed reservoirs; Pleasant Valley and Juniper. These two reservoirs were selected because: (a) they have a large difference in size (the maximum storage at Juniper is about 20 times the maximum storage at Pleasant Valley) which would allow the testing of different step sizes within the search technique for each reservoir; (b) they are well spaced in the basin (Juniper is located about 1/3 the length of the Yampa and Pleasant Valley about 2/3 the length of the Yampa upstream from the confluence

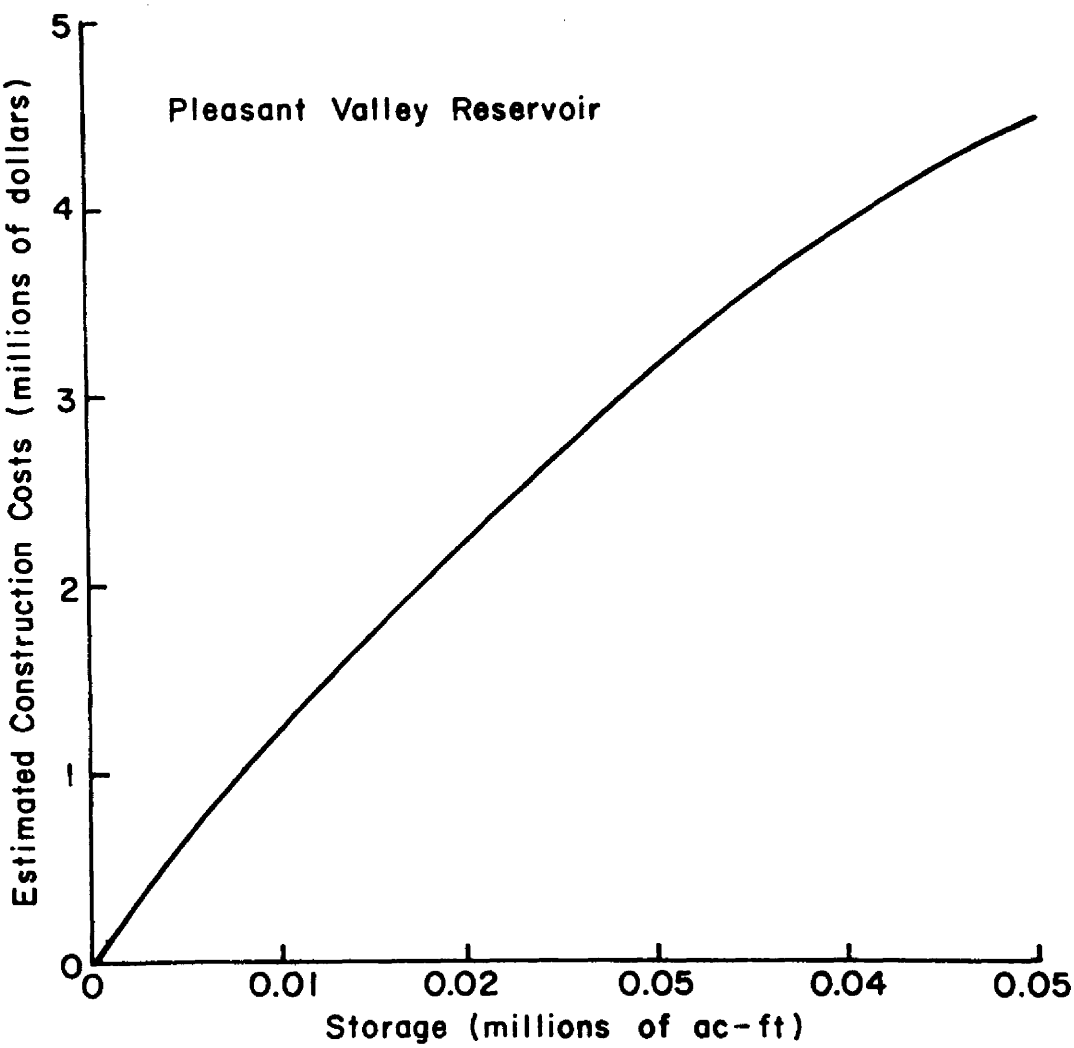

Figure 9. Estimated cost-storage relationship for Pleasant Valley Reservoir

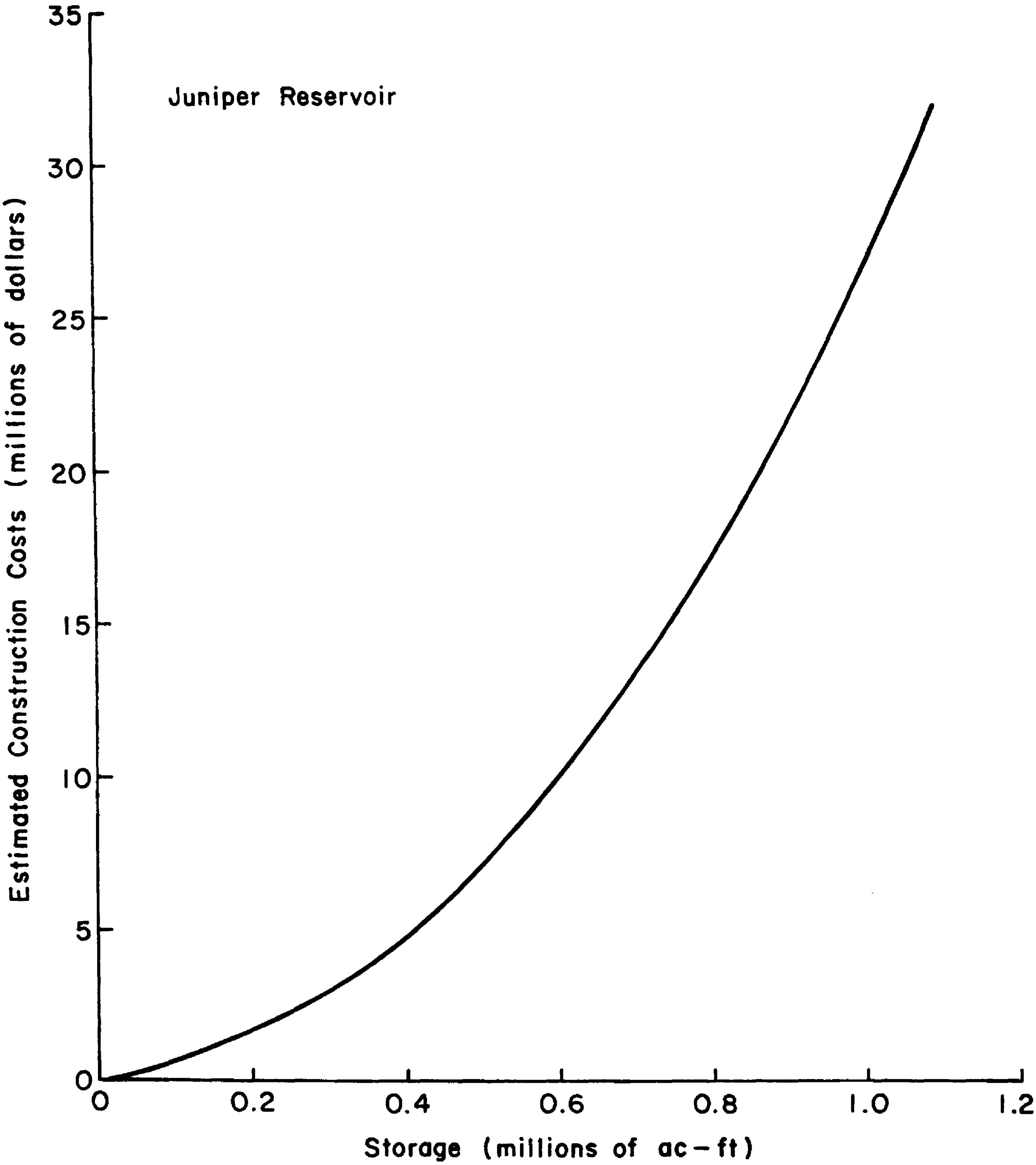

Figure 10. Estimated cost-storage relationship for Juniper Reservoir

of the Yampa and the Green); and (c) the solution for one given set of conditions should force Pleasant Valley reservoir not to be built. Unlike the cost curve shown for Pleasant Valley in Figure 9, the actual cost curve would be discontinuous at some minimum storage (see Figure11). This occurs because it is not practical to build the reservoir below some minimum size. The use of a discontinuous cost functions can create convergence problems for a search technique such as the Powell algorithm. Therefore, by evaluating Juniper and Pleasant Valley reservoirs, means of handling problems associated with discontinuities in the reservoir cost functions could be identified.

All initial testing was conducted with the objective of minimizing the total costs of both reservoirs. A minimum required flow of 750 cfs was established at a critical control point near the entrance to Dinosaur National Monument downstream of both reservoirs. A penalty term was added to the total costs for the reservoirs if the average flow at this control point was less than the 750 cfs required. Although the average flow was used in the initial testing, the OPTRES model has the flexibility to use other measures of the time distribution of flows at the critical points. The resulting objective minimized was:

$$\min[f_1(S_1) + f_2(S_2) + P(Q-750)^3] \tag{2}$$

where $f_1(S_1)$ = cost of storage S_1 at Pleasant Valley Reservoir

$f_2(S_2)$ = cost of storage S_2 at Juniper Reservoir

Q = computed average flow at the entrance to Dinosaur National Monument

$P = 0$ if $Q \geq 750$ cfs

$\quad\; 1$ if $Q < 750$ cfs

The Powell algorithm requires a user specified convergence tolerance. As discussed previously, convergence of the Powell algorithm is achieved when the change in the magnitude of the decision variables (the storages at Pleasant Valley and Juniper Reservoirs) between successive iterations is less than a user specified tolerance. This specified convergence tolerance is also

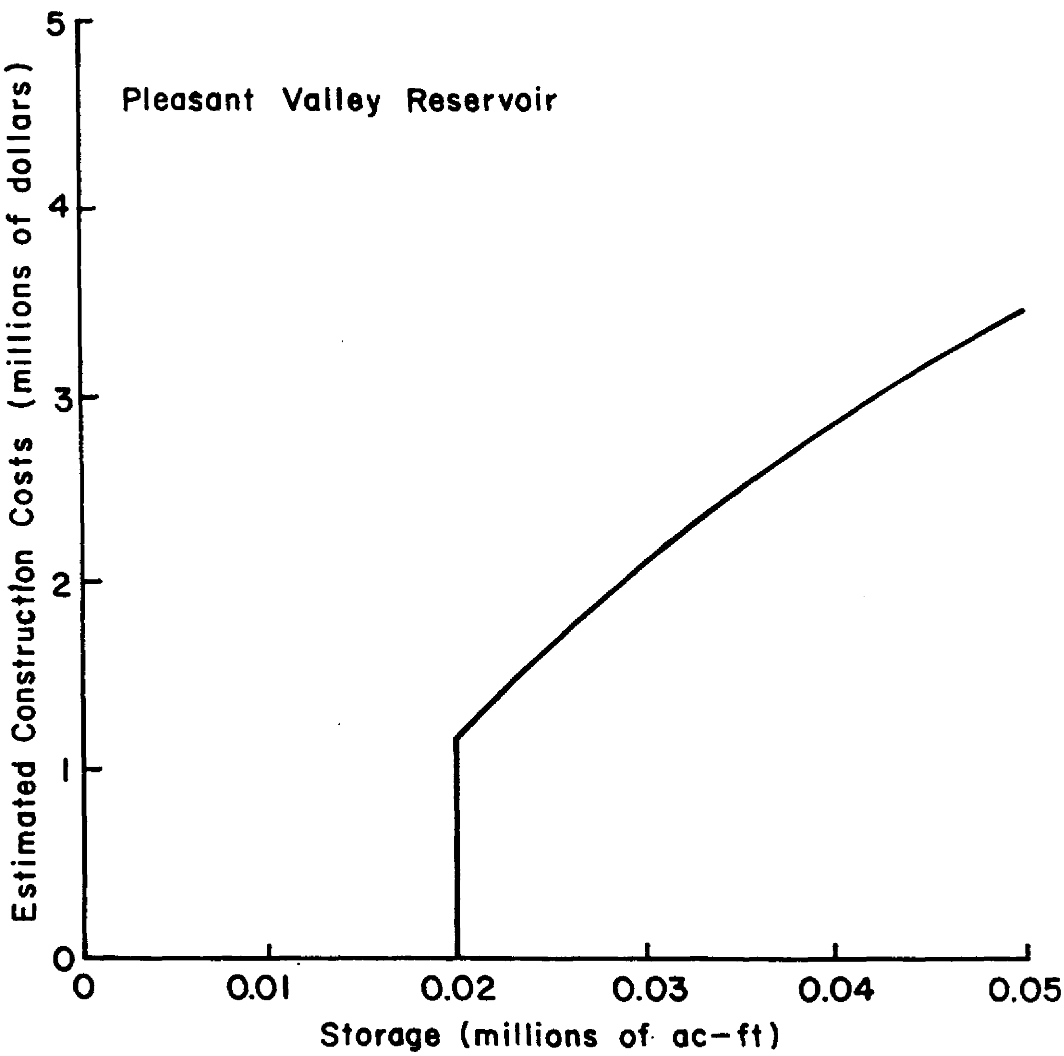

Figure 11. Estimated cost-storage relationship considering minimum storage for Pleasant Valley Reservoir

used by Powell's algorithm to determine a maximum allowable step size. As illustrated in Figure 4, the procedure of Powell's method consists of a sequence of minimizations along coordinate or conjugate directions. Along any given direction, the objective function is minimized by evaluating the objective function at three points (representing three combinations of storages at Pleasant Valley and Juniper Reservoirs). A quadratic is then fitted to these three points and the minimum point of the quadratic is located. The distance between adjacent points in the three point set cannot exceed the maximum allowable step size. In general, the closer the three points are the better the quadratic approximation. Therefore, the specification of a large convergence tolerance implies that extreme accuracy in the final solution is not required and consequently the search technique can use larger step sizes or greater distances between points in the quadratic approximation of the objective function. To evaluate the convergent properties of the OPTRES model runs were made with various step sizes (convergence tolerances) and with various initial conditions.

Two means of dealing with discontinuities in reservoir cost at minimum storage were tested. Both techniques are based on making the reservoir cost functions artifically continuous. It is possible for Powell's algorithm to select a storage for a particular reservoir that is less than the minimum storage practical to build at that site. Since the HEC-3 simulation model contains information on the minimum storage at each site, specification of a storage less than minimum storage in the simulation model would be meaningless. The OPTRES model is designed to determine whether a selected storage value for a particular site is less than the minimum storage for that site. If this is the case, the simulation model will set the storage for that site to the appropriate minimum storage which has the effect of treating the system as though the reservoir were not there (i.e., zero active storage). The actual storage selected by Powell's algorithm will also be retained for determining reservoir costs. The first means of handling cost discontinuities was to assume that the costs of the reservoir were continuous to zero; that is, the cost curves used by the OPTRES model were like the curves shown in Figures 9 and 10. Therefore, if a reservoir is not selected to be built in the final solution of the OPTRES model, the size of that reservoir in the final solution should be close to zero. This will occur since the reservoir has the same hydrologic effect for any storage between zero and minimum storage (as set in the HEC-3 simulation model); however, the cost of the reservoir is minimum at zero storage. Should a storage be selected in the final solution for a particular reservoir that is *below* the minimum storage and above zero, the associated cost of that reservoir will be subtracted (since this condition implies that the reservoir should not be built) from the final results.

Another approach is to add a penalty term to the cost of any storage level selected by the Powell algorithm that is less than the minimum storage. This type of penalty function will result in the cost for a reservoir being minimal at the minimum storage. If a reservoir is not selected to be built, its selected size in the final solution should be close to (within the specified convergence tolerance) the minimum storage. Again, the associated cost of that reservoir is subtracted from the final results.

Both of these techniques were tested in the OPTRES model for the apriori selected conditions that Pleasant Valley Reservoir should not be built in the final solution. Both techniques yielded essentially the same final results. The final storage selected for Pleasant Valley Reservoir was clearly below the minimum storage for the first technique, while it was slightly above the minimum storage (but within the convergence tolerance) for the second technique. Since any storage above the minimum storage will effect the hydrologic conditions of the system, the final storage for Pleasant Valley Reservoir for the second technique should be set to minimum storage and the simulation rerun. Adjustment of the penalty term in the second technique would be required to have the final storage for Pleasant Valley Reservoir selected at or below the minimum storage to avoid having to rerun the simulation. Additionally, the appropriate magnitude of this penalty term depends upon the particular cost curve for a particular reservoir and therefore the possibility of multiple penalty terms for multiple reservoirs exists. The technique of letting the reservoir costs be continuous to zero storage is the simplier of the two techniques to program and to use and was selected for incorporation into the OPTRES model.

Results from initial testing of the OPTRES model show satisfactory convergence to an optimal (not necessarily global) solution. Examples of the model convergence are displayed in plots of total system costs (reservoir costs plus penalty costs) versus iterations of the HEC-3 simulation model shown in Figures 12 and 13. Tests with different initial conditions showed that the OPTRES model could find different local optimal solutions. In a manner analogous to a grid search technique, the OPTRES model was first run with a large step size to find a *coarse* solution. The optimal solution found from this run, was used as the initial values for reservoir storage in an OPTRES run with a small step size to find a more *refined* solution. The results of those runs are the results shown in Figures 12 and 13. As seen from those results, the small step size was able to improve the solution found with the larger step size. In all runs for the two reservoir case, the OPTRES model required approximately 25 evaluations of the simulation (HEC-3) model.

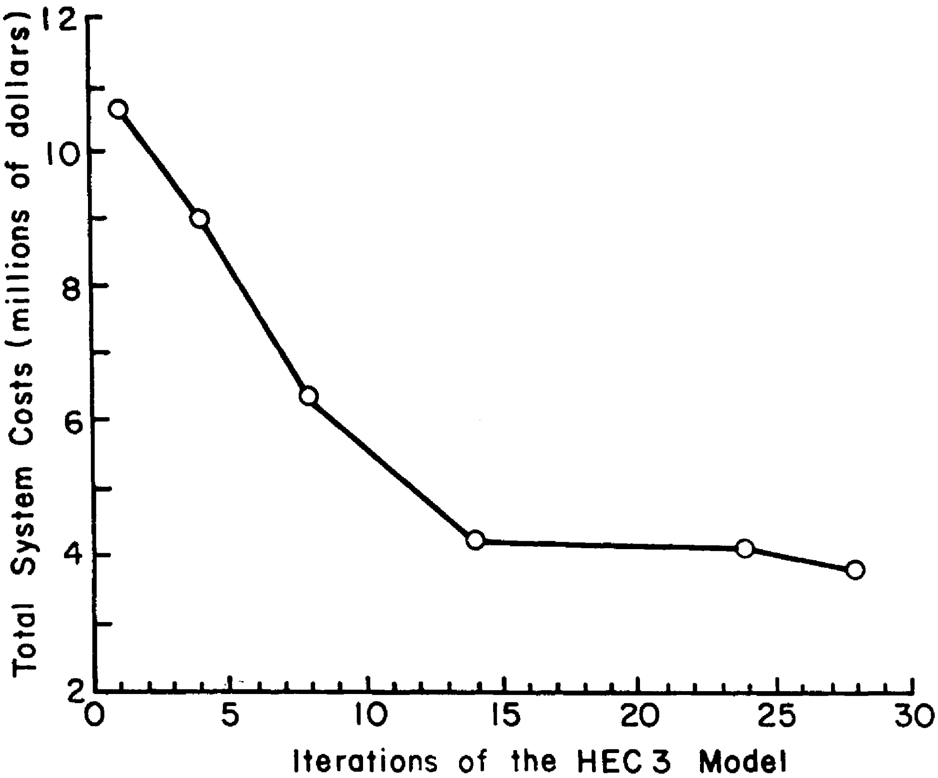

Figure 12. OPTRES Model convergence - large step size

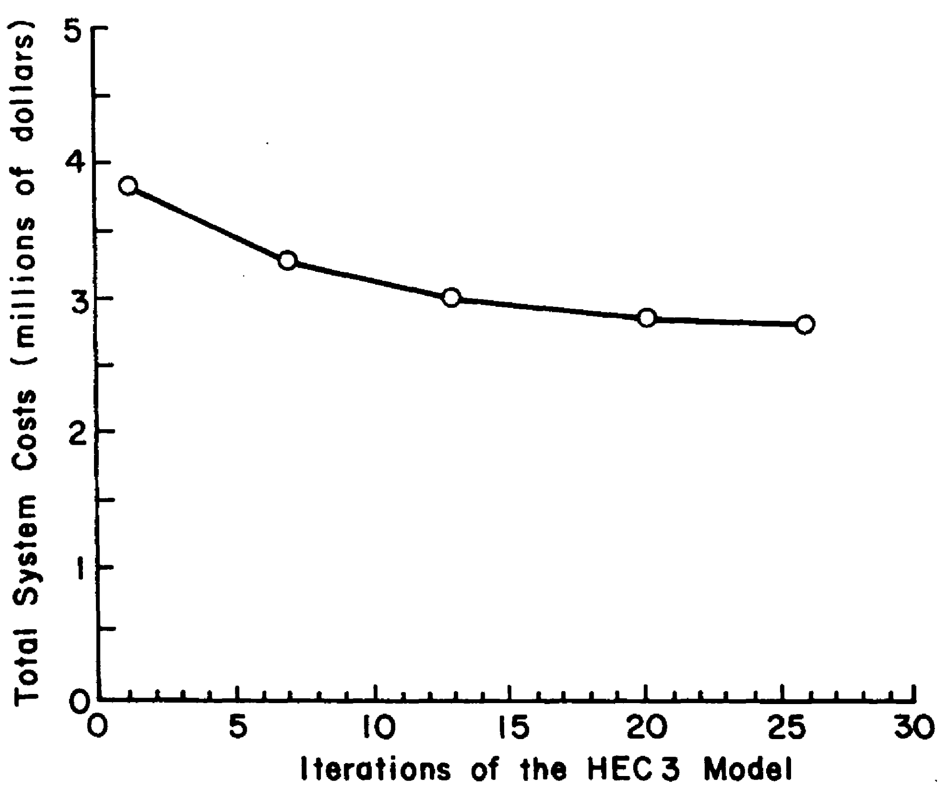

Figure 13. OPTRES Model convergence - small step size

CHAPTER V

CONCLUSIONS AND EXTENSIONS

A. CONCLUSIONS FROM INITIAL TESTING

The results of the initial testing of the OPTRES model indicate that the approach of linking simulation and optimization models to select optimal storage strategies is feasible and can provide satisfactory results. During the remainder of this effort, the input and output of the OPTRES model will be improved to facilitate interactive conversational use and to provide information to display tradeoffs among multiple objectives. Additional testing of the OPTRES model will be conducted with large numbers of reservoirs and with objectives other than minimizing total reservoir costs.

It has become apparent from the initial testing of the OPTRES model that the computer costs involved in the developed methodology could be substantial, although certainly not prohibitive. As noted by Wurbs, two items are important relative to the convergence characteristics of a combined simulation-optimization model. These are the number of iterations required to converge to a solution (and the associated computer time requirements) and the ability of the model to converge to the same range of solutions for a multi-modal objective function. It is likely that any objective function based upon a simulation model which accounts for interaction among various reservoirs and incorporates penalty terms will be multi-modal. In general, the closer the initial estimates for the reservoir sizes are to the optimal values of those reservoir sizes, the smaller the number of iterations that will be required to converge to that optimal solution. Additionally, the problems of converging to various local optima are minimized.

B. PROPOSED SCREENING MODEL

To develop good initial estimates of optimal reservoir storage configurations, an optimization screening model will be developed. It is envisioned that the screening model could be used not only to determine initial values for reservoir storage strategies but also could be used as a stand-alone technique for determining optimal storage configurations when the detailed data required by the simulation portion of the OPTRES model is not available or when the use of the study results do not warrant the detailed approach of the OPTRES model.

In general a screening model is used to determine an initial estimate of the optimal solution for a problem. Since the optimization model does not contain the detailed description of the system that is possible in a simulation model, the latter must be used to test or verify the screening model results. When the results of the screening model are not verified by the simulation model, then the optimization screening model must be modified such that the simplistic description of the physical system in the screening model gives more realistic results. The modification of the screening model often requires knowledge of optimization techniques and FORTRAN computer programming, which are well beyond the abilities of many water resource planners and managers. This difficulty will not be present in this methodology, however. Since the optimization screening model will be used in conjunction with the OPTRES model, which itself contains an optimization technique, it will not be necessary to modify the screening model. The screening model need only be run once to get initial values for the OPTRES model. The OPTRES model will then use those initial values and converge to a final optimal solution.

Many screening models have tended to be difficult to use by planners and managers unfamiliar with optimization and computer programming techniques. The proposed screening model for this study will be developed to be completely compatible with the OPTRES model, particularly in terms of model inputs and outputs. Like the OPTRES model, the screening model will be coded so that as much input and output as possible can be accomplished in an interactive, conversational mode. It is also planned to have the screening model display intermediate results such that the user can monitor and even alter the solution of the optimization technique.

C. MODEL DESCRIPTION

The proposed screening model will employ a Dynamic Programming technique developed by Hall [16]. Hall developed this technique to determine optimal storage configurations for a system of reservoirs based upon single or multiple purposes. For purposes of explanation, this technique will be described in terms of determining that combination of reservoirs (location and size) that will satisfy demands for water at a minimal total cost. This is identical to the situation used in the initial testing and development of the OPTRES model.

The screening model is based on the concept of decomposition, where we desire to decompose the original problem of multiple reservoirs into a series of smaller problems involving a very limited number of reservoirs. The essential characteristic of the screening model is the combination of any two reservoirs (which may be in either series or parallel) into a single "equivalent reservoir" which will provide water in some amount at a minimum cost. This "equivalent reservoir" is then combined with another reservoir (in either series or parallel) to find the optimal combination of the three, as illustrated in Figure 14. again giving the minimum cost as a function of the quantity of water they will provide. This processes is continued until

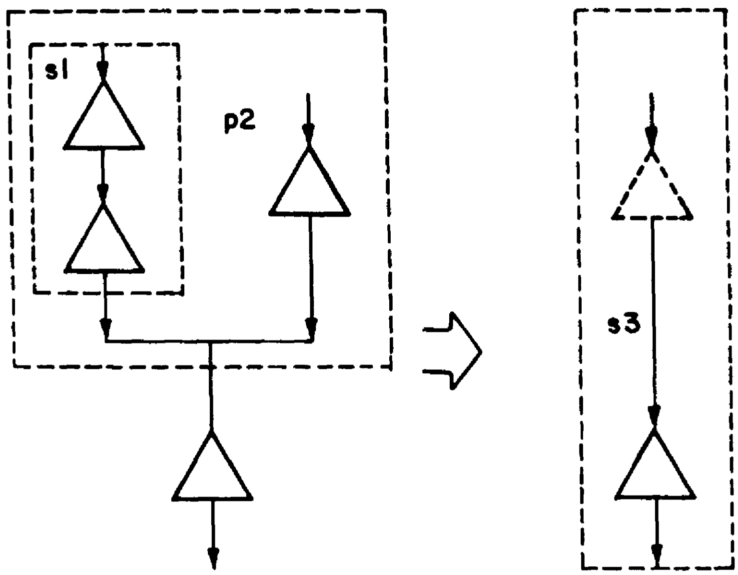

Figure 14. Finding an *equivalent reservoir* by dynamic programming

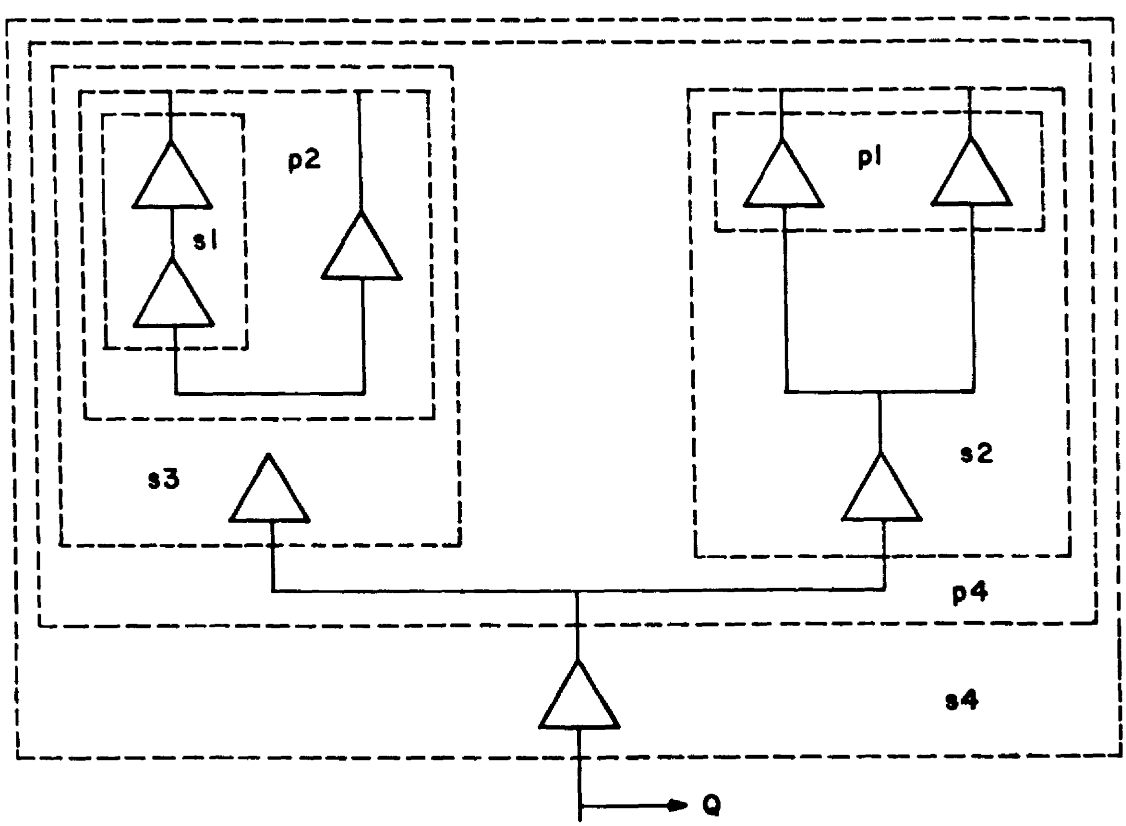

Figure 15. Illustrative sequence of subsystem combinations for reservoir sites in both series and parallel

all reservoirs have been combined into a single "equivalent reservoir" whose total cost is a minimum for any quantity of water (up to the maximum firm yield available for the system) which may be desired as the target level. Once a target level of water required for the system has been identified, that combination of reservoirs and their respective sizes which will provide the demand at minimum cost can be determined.

There are three implicit assumptions in the formulation of the screening model. The first assumption of this analysis is that the streamflows entering each of the potential reservoir sites are well correlated. Within a river basin such as the Yampa, the hydrology of the basin is relatively uniform and this assumption should not be restrictive. The second assumption is that the variation of demand for water over an annual period can be expressed in terms of a constant fraction (called a water use coefficient) of the total annual water demand. For example, if monthly periods are of interst, twelve water use coefficients α_t would be defined such that the demand for water in any month t could be computed as $\alpha_t \cdot Q$ where Q is the total annual demand. Since the demands for water are based upon actual or projected water uses, the variation in demands are a function of those uses and this assumption can be satisfied. The third assumption of the screening model is that all requirements for water occur downstream of all reservoirs. While this assumption appears restrictive, it can be easily handled by further assuming that a zero cost channel exists to deliver water upstream to the desired demand location. This implies the demand can be satisfied as long as the demand does not exceed the optimized storage capacity upstream of the demand location.

Prior to the application of the screening model all potential reservoir sites are independently analyzed to determine their firm yield (the amount of water delivered according to a firm schedule) as a function of reservoir storage. This analysis can be done using a simple simulation procedure, such as the procedure described by Hall and Dracup [17]. The development of the firm yield allows for the use of water use coefficients which reflect the varying demands for water during a yearly period. Since the cost of storage was estimated for each of the potential reservoir sites for the OPTRES model, the firm yield as a function of storage relationship and the cost as a function of storage relationship can be combined to develop a cost as a function of firm yield relationship. Once these cost vs. firm yield relationships have been developed for each site, the procedure begins to analyze the system beginning with the upstream reservoirs.

The screening procedure considers reservoirs in parallel and reservoirs in series as seperate situations. If the reservoir sites are in parallel, then none of the streamflows entering one site flow into any of the other sites. Therefore, the firm yields or outputs of each site are independent and directly additive. The combination of parallel sites into an "equivalent reservoir" involves minimizing the total cost or providing a quantity of water, subject to the constraints that the water provided will meet the demands and that the amount of water allocated from each site cannot exceed the firm yield capacity of that site. In Dynamic Programming notation the problem can be expressed as:

$$F_k^p(x_k) = \min[c_k(q_k) + F_{k+1}^p(x_k - q_k)] \quad k=1,\ldots,n-1$$

subject to:

$$0 \leq q_k \leq x_k$$

$$q_k \leq q_{kmax}$$

$$x_k \leq \sum_{i=k}^{n} q_{imax}$$

where

P = parallel reservoir combination

n = number of reservoir sites considered

q_k = annual firm yield of water to by provided by reservoir k

$c_k(q_k)$ = cost of the necessary reservoir storage at site k to provide q_k

q_{kmax} = maximum annual firm yield that can be provided by reservoir k

x_k = total firm yield of water to be supplied by reservoirs k through n

Solution of this minimization problem by Dynamic Programming will yield a cost as a function of firm yield relationship from the parallel sites. The cost vs. firm yield relationship can be thought of as representing the cost vs. firm yield relationship of an "equivalent reservoir" to the parallel reservoirs. The solution to the minimization problem by Dynamic Programming also determines how much of the yield should be provided from each site. The amount of firm yield to be provided from each site translates into the amount of storage required at each site which in fact determines which sites should be developed since a zero firm yield requirement implies a zero storage requirement.

If the reservoirs are in series with side flows between the sites, the analysis is different. The initial analysis of each site to determine the firm yield vs. storage relationship should be made considering all the natural unmodified streamflow upstream of each site. Again, the basic approach is to minimize the total costs of providing a given quantity of water, however, the problem is more constrainted than for the parallel reservoir case. For sites in series, the amount of water provided by the upstream reservoir can not exceed the amount available at the upstream reservoir nor can it exceed the storage capabilities of the downstream reservoir. Additionally, whatever quantity of water the upstream site provides, the remainder of the desired quantity of water must be provided by the downstream site. For the series system combination the problem can be expressed as:

$$F_k^s(x_k) = \min[c_k(q_k) + F_{k+1}^s(x_k - q_k)], \quad k=1,\ldots,n-1$$

subject to:

$$0 \leq q_k \leq x_k$$

$$x_k \leq q_{kmax}$$

where

s = series reservoir combination

Note that the above expression differs from the expression for the parallel combination in the constraint on x_k. The results of this analysis also yield a cost as a function of firm yield relationship for the combined reservoirs.

Although Dynamic Programming optimization problems solved for reservoirs in parallel and series are subject to different sets of constraints, the results of the analyses are the same; i.e., functions of costs vs. firm yield. Therefore any combination of parallel and series sites can be easily handled by this procedure as illustrated by Figure 15.

One of the major advantages of the Dynamic Programming approach is that the optimal solution obtained for the system as represented by the final "equivalent reservoir" can be a *function* of minimum costs vs. firm yield rather than a single value. Therefore without having to solve the problem again, the optimal configurations of reservoir storages (i.e., the optimal policies that led to the optimal solution) can be determined for a range of values of the total firm yield. As an example the output from the screening model might be displayed as illustrated in Table 2.

A schematic diagram of the projects in the Yampa Basin illustrating the relationships of the projects (parallel or series) for analysis by the screening model is shown in Figure 16. It is felt that the development of this screening model will greatly enhance the capabilities of the combined optimization-simulation model (OPTRES) and improve the methodologies under development for determining optimal reservoir storage strategies.

TABLE 2

EXAMPLE OUTPUT FROM SCREENING PROCEDURE

LEVEL OF DEMAND (AC-FT)	RESERVOIR SITES						MINIMIZED TOTAL SYSTEM COSTS (MILLIONS $)
	1	2	3	.	.	M	
250000.	0	10000	0				20
500000	0	10000	0				35
750000	5000	20000	0				60
1000000	5000	30000	0				90
1250000	5000	30000	0				140

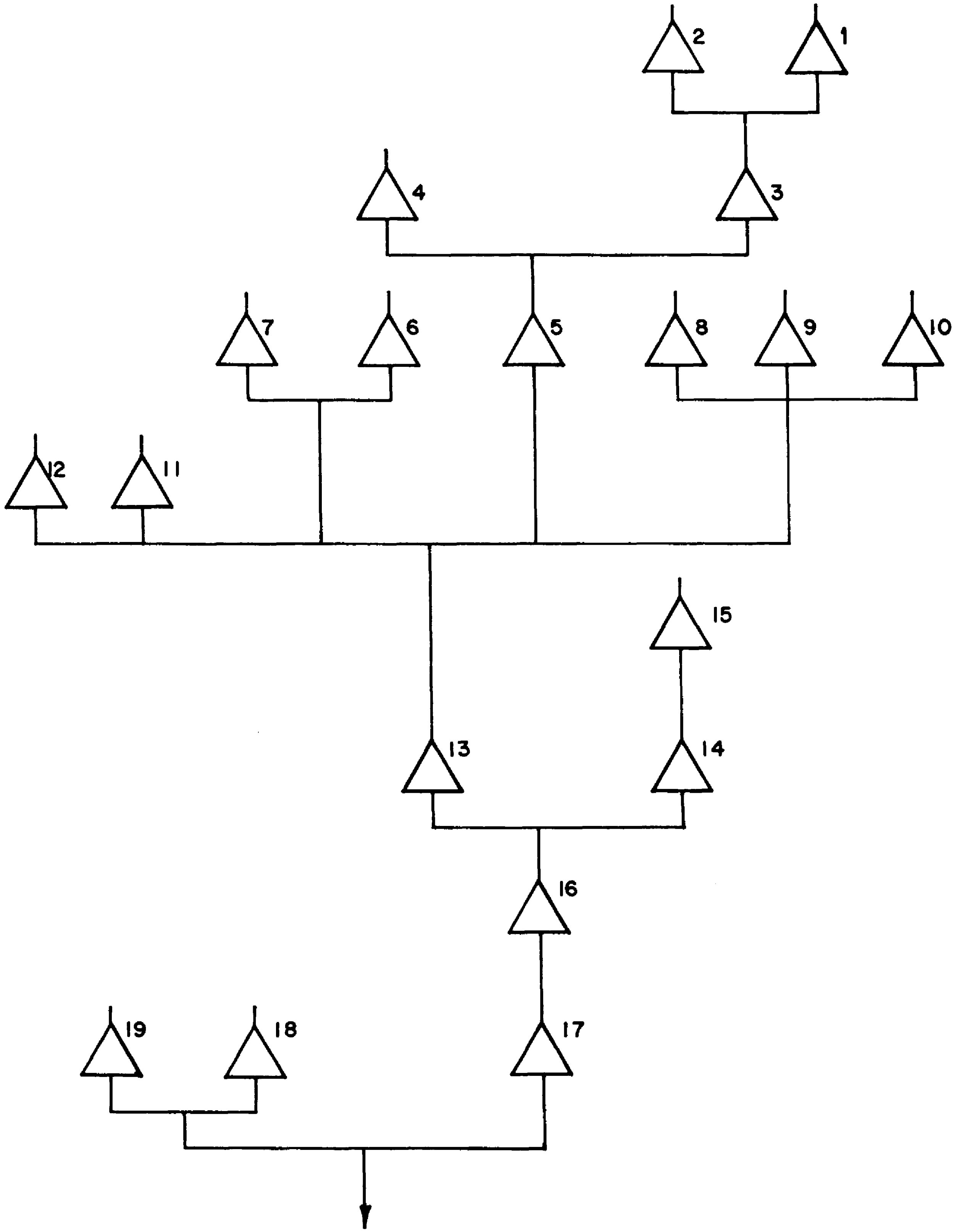

Figure 16. Series and parallel relationships of Yampa River Basin proposed projects

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