Real-Time Reservoir Operation Decision Support Under The Appropriation Doctrine

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ABSTRACT OF THESIS

REAL-TIME RESERVOIR OPERATION DECISION SUPPORT UNDER THE APPROPRIATION DOCTRINE

In the Western United States as competition for water from over appropriated rivers escalates, water rights decrees continuously increase in numbers and become more complex. The result is that the task of operating a multiple reservoir system according to the Doctrine of Prior Appropriation water rights system is becoming so formidable that the current procedures used by reservoir operators are unusable except for the obvious and straight forward water rights operations. To make matters worse, real-time data acquisition systems have further complicated the operations process by creating an information management crisis for reservoir operators.

This dissertation focuses on identifying and resolving the problems of operating a reservoir system in real-time under the Prior Appropriation Doctrine of water rights. Systems engineering methods were employed to analyze the currently used and accepted reservoir operations practices in order to develop a formalized reservoir operations procedure that could be used in real-time. Based on the latest decision support system technology, a framework for

real-time reservoir operations decision support was then developed to implement the procedure.

The framework is the major contribution of this research. It represents the organizing concept in which the developed reservoir operations procedure was integrated with automatic data acquisition into a real-time computer based decision environment.

Using the framework, a demonstration decision support system was developed and implemented for a typical multiple reservoir system in Colorado.

This research identified the current reservoir operations problems, and established that the demonstration decision support system used to implement the proposed framework was able to overcome these problems. The proposed decision framework can be used on any reservoir system which operates according to the Prior Appropriation Doctrine of water rights.

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CHAPTER I

INTRODUCTION

In recent years, the development of decision support systems for the real-time operation of multi-reservoir systems has been gaining recognition. The fundamental concept of these decision support systems is to meet as closely as possible certain goals, objectives, and constraints, in the form of prior established storage rule curves. Various techniques, including the latest operations research methods, estimate optimal reservoir system operations policies using the basic reservoir purposes of flood control, hydropower, navigation, recreation, and water supply. In the Western United States, where the Doctrine of Prior Appropriation for water rights is used, and in particular Colorado, where the strict Appropriation Doctrine applies, the legal and institutional aspects of a water rights system play a major role in reservoir operations. For example, in-priority storage, out-of-priority storage, exchanges, alternate points of diversion, and plans for augmentation, are just a few of the unique issues related to reservoir operations in Colorado. As a result, a decision support system for Colorado reservoir operations must not only employ the basic reservoir purposes and constraints, but additional limitations and flexibilities as a result of the water rights system requirements must also be considered.

Research to date has focused on the development, rather than the use, of the storage rule curves. As a consequence, the application of these rule curves in the form of decision support systems is limited. In fact, in Colorado today, computer based decision support systems are not being used by reservoir operators. Manual methods which use gage readers and accounting sheets are being used instead. Today's reservoir operator is fairly adept at using the manual method, however this has taken years of experience growing-up with the physical and water rights systems.

As competition for water from water-short streams escalates in Colorado, water rights transfers, exchanges, alternate points of diversion, and plans for augmentation continuously increase in numbers and become more complex. Trust between competing water users and the administrator is being strained. As a result, the task of operating a multiple reservoir system in Colorado according to the Prior Appropriation Doctrine in real-time is becoming so formidable today that the current manual procedures are unusable except for the obvious and straight forward water rights operations.

In order to overcome some of the difficult reservoir operations problems, reservoir operators have added automated data collection systems, accounting sheets have been computerized, and various types of hydrologic and hydraulic simulation computer models have been developed. Unfortunately most of these new developments have just complicated the operations process by creating a large amount of information that is generally not timely and cannot be assimilated by reservoir operators for decision making. In addition, operators commonly are not able to use the developed technology, in particular the computer models, for various reasons. An information management crisis has developed and even with today's computer technology, the operations of a multi-reservoir system according to an increasingly complex Prior Appropriation water rights system is becoming intractable.

Statement of Problem

A new approach to the development of decision support tools for real-time reservoir operations according to the Prior Appropriation Doctrine of water rights is needed. The currently accepted manual methods for real-time reservoir operations in Colorado are no longer able to handle today's complex reservoir and water rights systems operational and regulatory requirements. Currently developed computer decision tools are not being used by reservoir operators. The following basic reservoir operations decisions are no longer easy to make now that there are increasingly more water rights and the water rights are more complex:

- When, where and how much water can I divert?
- When, where and how much water can I store?
- When, where and how much water can I exchange?
- When, where and how much water must I release?

Answers to these questions are based on knowing in real-time not only how much water is physically available at each reservoir location, but how much is legally available.

The decision support tools available today generally do not reconstruct in real-time physically and legally available flows based on current and past operating conditions. They usually incorporate traditional modeling techniques which are not easily adapted to using real-time data, and require that inflows and demands be known a priori. As a result, current decision tools are more appropriate for reservoir operations planning than real-time operations. Consequently, although we have available advanced computer technology, very little of this technology is being used in Colorado today to operate reservoirs in real-time according to the legal water rights system.

The lack of use of current computer technology for Colorado reservoir operations can be attributed to several reasons:

1. In the past, there has not been much incentive to convert from manual to automated procedures because operators were able to comprehend and assimilate the data available to operate the relatively simple reservoir systems and corresponding water rights.

2. An operator cannot interact in real-time with the presently developed decision tools to stop computations, look at intermediate results and change operations criteria, data, or information without having an understanding of computer programming.

3. Real-time data is not trusted by operators nor is it automatically integrated into the decision tools and easily converted automatically into a form acceptable by current models.

4. Decision tools developed to date presently do not include or integrate a legal water rights system.

In order to overcome these factors and use available computer technology, currently accepted reservoir operations methods need to be formalized into one procedure. Once this is done, a framework can be developed which automatically integrates the formalized procedure with a real-time data collection system and operates in real-time to provide reservoir operators with decision information.

In summary, the problem proposed here is the need for a computer based decision support system framework for Colorado reservoir operations which operates in real-time, automatically uses a real-time data collection system, and will be accepted by reservoir operators.

Objectives

The objectives of this research project are stated as follows:

1. Based on the methods currently used and accepted within the realities of the Colorado water rights system, develop a formalized reservoir operations procedure which integrates multi-reservoir operations with the Colorado Prior Appropriation Doctrine of Water Rights.

2. Develop a general framework for a real-time Decision Support System which integrates the formalized procedure with real-time data collection.

3. Show the applicability of the general framework by constructing a real-time reservoir operations Decision Support System.

4. Demonstrate the Decision Support System developed in step 3 on a hypothetical case study to illustrate the following items:

a. The automatic integration of real-time data.

b. Reconstruction of physically and legally available or required flows at each decree location based on current and past operating conditions.

c. The automatic generation of information to assist an operator in the basic reservoir operations and water rights decisions, (ie. storage, release, exchange).

d. At-will operator interaction in real-time to develop reservoir operations decisions using "what if" scenarios.

Contribution

This study provides a theoretical and practical contribution to the existing body of knowledge pertaining to water resources operations and management. It is the writer's belief that the incorporation of a water rights system, in particular the Doctrine of Prior Appropriation, into a decision support system framework for real-time reservoir operations is unique and original. The framework as defined here is the organizing concept in which to implement and integrate a formalized reservoir operations procedure with a real-time data acquisition system into a computer based environment. Modern computer based technology will be used to demonstrate that the framework developed can integrate the legal water rights system with reservoir operations in real-time and that the developed decision support system is practical to use by an average reservoir operator.

CHAPTER II

COMPUTER-AIDED REAL-TIME RESERVOIR OPERATION METHODS: BACKGROUND AND PROBLEMS

The purpose of this chapter is to review the current state of technology regarding computer-aided reservoir operations. The first computer based aids were simply the automation of repetitive computations. Next, the simulation of physical processes developed in the form of computer models. Today this technology has evolved from aiding decision makers by using computer based decision support systems into simulating human decision processes using expert systems technology. Advanced decision support systems or supervisory control and data acquisition systems from the process control industry are currently finding their way into the reservoir operations environment.

Computer-Aided Mathematical Models

Many computer-aided mathematical models have been developed for the application of real-time reservoir operations, but only a few of these models have been practically used. Many reasons have been given for this disparity, for example see US-OTA (1982), but the nature of this ill-structured, messy, real-world problem requires models to incorporate many simplifying assumptions which do not completely represent the real-world. In addition, most models developed to date can be classified as operational planning models used to generate operational polices or rule curves and do not meet the needs of a real-time operation. As a result, operators have little confidence in these models, the models are very hard to use for most operators, there are no provisions for the automatic inclusion of real-time data, the models require a large amount of computer resources, they take too much time to run for most real-time operations, and they do not include the legal and institutional criteria used by the operators to make the required decisions. The Corps of Engineers, see Southwest Division (1983), is presently developing software to improve these shortcomings and list the minimum functions to be supported in real-time operations as: (a) data acquisition, (b) data storage and retrieval, (c) streamflow forecasting, (d) project simulation.

Data acquisition includes the communication with an information source, the decoding of the received message into engineering units, the screening of that information for errors, and the computation of parameters. An example of a typical hydrological data acquisition system is the communication with a GOES (Geostationary Operational Environmental Satellite) data receive site, the decoding of the DCP (Data Collection Platform) message sent from a stream gage location to yield river stage, screening the stage for errors based on range and rate of change criteria, and the conversion of the stage to discharge using a rating curve. Eckhardt et. al. (1985) describe an operational GOES based hydrologic data collection system used for gathering snow, weather and streamflow information. Use of the geostationary satellite limits the timing in which data is received. In the case of the GOES, data is reported to the receive site every four hours. Most hydrologic applications do not rapidly change and therefore can utilize near real-time communications. Water supply operations generally fall in this category, however each application must be evaluated for not only data needs but the reporting interval of that data.

A great amount of data is generated as the result of automated data acquisition, and therefore a user friendly data storage and retrieval system is needed for the proper management of this data. Generally a data base system is used for this function and incorporates the usual support functions such as cataloging of contents, editing of data, archiving and restoring historical data, backup protection, and the capability to transfer data in and out of the system. All stored data must be readily retrievable for graphical and tabular display, and processing by other programs. Adequate protection in the form of duplicate files and off-line backup files is usually included to protect against unexpected actions of human and machine origin.

Depending on the type of operation, such as flood warning systems or water supply systems, real-time streamflow forecasting may or may not be required. The distinction may be short-term or long-term forecasts and the related risk involved. For a multi-reservoir system operated according to water rights, long-term streamflow forecasts are primarily used for seasonal guidelines, such as wet, dry or average, regarding water volume availability. In addition, the daily river call (generally the most senior water right not able to divert its full legal entitlement as determined by the Water Commissioner) must also be forecasted to determine the yield and the operation of a water right. Operators generally put little value in these formalized forecasts. Real-time reservoir operations according to a water rights system require timely rate of flow information rather than seasonal volumes and as a result, streamflow forecast have proven little value in this area.

The final function, project simulation, according the Corps must be capable of determining the best project operation. This is generally accomplished by a computer model which uses one or more mathematical programming techniques. In the case of reservoir operation, a control policy is developed which involves the daily or shorter time step setting of reservoir releases to achieve stated objectives. In general the control policy consists of a function:

$$r_t=R(t,x_t)$$

where r_t represents the release at time t and x_t is a vector containing the important information on the system available real-time (ie. reservoir inflow, reservoir level, reservoir release, etc.). Although many successful techniques have been used to solve this relationship by keeping the dimension of the vector x_t small, there exists no general solution algorithm. The choice of techniques depends on the characteristics of the reservoir system, on the availability of data, and on the objective and constraints specified. The available methods include:

1. Simulation.
2. Linear Programming.
3. Nonlinear Programming.
4. Dynamic Programming.
5. Stochastic Programming.
6. Quadratic Programming.
7. Integer Programming.
8. Control Theory.

Reservoir operations work in each of these areas has been reported extensively. For example see Yeh et.al. (1979) for a list of work in each of the optimization techniques. Wunderlich (1985) groups these techniques into three model categories:

1. Physical Process Simulation Models.
2. Advanced Simulation Models.
3. Optimization Models.

Physical Process Simulation Models

These models mathematically simulate physical processes such as: (a) downstream channel flow and stage given an upstream reservoir release and reservoir stage; (b) inflow given outflow and meteorological conditions; and (c) local stream inflow given watershed and rainfall information. Simulation is based on the physical laws of conservation of mass, energy and momentum. Usually no decision making is performed inside these models since they are based on strict satisfaction of the physical law equalities. As a result, solutions obtained may violate constraints such as legal or institutional requirements not included in the set of continuity equations. By iteratively modifying the assumed unknowns, an implementable operation policy can be obtained. However, achieving a specified performance criterion (e.g., maximum hydro benefit) is difficult and not very likely. In addition, as Labadie et. al. (1980) point out, in a multi-reservoir and multi-period simulation this approach quickly becomes intractable due to the dimensionality of the problem, even if computer-aided. Zielinski et.al. (1981) explain how heuristic rules may be introduced with the effect of reducing the state vector x_t dimension and thus overcoming the dimensionality problem. The Corps of Engineers HEC-1 and HEC-5 models and the National Weather Service Sacramento model are examples of simulation models.

Advanced Simulation Models

These models simulate physical processes but include constraints that describe quantifiable operation policies as accurately as possible. Limits on reservoir elevations and releases, any a priori fixed release or operation rules, and minimum hydropower or water supply requirements are generally included. The aim of this type of model is to provide a range of feasible operation policies for operators and decision makers. Within these policies, reservoir levels and releases satisfy all known quantifiable constraints in some order of prespecified priority. This assumes that the most important constraints are satisfied before an attempt is made to satisfy less important ones. To assure a feasible solution, these models require that the operator specify target levels or releases in the form of a rule curve within the feasible range computed by the model. The model meets those targets with minimum deviations, subject to all previously satisfied constraints. An example of this type of model is the Tennessee Valley Authority's weekly scheduling model, see Gilbert and Shane (1982), the California State Water Project hourly operations scheduling model, see Coe and Sabet (1985), and the network model MODSIM3 used for raw water supply, see Labadie et. al (1986).

A special type of model in this category is water rights accounting models. These models generally use monthly time steps and are used as planning models to evaluate water rights transfers and yields. They generally adhere to strict river administration and require large amounts of computer time to use, for example see Morel-Seytoux et. al (1985). In a few cases, daily Water Commissioner duties have been modeled, for example see Thaemert (1976), and Sutter et. al. (1983), which include daily reservoir operations. However, a priori rule curves are used to operate these reservoirs and as a result the water rights accounting models are of little value to the real-time operations of reservoirs.

Optimization Models

Optimization models are based on satisfying some prescribed objective while meeting physical process requirements and minimizing constraint violations. They include mathematics in the form of state equations for the basic physical process but due to the complexity and non-linearity of hydraulic systems, these equations are generally of a first order or first derivative nature. The main focus of optimization models is to develop "best" outcomes given predefined time series input so that policies or rule curves can be developed. Tradeoffs must be made by these models for solution and require that operators understand these tradeoffs. As a result, optimization models are generally used for operations planning rather than real-time operations.

To use these models does not require the direct a priori target setting by operators as the advanced simulation models do but, knowledge of future inputs is required. In addition, the objective must be expressed in quantitative form. An example of such a function is the cost formulation for a hydrothermal power system. The model searches for those water levels and releases within all previously satisfied constraints so that the total operations cost to meet a given system load is minimized. An example of this type of model is the Green River Basin Operations Optimization Model, GRBOOM, developed by Yazicigil et. al (1983).

For simple systems or systems which can be linearized, optimization techniques work well. But because of the foreknowledge requirement and the large amount of computer resources required for complex systems, Helweg et. al. (1982) report that no major reservoir systems use optimization models for real-time operation. Currently the US Bureau of Reclamation, through a cooperative agreement with the Center for Advanced Decision Support Water and Environmental Systems at the University of Colorado, is studing and developing methods to overcome the problems related to the use of optimization techniques to operate multipurpose reservoirs, see Behrens et. al (1991).

Decision Support Systems

Grigg (1986) defines a decision support system (DSS) as the use of computers to develop and display information to improve decisions. As he explains, there are two main activities in a DSS, data management and studying alternatives. These activities convert data or information into knowledge that is useful in the decision-making process. The role of the DSS is to organize the processing of, analyze, and deliver information necessary for decision making. The information necessary for decision making is the basis for the DSS.

As Ackoff (1967) points out, the critical deficiency under which most managers operate is not the lack of relevant information but rather the over abundance of irrelevant information. Most decision makers receive much more information than they can possibly absorb now. Therefore the automation of data retrieval and processing can overload an already overloaded decision maker. Ackoff lists this as one reason why very few management information systems are in operation today. However, the need for decision-aiding techniques for complex real-world, real-time decisions, especially in the face of uncertainty, has been well documented. For example see Yevjevich (1985), and Sprague and Carlson (1982).

A conclusion of Slovic's (1981) work describes the shortcomings of unaided decisions: people's intuitive judgments and decisions violate many of the fundamental principles of optimal behavior. He further states that decision-aiding technologies are still in an early state of development and the following problems need to be resolved before we can reap its full benefits:

1. Techniques for structuring the decision problem need to be developed.

2. Formulation of a method to elicit subjective judgments of probability and value essential to decision analyses.

3. Decision aids must be easy to use or they will not be used.

The real-time operation of water resources systems represents a time-space complex decision process. Decision support systems in water resources are increasing in numbers due to the technology gains in the areas of computer hardware, software and automated data collection systems. Johnson (1986) lists the three main components of a water resources decision support system as:

1. A data (acquisition, management, and processing) subsystem.

2. A models subsystem (for analysis, prediction and decision guidance).

3. A dialog management interfacing (for interactive man-machine coordination).

Note that these components closely match the Corps of Engineers list of minimum functions to be supported in real-time operations. The data subsystem includes hydrologic, water quality and meteorological data sensing, telecommunication, data processing, and data base management. Although there are many implementations of automated data acquisition and processing systems in the water field, the direct connection of this module to the models subsystem is less common. This linkage is critical in any functional DSS. The models subsystem may include one or more types of simulation or optimization models as classified above. But, generalization and standardization in modeling appears to be a key factor. This allows the flexibility of changing system operational objectives or structural modifications within the model easily and without the help of the original programmers. The dialog management subsystem is an integral part of the other two modules. This subsystem depends on the level of hardware available to the user and can range from micro computer color graphics to sophisticated workstations.

Even though DSSs as defined by Grigg and others focus on decision making, currently work on water resources DSSs is concentrating on the computer model. Both pre- and post-processors are being added to existing computer models to make their use easier, data input easier and viewing results easier, but the resulting DSS does not represent the true real-world, real-time problems encountered in Colorado reservoir operations. These problems are ill-structured and explicit algorithms used in the current DSS models do not include the decision process. Rather it is assumed that there is time to rerun the model several times based on known data or that future events are know perfectly with no adjustments required. In addition, most models used today do not include a feedback capability whereby decision adjustments can be made in response to perturbations in the system. To overcome some of these problems, Supervisory Control and Data Acquisition Systems (SCADA) are being used. SCADA systems can be classified as advanced DSSs since all three components of a DSS are embodied in a SCADA system.

Supervisory Control and Data Acquisiton

The application of process control theory is being used to operate hydrological systems. The basic concepts of classical control theory are used to include the human element of operations. But, as the name implies, supervisory means human intervention and unless all processes of the system to be operated can be quantified, human interaction is required or the SCADA system will go into a fail mode of operation.

Various types of models as mentioned above have been included in a water resources SCADA system and linked with the data acquisition module. Gooch and Graves (1986) describe how complex scheduling models generate pump, checkgate, and turnout schedules for the entire Central Arizona Project aqueduct system. Optimization models can modify these schedules to take advantage of less expensive off-peak power costs.

The application of SCADA systems in real-time water operations is somewhat limited at this time probably due to the high costs of developing and installing these systems. Since this technology is relatively new in the water business, each application requires that special software modules be developed rather than off-the-shelf software being available. As a result, SCADA systems are very costly and only used when no other method will work. The Central Arizona Project SCADA system falls in this category as does the Yakima supervisory and control system. Casola et. al. (1985) explain that the Yakima system is a large water resources project that requires the integrated operation of irrigation, instream flow uses, and hydropower production. SCADA system technology was the only method available to meet these requirements and could be justified by increased revenues generated from the hydropower system.

Eckhardt (1986) describes a SCADA system in which cost justification was not the main reason for using SCADA technology. In order to operate the Windy Gap Project, an operations system was required that used a minimum of human interaction due to the remote location of the project, the operational complexity, the continuous 24-hr-per-day operations requirements, and the environmental concerns downstream of the project. No other technology was available to meet these requirements. Although this system used closed-loop control methods, all decisions were quantified allowing a structured process to be codified. This is not always possible in the case of legal and institutional requirements and therefore other methods must be used to reach the level of performance required for making decisions.

Expert Systems in Water Resoruces

Knowledge-based expert systems (KBES) technology is a branch of Artificial Intelligence and has been the subject of intensive research since the late 1950s. Research specific to KBES began in the middle 1960s resulting in several applications, however in the area of water resources and real-time operations, there have been few real-world applications. Those reported focus on user interface or pre- and post- processors for existing algorithmic programs, see for example Gaschnig (1981).

As defined by Rolston (1988), KBES are interactive computer programs that solve complicated problems that would otherwise require extensive human expertise. The real-time operation of a multi-reservoir system in Colorado as noted above represents an ill-structured real-world problem that requires human expertise in the form of judgment, experience, rules of thumb, and intuition. Researchers have attempted to included these characteristics in algorithmic computer programs with the use of if-then-else conditions with little success. As Rehak (1983) notes, the real-world problem solution must satisfy the following conditions for traditional algorithmic computer programs to be used successfully:

1. Completeness. The set of rules must provide an action for every possible combination of conditions.

2. Uniqueness. The set of rules must provide one and only one unique outcome for every possible combination of conditions.

3. Correctness. The set of rules must provide a correct outcome for all possible conditions.

Do to the complexity and size of real-world problems such as the operation of multiple, multipurpose reservoirs according to a water rights system in real-time, these criteria are almost impossible to obtain. Rehak points out that even if completeness, correctness and uniqueness criteria are met, there are still the following problems with traditional programs:

1. The program assumes all input data are complete and without error.

2. The program functions as a black box with no mechanisms to explain how it arrives at the results.

3. The program solves one problem in only one way, an all or nothing situation.

The main difference between algorithmic programs and expert systems lies in the use of knowledge. A normal application is organized as data and program. A KBES separates the program into a knowledge-base describing the problem solving strategy and a control program to manipulate the knowledge-base. The data describes the problem being solved and the current state of the solution process. According to Fenves (1986), two key features clearly separate a KBES from an algorithmic program: (a) separation of knowledge-base and control and, (b) transparency of dialog or explanation facility. This allows the inclusion of domain-dependent heuristics or the qualitative dimension in the solution of the problem and the explanation of their use to a user. In order to determine if a problem can be solved by a KBES, Rolston lists the following screening criteria:

1. Does the task require the use of expert knowledge?

2. Is the required expertise scarce?

3. Are experts who know how to perform the task available?

4. Is there some reason to believe that a traditional algorithmic solution would be difficult to implement?

5. Does the task require a reasonable amount of judgmental knowledge or dealing with some degree of uncertainty?

6. Does the task require primarily verbal skills?

7. Is a solution to the problem very valuable to the organization; that is, is the problem definitely worth solving?

8. Is a solution that is valuable today likely to stay valuable for several years to come?

9. Is it acceptable for the system to occasionally fail to find a solution; is it OK to produce a suboptimum response in at least some cases?

10. Is a significant amount of time available to develop the system?

KBES are designed to reach the level of performance of a human expert in some specialized problem domain and therefore appear to be able to overcome the shortcomings of traditional algorithmic computer programs. However, even though the real-time operation of a multi-reservoir system in Colorado appears to meet all of the above criteria, KBES have limitations also. Rolston points out that one area in which there is a definite limit to the capabilities of the current state of the art of expert systems is where the application domain requires temporal or spatial reasoning. The real-time operation of reservoirs in Colorado requires not only the human expertise of a legal water rights system, but the temporal and spatial reasoning of an algorithmic program.

In order to solve real-world problems several researchers have proposed the integration of KBES with traditional algorithmic computer programs to overcome the limitations of both approaches. Cunge et. al. (1988) describe a proposed project for the integration of the following sub-systems for a flood warning and flood control system:

1. A real-time data acquisition system.

2. A simulation and forecasting computer model.

3. A decision-making response system.

This work is currently in progress and is focussing on the links between the KBES and, the data acquisition system and forecasting model. The purpose of the project is to develop a generic prototype of an KBES for the management of processes whose evolution is slow enough to be monitored in real-time and influenced by human decisions and actions. It aims essentially at the catastrophic and potentially catastrophic situations involving risk processes.

Chen and Pruett (1987) propose a method to integrate current expert systems technology with decision support systems for a quality control system. The significant feature in this study is the ability to integrate a data base, a model base and an expert systems base. Using a workstation approach, a user may choose a model and an expert system to operate on the data base for a given application. The actual linking of these sub-systems is covered only through a pictorial presentation.

Floris et. al. (1988) describe the coupling of an expert system with a real-time data acquisition system for the operation of a reservoir which supplies water for irrigation, energy, navigation, recreation, wildlife and fish conservation, water quality, and flood protection. The expert system is essentially used as a user interface to access the real-time data, or a simulation model if the user so desires. The expert system has two knowledge-bases: one contains the special requirements and restrictions given by the system users, and the second contains the recommended releases based on the actual reservoir and river physical condition. This system is designed to operate one reservoir and train future operators to operate this reservoir. An advanced simulation model could have been used, but the flexibility of changing constraints in the future and the ease of development were the main reasons a KBES was used.

In summary, all of these techniques have been proposed but no actual applications have been reported. In addition, computer models currently available are generally not being used in real-time by operators today for the various reasons mentioned above. It appears therefore that after a review of literature, a computerized methodology for the real-time operation of a system of reservoirs for water supply collection operating according to a water rights system has not been reported.

CHAPTER III

REAL-TIME RESERVOIR OPERATIONS IN COLORADO: BACKGROUND AND PROBLEMS

The purpose of this chapter is to develop a background and describe various problems related to real-time reservoir operations in Colorado according the Doctrine of Prior Appropriation water rights system. The following discussion is based on 15 years of my personal experiences in actually operating reservoirs, being in charge of reservoir operations, and "hands-on" working with various reservoir operators throughout Colorado for this study. Several typical Colorado reservoir systems were used in this research ranging from one reservoir and one river to multiple reservoirs and multiple river basins. Working with the reservoir operators of these systems allowed the comparison of methodologies in order to develop the information that follows. Although there are many complex philosophies and differing opinions, the following chapter attempts to characterize the major concepts and concerns in simple terms. It may appear that some of the following concepts are cut-and-dry, and universal for the entire State of Colorado. However, the "Colorado Doctrine" of water rights allows for the operation of reservoir systems to be very individual and specific.

Water Law Characteristics Related to Reservoir Operation

Rights to divert, store, and use the water of streams in the United States are based on several different doctrines. The most prevalent are the law of riparian rights and the law of prior appropriation. Riparian rights are governed by common law and give each owner of land bordering on the stream a right to make reasonable use of the water. As Trelease and Gould (1986) explain, liability is imposed on the upper riparian owner who unreasonably interferes with that use.

Appropriative rights are governed primarily by statute. Trelease and Gould described an appropriation as a state administrative grant that allows the use of a specific quantity of water for a specific beneficial purpose if water is available. Prior appropriation has been the dominant law applied in the eighteen states west of the 98th Meridian according to Radosevich et. al (1985). In the State of Colorado where the strict Doctrine of Prior Appropriation applies, or what is known as the "Colorado Doctrine," access to water depends upon statutes as well as case law.

Specifically focusing on Colorado, the Colorado Constitution, Article XVI, Section 6, states that the right to divert the unappropriated waters of any natural stream to beneficial use shall never be denied. To insure that an appropriation of water for beneficial use is a vested right, a water right must be adjudicated by the courts. The decree of this water right by the court places this right in the priority system. According to the Colorado Revised Statutes (1973), CRS, § 37-92-03, priority means the seniority by date in which a water right is entitled to use water relative to the seniority of other water rights deriving their supply from a common source. One or more of the following items are usually included in a decree: allowable rate of flow, volume limitation, stage limitation, nature of use, place of use, point of diversion, and possibly period of use.

Colorado water law also incorporates statutes related to administration and operations. In the case of reservoir operations, CRS, § 37-87-101 states that a water storage facility may not be operated in a manner as to cause material injury to the senior appropriative rights of others. In order to release water from a reservoir to a natural stream, CRS, § 37-87-103 states that the owners of reservoirs must give reasonable prior notice to the Water Commissioner or Division Engineer of the date on which they desire to release stored waters into any natural streams, together with the quantity in cubic feet per second of time, the length of period to be covered by the releases, and the name of the structure to which the water released from storage is to be delivered. CRS, § 37-87-102 further states that the water released to the stream may not raise the waters above ordinary high watermark, and may be taken out again at any desired point with due allowance for evaporation and other losses from natural causes, such losses to be determined by the State Engineer.

Reservoirs may also exchange water when the rights of others are not injured. According to CRS, § 37-83-104, it is lawful for the owner of a reservoir to deliver stored water into a ditch entitled to water or into the public stream to supply appropriations from that stream, and take in exchange from the public stream higher up, an equal amount of water less a reasonable deduction for loss, to be determined by the State Engineer. In addition, the State Engineer may permit up-stream storage of water out of priority under circumstances such that the water stored can be promptly made available to down-stream senior storage appropriators in case they are unable to completely store their entire appropriative right due to insufficient water supply, see CRS, § 37-80-120.

To summarize, water law characteristics in Colorado, in particular the real-time reservoir operational issues such as releases, exchanges, and out-of-priority storage, allow for maximum flexibility of reservoir operations. These same characteristics, however, can also create additional operational constraints that may be classified as legal or institutional. The result is that although the Doctrine of Prior Appropriation can add flexibility in reservoir operations, it can also create difficulties and special operational issues for reservoir operators as described below.

River Operations and Administration

Water user operations and river administration or regulation and how operators and administrators interact must be understood to fully appreciate the real-time reservoir operations process. The State Engineer has general supervisory control over measurement, record-keeping, and distribution of the public waters of the state, see CRS, §37-80-102. Water distribution and administration at a local level are carried out by a Division Engineer and his staff. The state is divided into seven divisions each representing one or more drainage basins. Each division is divided into districts in which a Water Commissioner is responsible for day-to-day river regulation and administration. The diversion and use of river water in Colorado is legally accomplished under the Prior Appropriation Doctrine, i.e.: "first in time is first in right." The State Engineer through his Division Engineers and Water Commissioners enforces this doctrine by assuring that natural stream flow is diverted in the same order of priority as it was originally developed.

River operations and administration can be separated into two functions: real-time operations and regulation, and water accounting and reporting. Real-time operations can be defined as the task a reservoir operator performs to divert and store water using his system. In simple terms this means the setting or adjustment of physical features, such as gates, valves, or pumping rates, according the physical and legal availability of water, in order to meet demands. Real-time administration or regulation is performed by Water Commissioners and is the determination of which water rights can divert based on the current river conditions. Water accounting and reporting for reservoir operators involves operations and maintenance issues as well as required institutional requirements. Water accounting and reporting for a Water Commissioner pertains to the legal requirement of reporting river diversions and storages.

Real-Time Operations and Regulation

The legal availability of water is determined by the Water Commissioners and conveyed to reservoir and water rights operators generally in the form of what is known as river calls. According to the Doctrine of Prior Appropriation, a simplistic definition of the river call commonly used today is the most senior water right not able to divert its full entitlement. This definition does not mention the spatial and temporal aspects of a river call. For example, there can be several river calls in one reach of a river and these calls can change over time. The actual determination of which water rights are in priority is a very complicated process performed by the Water

Commissioners and includes many legal and physical factors such as "futile calls" and return flows. The intent here is not to discuss the details of how this is done, but a portion of this procedure from a reservoir operator's perspective.

The process of setting river calls depends on reservoir operators providing physical data and information to the Water Commissioners on a timely basis. Figure 1 depicts the exchange of information between reservoir operators and their raw water collection systems with a Water Commissioner and the river system. As shown on this figure, Water Commissioners need to know operational information from the reservoir operators as well as the physical river information. Examples of operational information include when and what is the rate of release from the reservoirs storage to the river; when and where is this storage release going to be diverted back from the river; and when and what is the rate of exchanged water between two points on the river. The physical river information primarily includes river flows at all river diversions and gages over a certain time period. A gate setting or valve percent opening are examples of control information.

Setting the river calls and operating reservoirs not only require that river flows at each structure on the river system be known, but that the breakdown of these flows into natural and "other" flows also be known. For example, at any given time the flow at a stream gage can be composed of

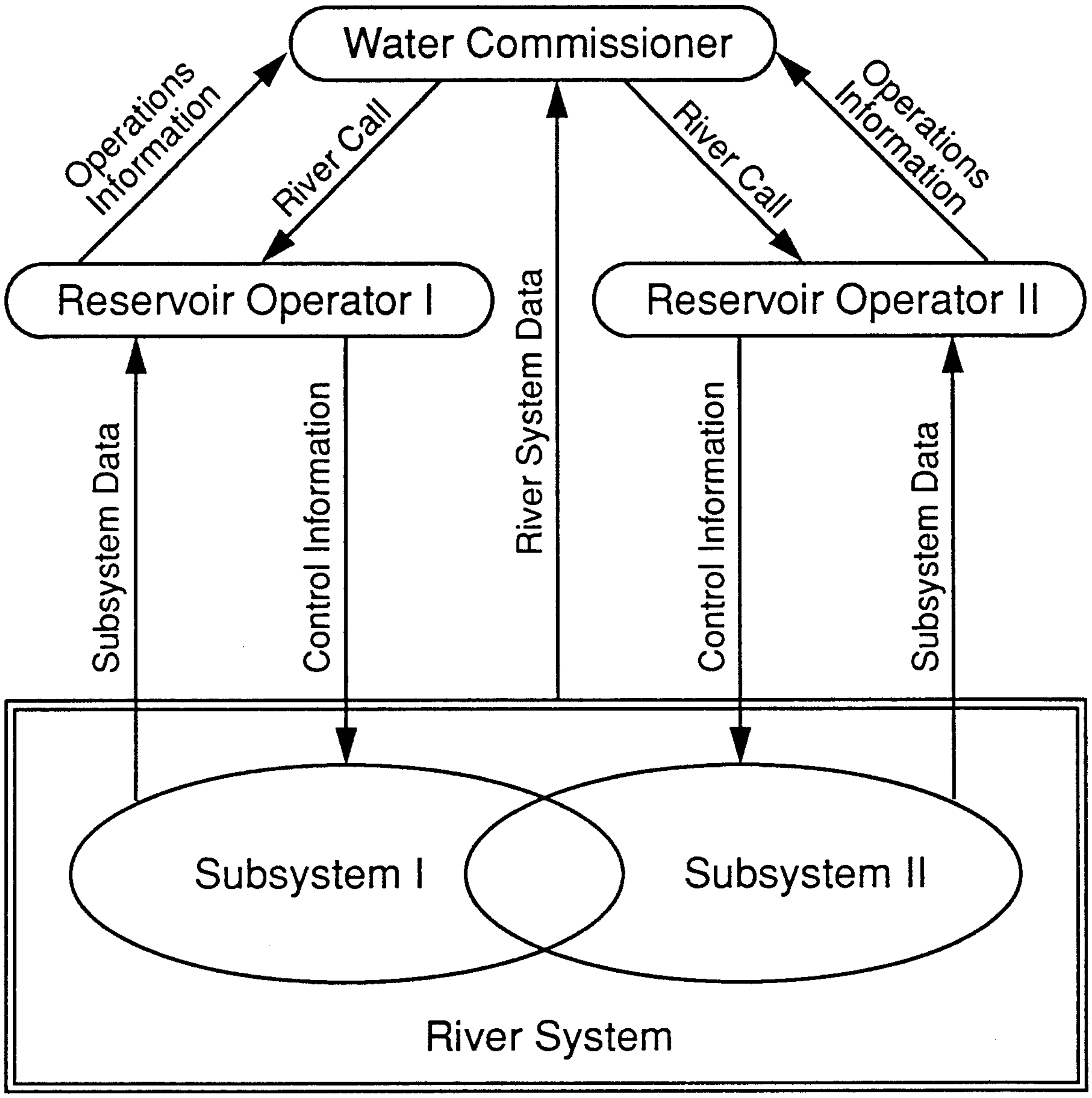

Figure 1. Operator - Water Commissioner Information Exchange.

natural flow, trans-basin flow, reservoir releases, exchanges, transfers and augmentation flows. In order for a Water Commissioner to determine this flow breakdown, each reservoir operator's operational information of time and amount of reservoir releases to, and diversions from, the river must be known. Using a simple routing technique of travel time and stream losses, each reservoir release to the river can be computed at a given gage and given time. The actual or total gage flow less the sum of all "other" flows represents the natural flow. Once this flow breakdown is known, the Water Commissioner can distribute the natural flow according to the Prior Appropriation Doctrine and the "other" flows according to ownership. Presently this flow breakdown computation is done manually by the Water Commissioners and is becoming so complex and difficult that it is generally only completed once or twice a day.

With today's condition of over-appropriated river systems, Water Commissioners are forced to make timely decisions regarding the river calls to maximize the beneficial uses of the water to all water users. He can only make those decisions if reservoir operators are providing timely and accurate operations information. Today some reservoir operators may take as long as four to six hours to complete their operations decision process before the operations information is available for the Water Commissioner. In some cases, the Water Commissioners cannot wait the four to six hours and are forced to make assumptions on operations information to set the river calls. Consequently the river calls at that point in time may not reflect the true physical and legal river system.

Once the reservoir operators provide the operational information required by the Water Commissioners, the Water Commissioners can recompute the river calls. The reservoir operators can then adjust their operations to account for the new river calls. In order to determine reservoir releases, storages, and exchanges, a reservoir operator needs to know not only river calls but the natural flow at each reservoir and diversion. However, in order to set the river call a Water Commissioner needs to know the reservoir operations information. This is somewhat of a "catch 22," as will be discussed below under On-Stream Reservoir Problems, this problem is currently overcome by using "day-late" operations and regulation.

<u>Water Accounting and Reporting</u>

The second aspect of river operations and administration is water accounting and reporting. As defined here, water accounting is the tracking or record keeping of water through a water resources system. For a Water Commissioner, the water resources system is the river system. For a water rights operator, the water resources system is generally his raw water collection system.

A reservoir operator is interested in all aspects of his system and keeps records for not only reporting reasons, but for operations, maintenance, and efficiency reasons. It is very detailed and specific to each system. He generally keeps track of not only each and every storage facility and conveyance structure, but each water right. Just as in money, several water accounts can be developed based on each water right and structure, and debits and credits to each of these accounts must be taken into consideration. Real and paper transfers and exchanges can take place as long as the debits and credits balance and water rights of other systems are not affected.

From a Water Commissioner's perspective, accounting involves only those structures or features directly related to the river system. Water accounts are kept by structure and ownership rather than by individual water rights. A Water Commissioner performs water accounting for record keeping only and is legally required to report river operations at the end of the year in a report known as the Annual Diversion Report. The State Engineer's Office stores this information in a computer data base system for the generation of various reports including the Annual Diversion Reports.

Much of the information required for the Annual Diversion Report is contained in the water rights operators accounting systems. But, typical water rights owner's accounting systems are usually not designed with the State's diversion records system in mind. For example, water rights operator's accounting systems generally keep track of diversions and storage by water right, whereas the Water Commissioner is required to report diversions and storage by structure and owner. As a result, the information needed by the Water Commissioners for the Annual Diversion Report is not readily available in the water rights owners accounting systems and requires that a water rights operator either keep two separate accounts or develop a system which generates the required Water Commissioner information. The water rights operator is required to report this information to the Water Commissioners upon request.

On-Stream Reservoir Problems

Natural river flow varies continuously and since on-stream reservoir releases are generally changed only once a day, the possibility of an over or under diversion for storage according to the Prior Appropriation Doctrine exists. Currently, "day-late" accounting is used and the concept of authorized flow has developed to take care of this over or under diversion. Each morning, average daily flows at each on-stream reservoir are computed for the previous day. Knowing the river call for the previous day (generally the most senior water right not able to divert its full legal entitlement as determined by the Water Commissioner), the amount of water that could be legally diverted is determined and accounted for as an authorized inflow. Based on the previous days' reservoir gate changes, reservoir releases are computed as authorized outflow.

Comparing the authorized flows with the actual flows results in a difference which is the "over" or "under" diversion. This difference is accounted for as an administration account or in some cases an owe-the-river account and may be positive or negative depending on if the actual amount diverted is over or under the authorized amount diverted. Since it is illegal to over divert, the administration account should be zero at all times. This is not possible with on-stream reservoirs and day-late accounting, unless reservoir gate changes are made continuously to track natural inflow.

If there is no injury to intervening water rights, storage exchanges can be made with lower reservoirs in order to keep water as high in the system as possible for future use. However, each reservoir must then have a storage account which represents all other reservoirs for proper water accounting. For example, if the up-stream reservoir is legally full, no more water can be stored. But if there is physically space available, a portion of the up-stream reservoir can be allocated to a lower reservoir. Water in the lower reservoir can then be exchanged to this account by the up-stream reservoir storing water out of priority, and the lower reservoir releasing the same amount. Since current accounting takes place a day late, and the exchanged physical release did not take place, an administration or owe-the-river account can develop at the lower reservoir. This account can then be released one or more days later based on day-late accounting to down-stream users. But, possible injury to down-stream water rights can occur as a result of this delayed release unless the administration account was allocated to specific down-stream water rights. This allocation is not presently done.

In order to determine authorized exchanges, releases, and storage, natural river inflow and legal diversion amounts or river calls must be known. According to CRS, § 37-84-116, the State Engineer has general supervisory control over measurement of the public waters of the state. As a result, all headgates, measuring weirs, flumes, and devices used in connection with canals, flumes, ditches and reservoirs for measuring and delivering of waters are under the supervision and control at all times of the Water Commissioners. In the case of reservoirs in streams or on-channel reservoirs, CRS, § 37-84-117 requires an elevation-capacity table. It is therefore the responsibility of the Water Commissioners to not only determine river calls, but natural flows, at all locations. Although reservoir operators determine natural flows through the reservoir operations process, the Water Commissioners have the final say as to what the natural flows are in the system.

One unique aspect of on-channel reservoirs related to the determination of natural inflow is the interaction with the river system regarding losses and gains resulting from seepage, evaporation, ungaged inflow, and measurement of stream inflow. Generally, inflow to off-channel reservoirs in Colorado is measured using a flow measurement device on the inlet channel unless the storage decree allows the use of reservoir stage change. The difference is who absorbs reservoir losses, the river or the water rights owner. For example, if the amount stored in a reservoir is measured at the inflow channel, reservoir loss is not included in the storage amount and the reservoir is legally filled when the inflow volume reaches the decreed amount, regardless if the reservoir is not physically full because of losses. In this case the water rights owner must absorb the loss rather than the river. Generally in Colorado the plains reservoirs are off-channel and use stage change accounting to take advantage of losses as a result of dam underflow, seepage and evaporation. On-channel mountain reservoirs on the other hand are usually gaining reservoirs due to positive dam cutoff and ungaged inflow. This gain is part of the river system and was historicly used by down-stream water rights before the reservoir was built. Consequently, measurement of inflow cannot be made by stream inflow gages to on-channel mountain reservoirs since gains are not included in the measurement. Stage change computations must therefore be used to determine natural inflow for operations and accounting.

The only problem with this technique is that small stream inflows compared to large reservoir surface areas require very accurate stage - storage curves and an accurate method of reading stage changes to 0.01 feet. Currently, automated sensors cannot ensure this kind of accuracy over the range of stage variations encountered, and the accuracy of the presently used stage - storage curves is unknown. The net result of these potential inaccuracies is that the river natural inflow to on-channel reservoirs is not exactly known and the resulting reservoir operations decisions could unknowingly affect senior down-stream water rights.

The computation of reservoir inflow requires that evaporation be known. Currently monthly evaporation factors are used based on studies performed by reservoir owners. Rather than using factors based on average conditions, real-time measurements of evaporation could be made to insure an accurate natural inflow. For example, when an on-channel reservoir storage right is not in priority, all natural inflow should pass through the reservoir. Since inflow is computed based on reservoir stage change, evaporation rate must be known to ensure that the reservoir owner is not storing natural flow to make up reservoir losses. Rainfall on a reservoir generally must pass through to senior down-stream water rights also. Precipitation amounts are usually measured and therefore can be passed through a reservoir to senior rights when the reservoir storage decree is not in priority.

Currently, the Prior Appropriation Doctrine recognizes the fact that prior to the reservoir construction, phreatophytes were consuming water from rainfall and have stopped due to inundation as a result of the reservoir.

Reservoir owners, however, cannot claim this prior phreatophyte rainfall use as a water right, but some operators credit this amount towards reservoir surface evaporation. The term "net evaporation" therefore includes not only rainfall but this prior phreatophyte use. Based on studies, monthly factors are sometimes used to determine the percent of precipitation a reservoir owner can use to off-set evaporation. The remaining precipitation or "net" precipitation must therefore be released from the reservoir. When using the monthly net precipitation and evaporation factors during dry or low inflow periods, negative reservoir inflows can result since the factors are usually based on average conditions rather than dry conditions. Adjustments to the real-time operations and accounting must be made for this situation in order to prevent potential injury to down-stream water rights. Presently, no accepted methodology exists for these accounting or paper adjustments as a result of negative inflows.

Forecasting vs. Hindsight

River flows and user demands are continuous parameters that vary over time and space. Using these parameters at an instant in time for real-time operations and accounting does not reflect the continuous fluctuations that occur. To overcome this problem, a period of time over which an average can be established is used. This time period in Colorado corresponds to the use of the basic water unit, day-second-feet, which requires 24 hours. The question then is which 24 hour period to use, the previous 24 hours, the future 24 hours, or some combination.

The concept of hindsight currently used in Colorado refers to the previous 24 hours. However, the Prior Appropriation Doctrine requires that owners of reservoirs give reasonable prior notice to the Water Commissioner of reservoir releases to a natural stream of the date on which they desire to release stored waters, the quantity in cubic feet per second of time, the length of period to be covered by such releases, and the name of the structure to which the water is to be delivered. Since currently authorized on-channel reservoir releases are determined based on previous days' parameters, prior notice of reservoir releases cannot be given unless future inflows are known. This would require real-time inflow and demand forecasting, which most reservoir owners don't do and probably don't have the resources to accomplish. Even if they did, precise real-time forecasting methods do not presently exist.

The stochastic nature of raw water inflow and user demands is so complex that even with today's latest techniques, real-time forecasting is not exact. If forecasted numbers are used for operations and accounting and they are not exact, the potential for large out-of-priority storage or loss of water for storage exists compared to hindsight accounting. As a result, forecasting is not used for real-time river operations. In the South

Platte basin, the State Engineer currently allows the use of hindsight accounting, as long as the administration accounts are maintained near zero and any large build-ups are reduced within 72 hours. Presently this is a very difficult task due to the number of reservoirs on-channel and the complex nature of the water rights transfers and exchanges.

Routing - Flow Timing and Losses

The Prior Appropriation Doctrine is generally not consistently interpreted regarding river flow timing of reservoir releases and exchanges. For example, an exchange can be instantaneous but a reservoir release must be routed or lagged. In an instantaneous exchange, the down-stream replacement location adds water to the river before that water would have naturally occurred. If down-stream senior diverters are at full capacity when this happens, this water will bypass them. But, if at a later time this water would have naturally arrived when the senior diverters are not getting their full entitlement, they could use this same amount of water.

The law also requires that evaporation and other natural losses are to be determined by the State Engineer. Both flow timing and the determination of stream losses are needed to reconstruct the natural flow hydrograph. Then natural flows can be allocated according to the Prior Appropriation Doctrine, and "other" flows can be delivered to the appropriate owners.

Routing relationships are complex and hard to determine since they vary according to the amount of flow in the river and the time of year. As a result, most Water Commissioners uses an empirical approach. Based on years of observing the river, Water Commissioners use average numbers representing a time lag for average flow conditions and a loss coefficient also based on average conditions. Since these parameters are subjective, continual disagreement results between Water Commissioners and water users regarding the values of these parameters.

Not knowing the natural inflow hydrograph creates additional problems related to on-channel reservoirs. The computed inflows from up-stream reservoir releases, both in time and amount, compared to the actual inflows differ and affect the natural inflow computations used in the real-time operations of reservoir releases. For example, the reservoir computed natural inflow can be smaller than the actual natural inflow one day and larger the next because the timing and loss errors either borrow water from or add water to the natural inflow hydrograph. Consequently, empirically routed flows and resulting reservoir releases can cause potential injury to down-stream senior water rights.

To compound the flow timing and loss problems, reservoir routing should also be taken into consideration. Presently this is not done due to the complexities of developing and using the routing relationships in real-time.

Since inflow is measured by change in reservoir stage, and reservoir gains and losses are not accurately known, the river system must stand the flow timing and loss errors of water passing through an on-channel reservoir. This potentially could injure down-stream senior water rights similar to the river routing problem. On-channel reservoirs with large surface areas dampen out the natural river flow fluctuations over time but, since reservoir releases are generally made only once a day, a continuous inflow hydrograph gets changed into a step function outflow hydrograph.

Since reservoir releases and transfers are reduced by a river loss coefficient as they move down-stream, the concept of a "reverse loss", that is a gain, is often considered by some water users. For example, if an up-stream reservoir stores a certain amount of natural flow out-of-priority, that same flow if allowed to move down-stream could be reduced by stream loss. Currently, when exchanging water out of a lower reservoir, the full volume stored out of priority must be released. In reality, however, only a portion of the original up-stream flow would have been available at the down-stream reservoir for other senior water users. The State Engineer does not recognize this concept since the physics of the stream system are not fully understood. The water rights owner that is making the exchange must make up the stream loss in an exchange condition.

Multiple Water Users

When operating a system of reservoirs, an operator must not only consider natural flows and other water rights but other water user systems. For example, water user A could have a reservoir on the same stream between two reservoirs of water user B. Water user A can not only store water according to the Prior Appropriation Doctrine, but release and exchange water just as water user B would. When computing natural inflow into a reservoir, the amount of the total inflow that belongs to other water users must be known. The same problems of river routing are involved with other water user releases as mentioned above. But, an additional problem is the real-time communications of knowing when another water user makes reservoir gate changes.

Currently, communications between water users is through the Water Commissioners. Reservoir owners must give the Water Commissioners prior notification of all releases to a natural stream including the time, amount, and where the water will be diverted back from the river again. Water users must either call the Water Commissioner, or agree to share this same information with other water users before reservoir operations and accounting can be completed. Once this information is known, a reservoir operator can determine the allowable storage amount and the required gate release. In some cases, an exchange can be made on other users water if no other water rights are injured and the owner of the water being exchanged on is not injured at their required diversion point.

Another interesting multiple water user occurrence is that in some cases more than one water user owns or uses a single reservoir. Each user can have a separate water right in this reservoir requiring separate accounts with several additional accounts to track each users different types of water. For example, it is possible for one water user to borrow water from another water user within a single reservoir and repay it at a later date. In addition, like a single user of a reservoir, water can be "booked" over or paper transferred from one account to another, based on various agreements and contracts.

Data, Real-Time and Record

Reservoir operations decisions require real-time data based on converting sensor information into engineering units. The conversions used in some cases vary based on such factors as time of year, climatic conditions, and natural occurrences. For example, stream flow requires converting depth of flow to rate of flow using a stage - discharge rating curve. In natural streams, the stage - discharge curve varies over time for the reasons mentioned above and is checked periodically by manual flow measurements. If the flow measurement is not within a certain tolerance of the stage - discharge curve, a shift is applied to the stage - discharge curve in order to match the current measurement. The shift is prorated back in time to past data, from the present flow measurement to the last flow measurement. Therefore, when looking at stream flow records, flows that operations decisions where based on have been changed to match the prorated shift, and in some cases, the original flow values are purged. This also occurs when sensor data such as reservoir stage, precipitation, evaporation, wind run, and solar radiation, are corrected for temperature or other natural and hardware phenomenon. This adjusted data is usually archived in computer readable media for future use. In addition, for publications reasons, total river system data are sometimes adjusted to meet mass balance principles or other concerns. An example of this is the United States Geological Survey's publication of stream gage records.

Since the published records and computer archived adjusted sensor data are easy to obtain and retrieve, they are generally used to reconstruct past operations decisions. Therefore when studying past reservoir operations decisions based on what are now the adjusted real-time data, questions sometimes arise since some decisions appear to be in error based on the data available. If a disagreement ensues, it is hard to reconstruct the original decision process since the original data have been altered or no longer exist. Accusations of improper operations decisions related to the Prior Appropriation Doctrine, such as over storage or improper release amounts, result. To overcome this situation, current methodologies which adjust and purge real-time data used for decision making need to be reviewed and revised.

Agreements

Many agreements between water users have evolved over time related to water rights operations and, have even attempted to clarify river administration or regulation. Some examples of these types of agreements are reservoir prior filling, subordination, municipal effluent reuse, and "gentlemen". Reservoir operators and in some cases, water administrators must be aware of these agreements when making operations and regulation decisions. In instances where the agreement is not decreed, water users may recognize an agreement while the State Engineer's office may not. Most of these type of agreements have not been adjudicated in Water Court and unless problems arise, the legality of the agreements have not been challenged.

Reservoir operators generally try to factor the details of these agreements into their real-time operations decision process. This is no easy task, since in a good share of these agreements the provisions may be contrary to law or potentially injure other water users not included in the agreements. As a result, an operator using his best judgement, factors in those provisions of the agreements he can handle while meeting the requirements of the Prior

Appropriation Doctrine. Presently, computer simulation and other computerized tools used to operate reservoirs, do not include the capabilities of integrating the Prior Appropriation Doctrine with special agreements into the operations decision process.

Water Quantity - Quality

The Colorado Prior Appropriation Doctrine originated during the mining era and the major concern at the time was having enough water for mining operations. Later on when agriculture was the major industry, again the quantity of water available for crop production was the major concern. Today, with increasing urbanization in Colorado, the switch from agriculture to tourism as the main industry, and the emphasize on the environment, water quality issues are also a major concern. Water quality must be considered when diverting water from streams according to the Prior Appropriation Doctrine. A common water quantity - quality issue today is related to the protection of fish habitat. When a reservoir is constructed on a stream channel, the fish migration patterns are changed, the geomorphology of the stream channel is altered, and the natural flow hydrograph is affected. For example, stream flows are decreased and in some cases even stopped as a result of a dam and reservoir constructed on a natural stream channel.

To account for potential adverse fish habitat effects, minimum release requirements may be imposed on the reservoir owner. The required rates of flow usually vary based on the time of year,the historic flow patterns, and the current climatic conditions. In addition, since on-channel reservoirs usually capture the high flows, the reservoir releases may not flush sediment properly from the stream bed below the reservoir to allow adequate conditions for fish spawning. Consequently, flushing flows are usually added to reservoir minimum flow release requirements to correct for this situation. For example, a reservoir may be required to release from storage minimum flows in the fall for fish spawning and, an amount equivalent to the average high flow for a certain duration in the spring to simulate the historic hydrograph high flow sediment flushing effects.

Required reservoir releases can also be imposed for recreation, such as rafting, certain times of the year. Reservoir water surface elevations may also have limitations related to habitat and recreation use. For example, a minimum pool elevation may be imposed to protect fish habitat, provide an adequate water surface for boating activities, and prevent blowing sand from dry reservoir bottoms to surrounding houses.

In addition to habitat and recreation water quantity - quality concerns, agriculture issues such as water quality effects on edible vegetables, soils and farm workers, and municipal concerns related to water treatment costs, are of major importance. Water short streams as a result of growing user demands, are forcing the Prior Appropriation

Doctrine to address the water quantity - quality concerns. The issue of exchanging lower quality water for good quality water is currently being addressed in the Water Courts. The practice of using natural stream flow and replacing this amount with treated sewage effluent could be curtailed if down-stream users are injured as a result of this practice. The question of injury will be determined by the courts and, based on the current societal values, water quality could have an impact on the operation and administration of water rights.

On-channel reservoirs have some unique problems related to water quality. Thermal pollution and dissolved oxygen content are of concern related to down-stream fish habitat. In some cases, multiple elevation outlets have been constructed to mix the various levels of reservoir water in order to restore pre-reservoir water temperature and dissolved oxygen conditions as closely as possible. As a result, which levels of reservoir water to release and how much at each level must be included in the reservoir operations process. Some reservoirs when drawn down will create sediment laden water which also creates problems in the reservoir and the release. The released water not only has a higher sediment loading but the sediment itself may have various chemical and biological characteristics that affect fish habitat, recreation, and municipal treatment problems.

Water quantity - quality problems could eventually be included in the Prior Appropriation Doctrine and affect reservoir release and exchange operations in the future. Currently, many reservoir operators are trying to included water quantity - quality issues in their operations decision process but, have found this to be a complex and challenging problem to address. Since the Prior Appropriation Doctrine governs reservoir operations in Colorado, a more complex and potentially less flexible decision process will need to evolve.

Decree - Law Interpretation

The Prior Appropriation Doctrine requires that a water right be adjudicated in order to be included in the priority system. Water rights decrees today evolve as a result of engineering and legal collaboration. When a decree is adjudicated, existing water rights holders can impose conditions in order to prevent injury to their water rights, provided the Water Court approves the conditions. As a result, decrees can become very involved and complex. Once a decree is adjudicated, the reservoir operator must interpret the decree from an operations point of view rather than a legal or engineering perspective. This is a very difficult task and in some cases, decree interpretations vary between other water rights owners and administrators. The disagreement of interpretation can be resolved by the State Engineer or even the Water Court if necessary.

Operation and administration of the decree in some instances may be placed under court or State Engineer jurisdiction until every one agrees that the decree requirements are being met. As a result, the inclusion of most water rights decrees, especially those under some type of court or State Engineer retained jurisdiction, in an automated decision process is very difficult if not impossible. Currently, this has been attempted for only the simplest water rights decrees.

In addition to water rights decree interpretation, statutes and court cases must also be interpreted in order to operate water facilities according to the Prior Appropriation Doctrine. As statutes change and water court cases are completed, water rights owners and reservoir operators must review the statutes and court cases in order to change certain operations methods if required. This is a difficult task that requires years of experience. Even more difficult is to include this process in a computerized model or operations decision tool. Other than the straight forward statutes and court cases, current computer models for reservoir operations do not include the full complexities and flexibilities required of the Prior Appropriation Doctrine. As a result, little if any automated techniques are used to aid operations decisions related to the Prior Appropriation Doctrine.

In summary, although the Doctrine of Prior Appropriation, allows flexibility in reservoir operations, many institutional and legal constraints can make a difficult task of reservoir operations. The issues discussed in this chapter represent the major concepts a reservoir operator must deal with daily. They are becoming more complex as the demand for water increases from water short streams. As a result, the currently used and accepted operations procedures are not able to handle these problems or at least handle them in a timely fashion. Both reservoir operators and Water Commissioners need additional tools to meet today's needs for real-time river operations and administration.

CHAPTER IV

A DECISION SUPPORT SYSTEM FRAMEWORK FOR RESERVOIR OPERATIONS: CONCEPTS AND THEORY

The purpose of this chapter is to meet the objectives of this study by developing a framework for a computer based Decision Support System to operate Colorado reservoirs in real-time. The heart of the framework is a formalized procedure based on currently accepted methods and practices used to operate reservoirs in Colorado today. The procedure as defined here is the specific methodology or process for operating a multiple reservoir system in real-time. The framework represents the organizing concept in which to implement and integrate the procedure in a real-time reservoir operations environment.

As stated in Chapter II, currently developed computer based DSS's are not being used by reservoir operators today. Therefore, a new approach will be used to develop a DSS in order to overcome this problem. Using my past experience and work with several reservoir operators in Colorado, a generalized and routinized reservoir operations procedure will be developed which represents currently accepted methods. Finally, a framework will be developed in order to integrate the procedure in a real-time computer and data collection environment. The procedure and framework will be generic, so that the computer application of the framework will be relatively simple. Consequently, a potential user will be able to implement the framework using his choice of computer hardware and software. This will be demonstrated in Chapter VI.

Current Reservoir Operations Procedures

The primary function of a reservoir operator in Colorado is to meet his water system demand requirements, in both time and space, while satisfying physical and legal constraints. The procedure currently used by most reservoir operators to perform this function is generally accomplished on a daily basis using day-late accounting. This reservoir operations procedure is depicted in the flow chart in Figure 2 and can be classified as a manual feedback process. Major reservoir outflow changes are made once a day based on instantaneous values of river flows, water system demands, and the legal requirements set by river calls. Day-late water accounting is then completed and the results are used to adjust the previous estimated reservoir outflows.

Although the current manual procedure, as shown in Figure 2 and described below, has been broken down into various steps or functions for illustration, in fact it is very complex and ill-defined. The process differs somewhat from reservoir system to reservoir system, probably based on the historic development of the reservoirs or other

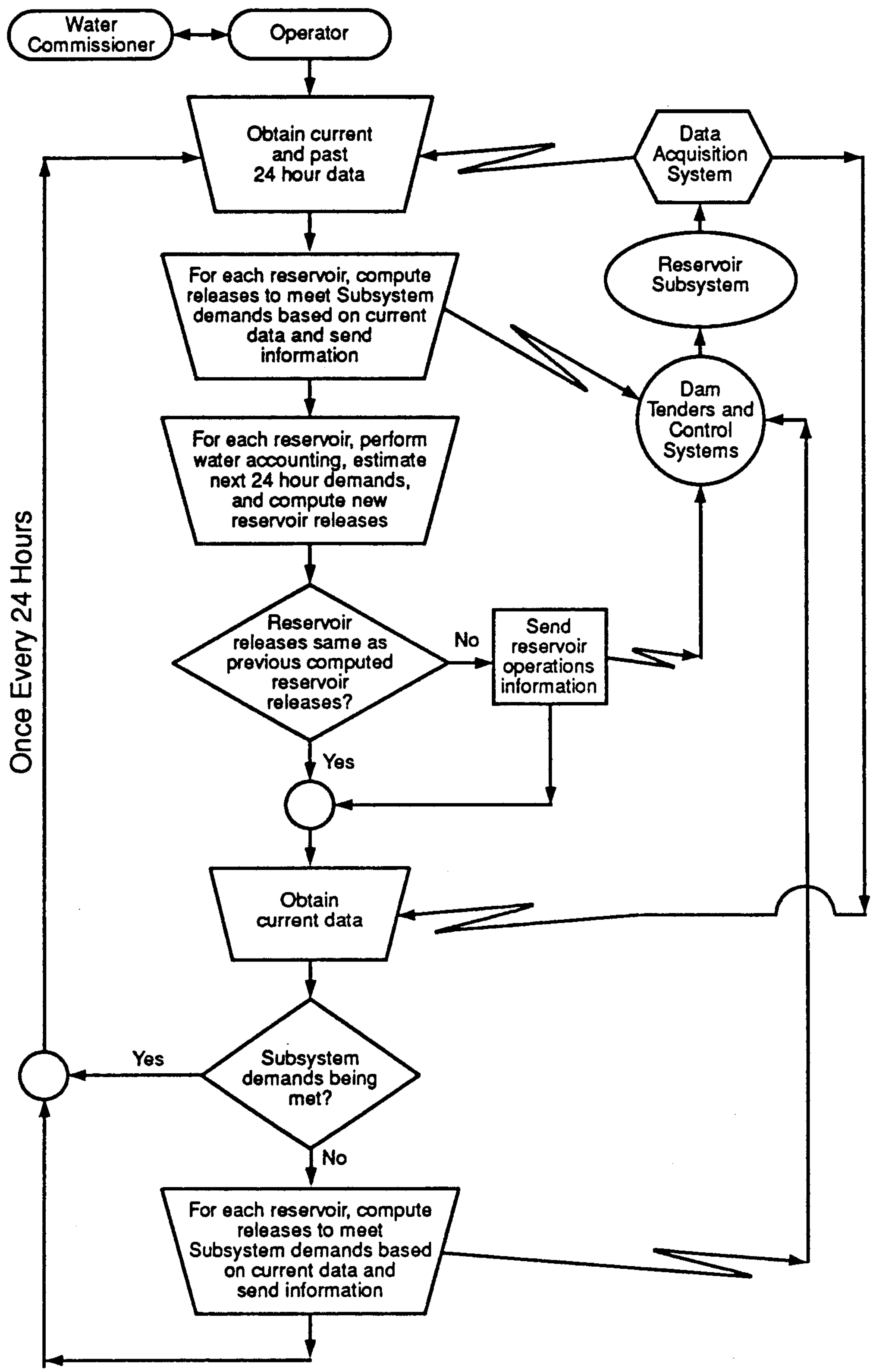

Figure 2. Current Manual Reservoir Operations Procedure.

intangible factors. These basic steps, however, are required to operate reservoirs in Colorado. The order in which each of the steps is performed may vary by system and operator, but the process works and until recently has met the needs of reservoir operators.

The following is a general breakdown of the reservoir operations procedure currently used by Colorado reservoir operators.

1. Obtain current or end of accounting period flows and volumes from gage readers or data acquisition systems.

2. Using current river flows, reservoir volumes, and system demands, estimate required outflows to meet current water system demands and, reservoir and stream limitations. Convey this information to dam tenders and control systems.

3. Perform water accounting at each reservoir using the past 24 hour reservoir storage change, total outflow, and deliveries.

a. Using mass balance equations at each reservoir, yesterday's total inflow is computed. The total inflow includes ungaged flows and up-stream releases from other reservoirs.

b. At each reservoir, using yesterday's river call from the Water Commissioner, allocate yesterday's total inflows to storage, deliveries, and releases based on water rights in priority.

c. Determine exchanges based on the physically available inflows at each reservoir and any over or under storage according to the water rights in priority. Any over or under storage of water that cannot be accounted for through exchanges is included in an administration account or "owe-the-river" account as explained in Chapter III.

4. Using weather reports or "rule-of-thumb" techniques, demand and natural inflow changes are estimated for the next 24 hours.

5. Using the current river call and current reservoir outflow settings, new reservoir outflows are computed based on the administration accounts, potential river call adjustment, and estimated change in demand and inflow. These outflows are then transferred to the dam tenders and control systems.

6. The system is monitored the remainder of the day to insure that all demands are being met.

The procedure is manual except possibly for data acquisition and gate and valve control systems. Notice that system models, forecast models, and automatic transfers of data are not used. Day-late or 24 hour water accounting is required which can take some time to complete based on the size and complexity of the reservoir system. The procedure is fairly inflexible as a result and cannot be adjusted to meet today's overall objective of maximizing water capture.

Today this procedure is becoming obsolete and difficult to use due to the complexity and size of reservoir systems, and the complexity and large number of water rights. Using this manual process to meet today's needs of maximum water diversion and storage is creating many problems as described in Chapter III. These problems have to be resolved in a new process in order for reservoir operators to even consider using a new computer based procedure. The primary procedural issues that need to be corrected in order to solve the operations problems can be summarized into two major categories as follows:

1. The process must execute in real-time using current and past data to provide river flow rates at all required locations at any given point in time.

2. The process must automatically integrate the legal water rights requirements in real-time by providing legally available or required flows at all required locations at any given point in time.

Although various components of the manual procedure have been upgraded to alleviate some of the operations problems, the current procedures still do not resolve the two procedural issues mentioned above to meet today's reservoir operator's needs. For example, automated data collection systems have replaced phone calls, and accounting sheets have been computerized. But, the updated manual procedure still uses daily time steps and doesn't provide up-to-the-minute information. The integration of real-time data with the computation spread sheets is not automatic and the requirements of a legal water rights system are still dealt with manually. The entire process is slow and inconsistent, varying from day to day depending on which operator is operating the reservoir system.

Proposed Reservoir Operations Procedures

Using a systems approach, the current manual process can be converted into a formalized procedure for computer adaptation. The current manual approach is inconsistent and ill-defined primarily because each component or reservoir being operated is treated individually rather than as one system where information and procedures need to be consolidated. The systems perspective stresses the interdependences between the elements of the system and focuses specifically on those relationships rather than on the behavior of the individual elements. Using this approach then allows the integration of the physical and legal relationships required to operate multiple reservoirs in real-time. The current manual operations process in most cases provides the data and information necessary to use the systems approach but needs to be structured differently and integrated.

The definition of the system is critical in order that all data, information, and relationships between the elements of the system be identified. To illustrate this, Figure 3 depicts a portion of a river basin with two typical Colorado multi-reservoir raw water supply collection systems. Subsystem I can be defined as reservoirs A, B, and D and diversion 3, since they are facilities owned and

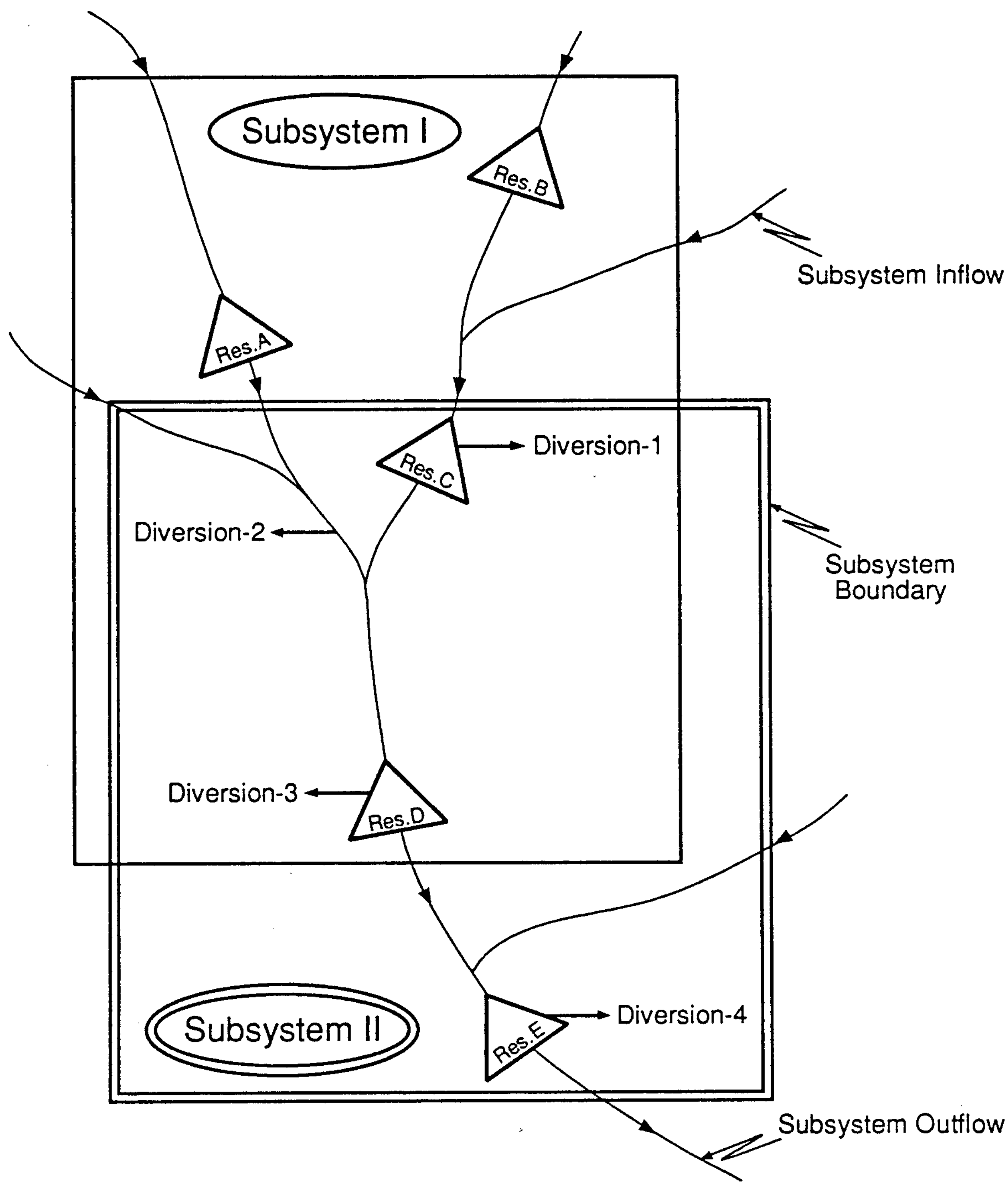

Figure 3. Typical River System With Reservoir Subsystems.

operated by one entity. Subsystem II can be defined as reservoirs C and E and diversions 1, 2 and 4, since they are also owned and operated by another entity. Each subsystem boundaries are selected to include all facilities to be operated because this allows the relationships of the elements of each subsystem, in this case the reservoirs, diversions, and river segments, to be defined independently of the relationship between the subsystem and the river system. For example, typical relationships between elements of a subsystem might be exchanges and transfers of water between two or more reservoirs. The fact that elements of one subsystem are included in another subsystem can be handled by the relationships between subsystems. An example of this type of relationship might be a required river flow from one subsystem to another.

In defining the subsystem relationships with the river system, all inflows and outflows to the subsystem, including reservoir storage and diversions, must be identified as shown in Figure 4. The subsystem relationships with the river system can then be defined as subsystem diversion, storage, and outflow. Subsystem outflow is defined here as the subsystem required outflow hydrograph. Knowing the river call and total subsystem inflow over time, the native or natural flows at all points within the subsystem can be computed in real-time. Then the subsystem diversion, storage, and required outflow hydrograph can be determined. Once the required outflow hydrograph is defined and the

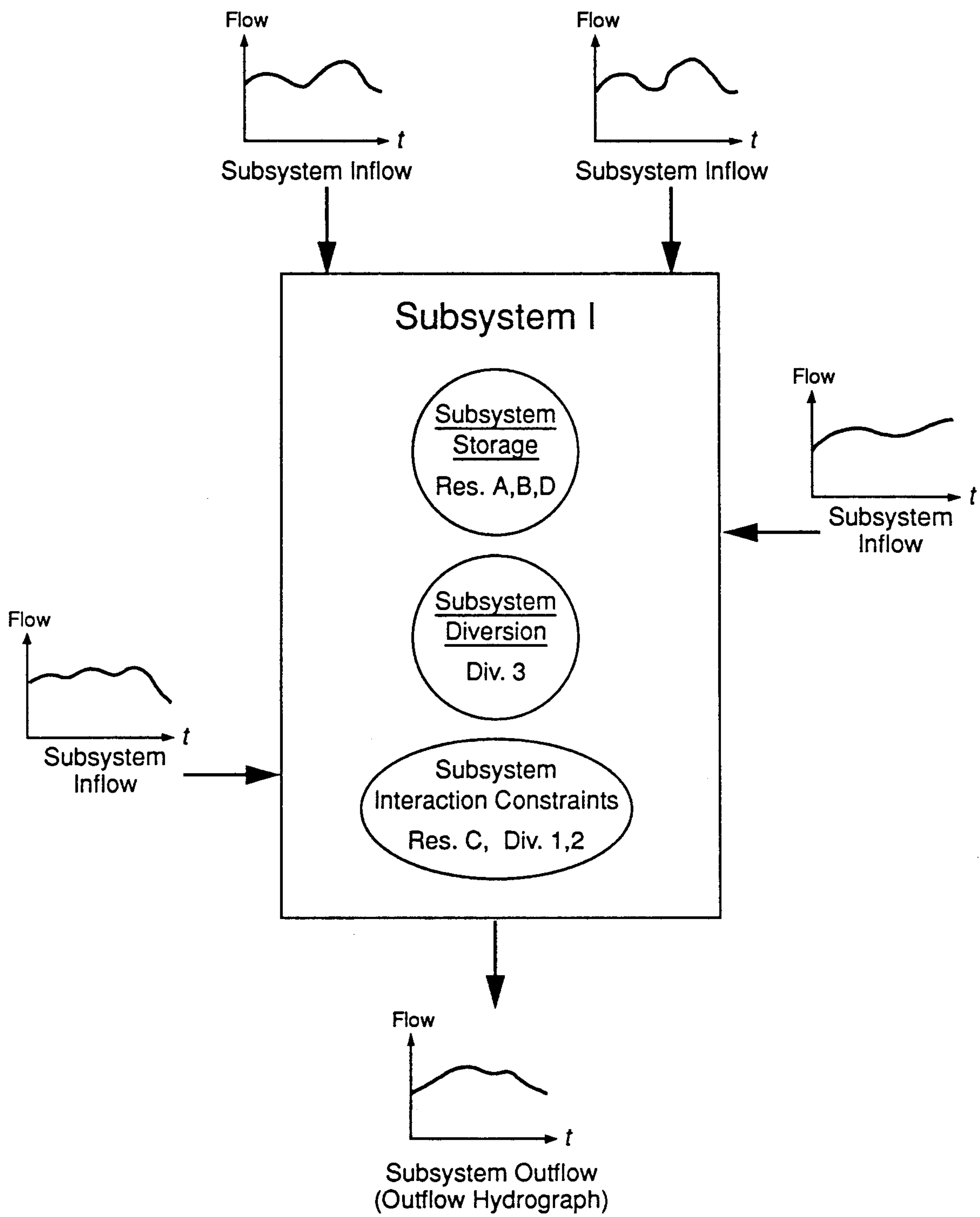

Figure 4. Subsystem Representation.

subsystem actual outflow is set to the required outflow, operation of the elements of the subsystem can be accomplished independently of the river system.

The key to systems theory is the decomposition of the river system into subsystems and the definition of relationships between subsystems and between the elements within a subsystem. The operation of a subsystem requires the determination in real-time of reservoir storage, diversions, exchanges, and transfers as well as meeting constraints. These constraints consist of the water rights of other entities, minimum and maximum stream flows, and minimum and maximum reservoir levels. This can only be accomplished if natural flows are known at all points within the subsystem. If the subsystem is operated with no exchanges or transfers, the natural flows can be computed at each point within the subsystem in real-time. Once the natural flows are known, the subsystem relationships with the river system can be completed and the operation of the elements of the subsystem can proceed in any fashion as desired by the reservoir operator, including exchanges and transfers.

Figure 5 shows the proposed procedure using this systems approach to operate a reservoir subsystem in real-time according to the Prior Appropriation Doctrine of water rights. The following steps describe this procedure.

1. Collect real-time data automatically using a time step less than or equal to the smallest river flow travel

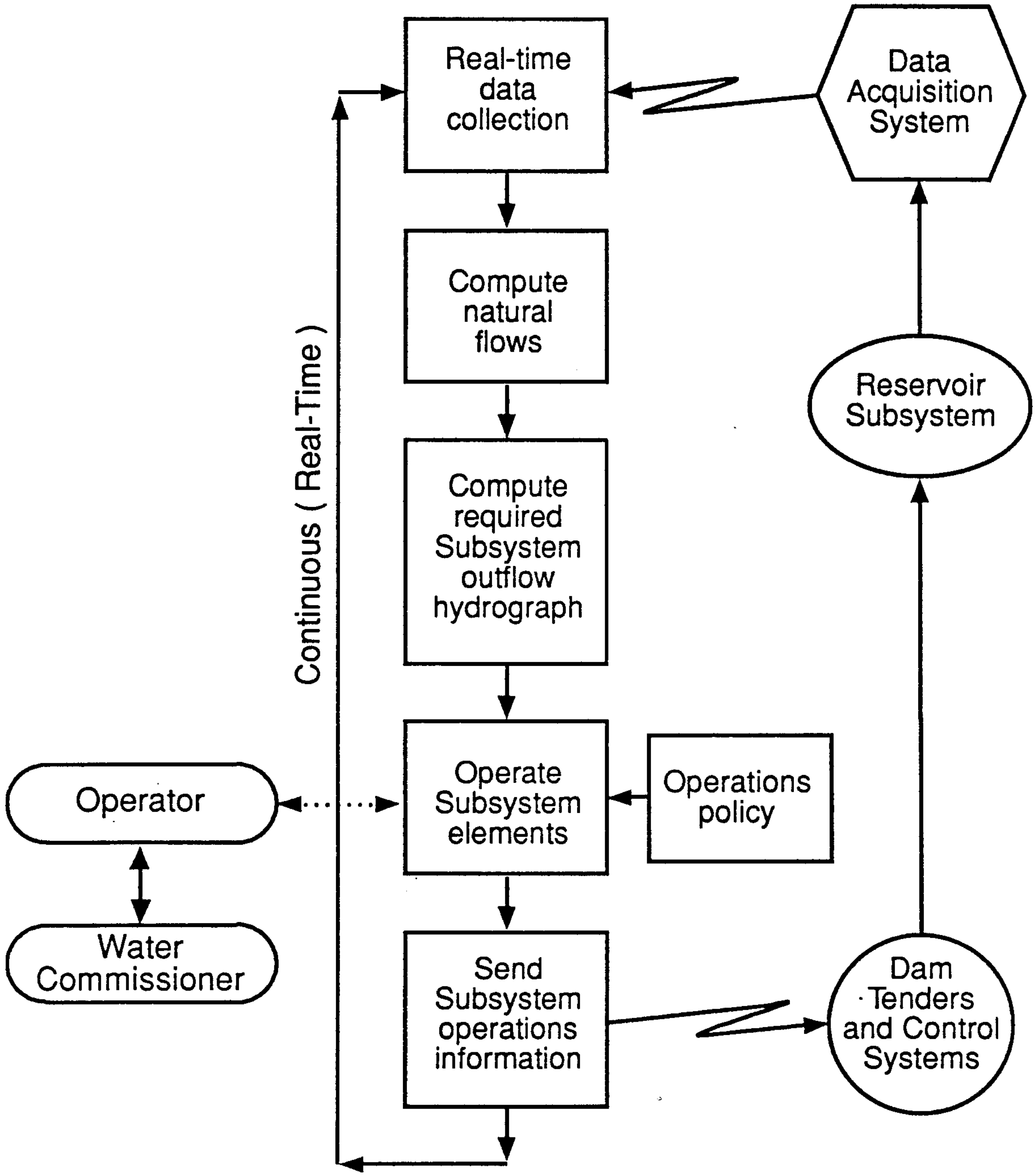

Figure 5. Proposed Real-Time Subsystem Operations Procedure.

time (lag time) between reservoirs. Fill in missing data and check for out-of-range data.

2. Reconstruct native or natural flows at all reservoirs and diversion points from the real-time data.

3. Simulate the subsystem with no exchanges or transfers in real-time using the natural flows and water rights that are in priority to determine the required subsystem outflow hydrograph.

4. In real-time, determine system potential transfers and exchanges. Recommend exchanges and transfers based on operational policies.

5. Provide this information to an operator in real-time for concurrence or adjustments.

6. Based on operator input and estimate of future events, simulate subsystem with exchanges and transfers for a future period of time. If operator likes simulation results, recommend reservoir outflows.

As can be seen when comparing Figure 5 with Figure 2, the proposed process is simpler and straight forward. The manual procedure treats each reservoir and feature being operated as independent which requires that trial and error is required to balance exchange and transfer values. The result is that administration accounts are required. The proposed procedure does not require administration accounts if it is operated in real-time. Using the manual procedure never defines the required outflow from the subsystem, as is the case for the proposed procedure. The manual procedure intermixes water accounting with real-time river operations and consequently only average daily flows and volumes are known. The state of the river system is known only once every 24 hours. In the proposed procedure, water accounting is done after-the-fact while river operations are performed in real-time. As a result, the state of the river system is known at any point in space and time. The manual procedure only allows decisions for diverting, storing, transferring, and exchanging water to be made after-the-fact or a day late. Other water rights can be injured using this process based on a delayed reservoir release of natural river flow. The proposed procedure computes in real-time natural river flows at any point on the river system, which allows the timely release of water to other water users. The end result is that the proposed procedure resolves the major operational problems described in Chapter III that exist as a consequence of using the manual procedure.

Proposed Reservoir Operations DSS Framework

Once the reservoir operations procedure is defined and formalized, a decision support system (DSS) framework can be developed that implements this proposed procedure in a real-time reservoir operations environment. The main purpose of the framework is to automate and computerize the proposed procedure. The framework will be general so that various types of computer hardware and software can be used for implementation. This framework is designed to overcome the current manual procedure problems discussed in Chapter III as well as the past DSS lack of use problems described in Chapter II, where state-of-the-art technology was developed but never used. Solutions to these problems can be summarized as follows:

1. The capture and use of real-time data must be automatically integrated into the process.

2. The use of water rights information must be automatically integrated into the process.

3. An average operator must be able to interact with process at-will, look at intermediate results, and change operations criteria, data, or information to develop "what if" scenarios.

The above criteria were the basis for developing the proposed decision support system framework, Figure 6 shows the proposed framework. The three key elements in this framework are:

1. Operator interface (dialogue management)

2. Information management (data acquisition and management)

3. System simulation (required computations).

These elements are similar to what the Corps of Engineers (1983) and Johnson (1986) recommend as the main components of a DSS. Following is a discussion of these elements.

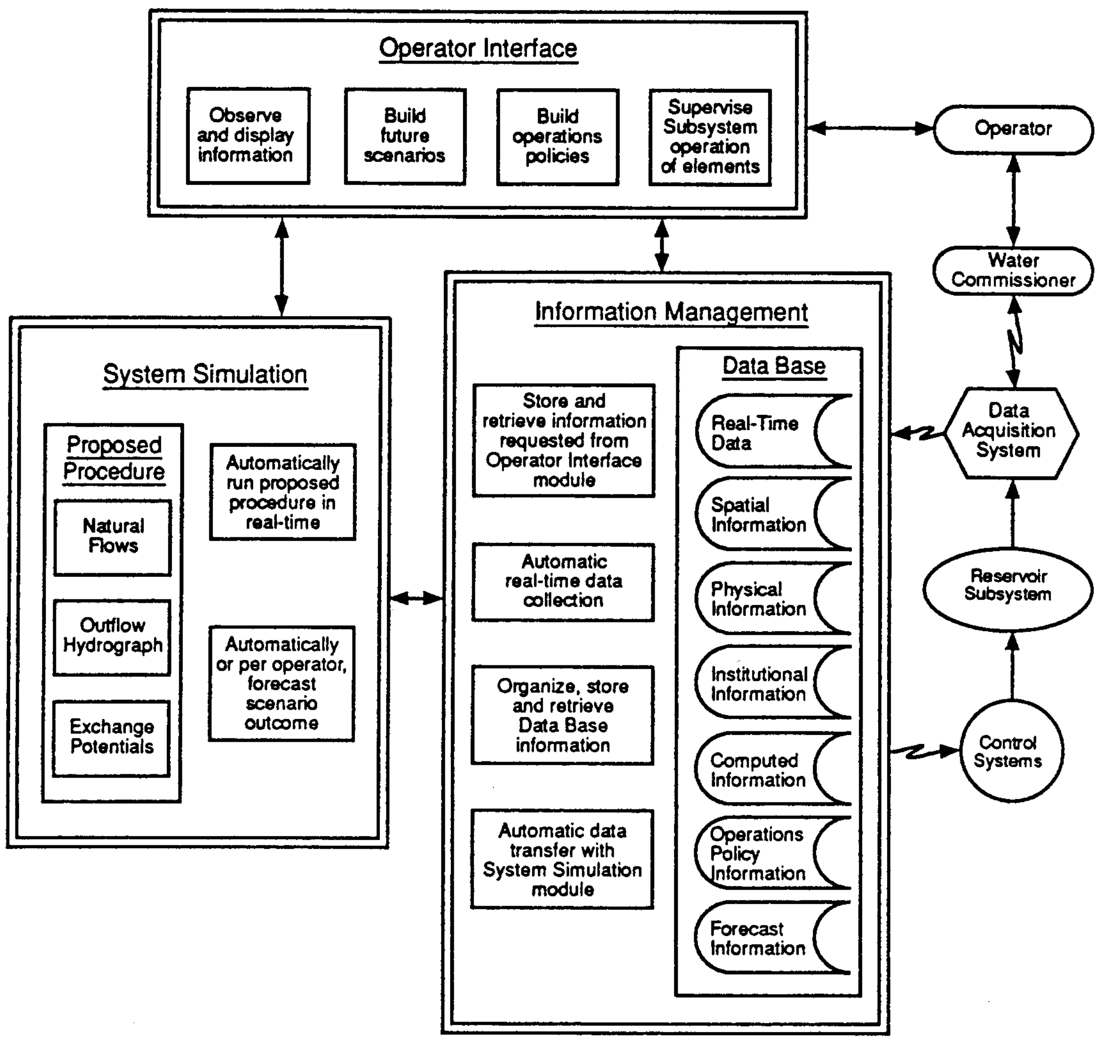

Figure 6. Framework For Real-Time Reservoir Operation Decision Support System.

<u>Operator Interface</u>

The operator interface provides dialogue between the operator and the information and simulation components of the framework. All information available for decision making needs to be presented in a useable and understandable fashion. The latest graphics technology to simple black and white tabular formats can be used based on users preferences and available computer hardware. The use of the proposed reservoir operations procedure in the framework allows the operator interface to operate and provide information in real-time. Various automated processes need to be included in the operator interface which allow an operator to interact with the DSS "at-will" to change any desired information and view results in any desireable format. The interface should be designed to be used by an average reservoir operator rather than a computer programmer or engineer.

The primary decisions to be made by a Colorado reservoir operator in real-time are as follows:

1. How much and when can I divert river flow at each reservoir and diversion?

2. How much and when can I store river flow at each reservoir?

3. How much and when can I exchange river flow and storage between reservoirs?

4. How much and when must I release river flow and storage from each reservoir?

Based on operations polices and current conditions, these questions can be answered by the framework and adjusted by the operator through the operator interface. This is a simple process if the framework provides all the information available in real-time required to make these decisions, and can simulate the results of an operator's decisions before actual system changes are made.

Through the operator interface, an operator can therefore select amounts to divert, store, exchange, and transfer; propose a future scenario; and view the results of his decision. If he is not satisfied with the outcome, he can propose other diversions, storages, exchanges, transfers, and scenarios. By viewing several possible results, an operator can select the criteria he is most comfortable with and the proposed framework will recommend reservoir outflow amounts through the operator interface.

This process can be automated without operator intervention if predefined scenarios are included in the DSS. If the operator at some point in time wants to change a preset scenario, he can do so through the operator interface. The scenarios can be defined based on system policies but generally consist of estimating or forecasting future conditions. These conditions in most cases are natural inflows, demands, and river call. Based on experience, an operator can vary any or all of these quantities "at-will" using the operator interface and project them into the future to create a scenario in which to view the results of his decisions.

The use of expert systems or knowledge based systems as explained in Chapter II could have application in the operator interface. As explained above, the "what if" process uses the proposed procedure which is a sequential algorithm and does not require expert systems technology to solve. But, if the operator's qualitative decision process is coupled with the proposed DSS framework, it is possible that expert systems technology could be used. The use of expert systems is beyond the scope of this study; however this study does represent the first step in implementing an expert system.

Information Management

The information management component of the framework must automatically provide data and information to the operator interface and system simulation elements when requested or required. To do this, information must be categorized and organized into a computer useable data and knowledge base. A break down of this information according to the following categories must be made:

1. Geographic or spatial
2. Physical
3. Institutional
4. Real-time data.

The geographic information defines the spatial relationships of the system to be operated. The river system configuration, and the diversion and storage structures locations define these relationships. For example, the geographic relationships define which reservoirs can release water to other reservoirs and which reservoirs can exchange water with other reservoirs.

The physical information describes the physical capacities and constraints of the system. These data include the maximum and minimum reservoir outlet capacities, the maximum and minimum storage capacities, and maximum and minimum diversion capacities. In addition river properties such as routing coefficients, channel capacities, and overbank capacities are included in these data.

The institutional information is made up of water rights decrees, agreements, and administrative and legal constraints of the subsystem. Before this information is usable, each water right must be quantified into values representing maximum flow rates and volumes, and corresponding priority of use according to the water rights system. This information must also be quantified in a spatial sense. For example, a water right may not exist for an exchange between two specific reservoirs even though it is geographically possible to make this exchange.

The real-time data consists of flow rates and volumes in rivers, canals, pipes, and reservoirs, and the river calls from Water Commissioners. These data are used to define the current state of the system as well as a recent window of past information. Today these data are generally acquired through automatic data collection systems and a process must be developed which automatically transfers these data to the DSS in real-time. Before this data is transferred however, it must be analyzed to correct for missing and out-of-range values before it is used in the proposed decision support system.

System Simulation

Rather than using a traditional computer model approach as explained in Chapter II, the proposed procedure will be used as the system model. This procedure requires that certain computations related to the physical and legal characteristics of real-time reservoir operations in Colorado be made. These required computations can be divided into three categories as follows:

1. Natural flows at required points within the system.

2. Required subsystem outflow hydrograph.

3. Exchange potentials.

Natural Flows. The reconstruction of natural or native flows at all reservoirs and diversion points must be automatically computed using the real-time data. Generally the known information at each reservoir is total river outflow, releases to diversions to meet demands, routed inflow from up-stream reservoirs, and change in storage.

Either by decree or Water Commissioner recommendation, reservoir evaporation, stream loss, and travel time between reservoirs is also known. Using these data in real-time, the basic reservoir mass balance equation can be solved for natural inflow. For example, the basic mass balance equation is:

$$I(t) - O(t) = S(t)-S(t-1).$$

The total reservoir inflow, I(t) can be broken down as follows:

$$I(t) = I_n(t) + I_o(t)$$

Solving for natural inflow,

$$I_n(t) = I(t) - I_o(t),$$

where,

$$I_o(t) = U(\text{routed}).$$

The total reservoir outflow can be broken into two components as follows:

$$O(t) = R(t) + L(t).$$

Variable definitions are as follows:

$I(t)$ = Total reservoir inflow at time t

$O(t)$ = Total reservoir outflow at time t

$S(t)$ = Reservoir storage at time t

$R(t)$ = Reservoir release at time t

$L(t)$ = Reservoir losses (evaporation and seepage) at time t

$I_n(t)$ = Natural inflow at time t

$I_o(t)$ = Other inflow at time t

U(routed) = Up-stream reservoir release.

Stating these equations in words,

Natural Inflow = Total Inflow - Other Inflow

where: Total Inflow = Change In Storage
+ Total Release
+ Losses

Other Inflow = Up-stream Reservoir Release[Routed].

Other inflow represents all other inflow from up-stream releases to the river system. Other inflow includes natural inflow released from up-stream reservoirs since this natural flow has already been accounted for. Natural flow as defined here is the new or additional natural flow at each location. This definition is similar to the concept of local inflow between two points on a river. As required by the outflow hydrograph computations, rather than water accounting, each time the total reservoir inflow is computed, it is divided into only two components, natural or local and other. The accounting of this water is not the topic of this study.

Required Outflow Hydrograph. The subsystem required outflow hydrograph must be computed in real-time to determine up-to-the-minute reservoir releases required to meet in-priority water rights. The outflow hydrograph is easy to develop if the entire subsystem is operated with no transfers, exchanges, or out of priority storage. The computations are specific to each subsystem and cannot be generalized in equation form. But, a general process can be developed which uses the computed natural flows at each reservoir and point of diversion. Figure 7 shows a schematic of this calculation process. The process can be explained as follows. Starting at the most up-stream location of the subsystem, given the natural inflow, check to see if a water right exists at this location and if it is in priority according to the river call at that time. If this water right can legally divert, the full water right entitlement, or the needed amount if less, is diverted, and the remaining natural flow is routed to the next diversion point or reservoir. This process is repeated until the most downstream reservoir computations are completed. At this point, the calculations produce the current required subsystem outflow hydrograph. This process can be automatically repeated each time real-time data is entered into the DSS.

Exchange Potentials. Once the required outflow hydrograph is computed at a point in time, the subsystem release to the river system can be set. Operation of the elements of the subsystem, in particular exchanges and transfers, can then be completed in any fashion. In order for an operator to determine the exchanges and transfers, he must be provide the maximum and minimum limits of the exchanges and transfers. Therefore, when ever real-time data enters the DSS and the required outflow hydrograph is

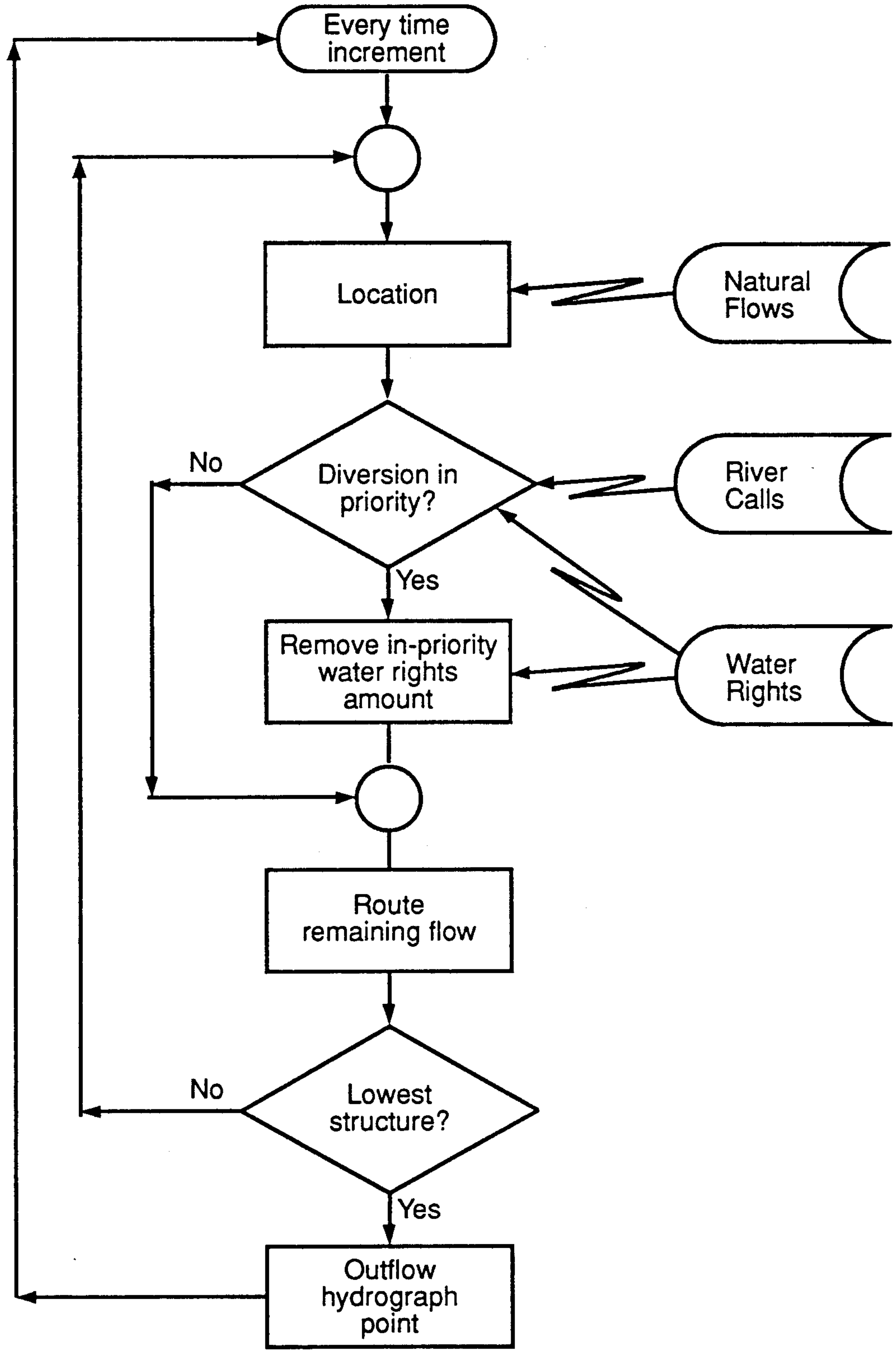

Figure 7. Subsystem Required Outflow Hydrograph Computations.

computed, the maximum and minimum exchange and transfer potentials need to be computed.

These potentials are computed based on the amount of natural inflow available for exchange, remaining storage capacity within a reservoir, amount of storage within a reservoir, outlet capacities, maximum and minimum stream level requirements, and maximum and minimum reservoir levels. Finding the exchange potentials between two reservoirs requires that each limitation at each reservoir is compared. This process is very specific to each system and each reservoir within each system.

To illustrate this process, Figure 8 shows a two reservoir subsystem with constraints, flows, and storages defined. Based on this subsystem, the following equations can be used to determine the exchange potential between these two reservoirs:

$$S_a(\text{Remain}) = S_a(\text{Max}) - S_a(t)$$
$$I_a(\text{Avail}) = I_a(t) - O_a(t)$$

$$E_a(\text{In}) = \text{Min}\ \{S_a(\text{Remain}), I_a(\text{Avail})\}$$

$$S_b(\text{Avail}) = S_b(t) - S_b(\text{Min}) + I_b(t)$$
$$O_b(\text{Remain}) = O_b(\text{Max}) - O_b(t)$$

$$E_b(\text{Out}) = \text{Min}\ \{S_b(\text{Avail}), O_b(\text{Remain})\}$$

$$E_{a-b}(\text{Max}) = \text{Min}\ \{E_a(\text{In}), E_b(\text{Out})\}.$$

Where:

S_a(Remain) = Remaining Storage in Res. A
I_a(Avail) = Available Inflow to Res. A
E_a(In) = Res. A Exchange-In Potential
S_b(Avail) = Available Storage From Res. B
O_b(Remain) = Available Outlet Capacity from Res. B
E_b(Out) = Res. B Exchange-Out Potential
E_{a-b}(Max) = Maximum exchange potential between Res. A and Res. B.

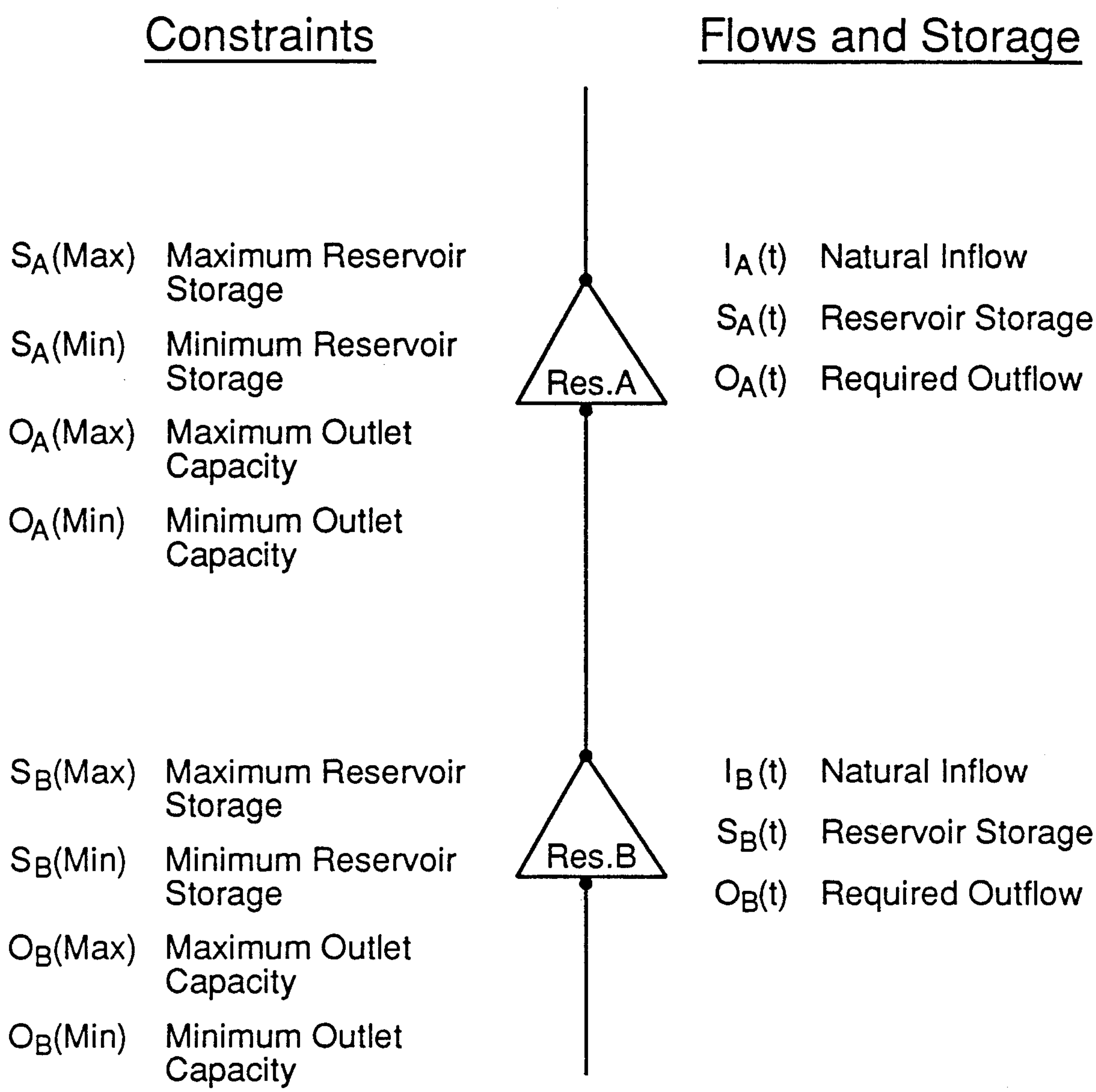

Figure 8. Exchange Potential Computations.

This exchange potential must be computed between all combinations of reservoirs within the system. If an exchange is made between two reservoirs, this amount must be included as a constraint in the above calculation for any other exchanges to be made. Releasing or transferring water from Reservoir A to Reservoir B follows a similar process of comparing constraints and capacities.

To summarize, the three basic components; (a) operator interface, (b) information management, and (c) system simulation, were used to develop a framework for a decision support system to operate Colorado reservoirs. The key to this framework is the use of the proposed reservoir operations procedure developed from the currently used and accepted manual procedures. Based on my experiences as a reservoir operator, this framework should be easily understood by today's reservoir operator and as a result, stands a good chance of being implemented in Colorado.

CHAPTER V

DECISION SUPPORT SYSTEM DEMONSTRATION AND IMPLEMENTATION: CASE STUDY

The purpose of this chapter is to demonstrate that the framework proposed in Chapter IV can be used to develop and implement a computerized decision support system for real-time reservoir operations according to the Doctrine of Prior Appropriation. The development of the DSS explains how the specifics of the framework are used in a computer environment. The implementation of the DSS focuses on setting up the data and information required to operate the DSS, and the actual operation of the DSS. In order to concentrate on the study objectives and avoid additional complexities, the developed DSS will be a demonstration DSS since certain aspects of the real-time operations process are simulated. Based on my fifteen years of experience either operating reservoirs or being responsible for reservoir operations, a typical decision process will be explained using the DSS.

A case study has been selected to show how the developed DSS can be implemented. In selecting a typical reservoir system, it was realized that the potential for legal conflicts between water agencies dictates that reservoir operations methods and philosophies not be revealed other than by staff members of those organizations. My present position with the State Engineer's Office allows the access to some of this information in strict confidence. In order to use and publish this type of information, however, requires that in some cases I legally obtain it through a court order or risk a law suit on my part. As a result, a hypothetical reservoir system, which represents a large scale multiple reservoir raw water collection system in Colorado, will be used for the case study.

Demonstration Decision Support System

The objective of the demonstration DSS is to illustrate that the proposed framework can be used to develop a computer based DSS for a Colorado reservoir system. A schematic of the multiple reservoir raw water system used for this demonstration is depicted in Figure 9. It represents a typical large scale system in Colorado with reservoirs in parallel and series. The details of the system will be explained below under DSS case study implementation.

Due to the size and complexity of this problem, a computer environment will be used which focuses on the overall concept, rather than the details of an individual element of the proposed decision framework. Each component of the framework could be developed to greater levels of sophistication based on a user's desires and availability of

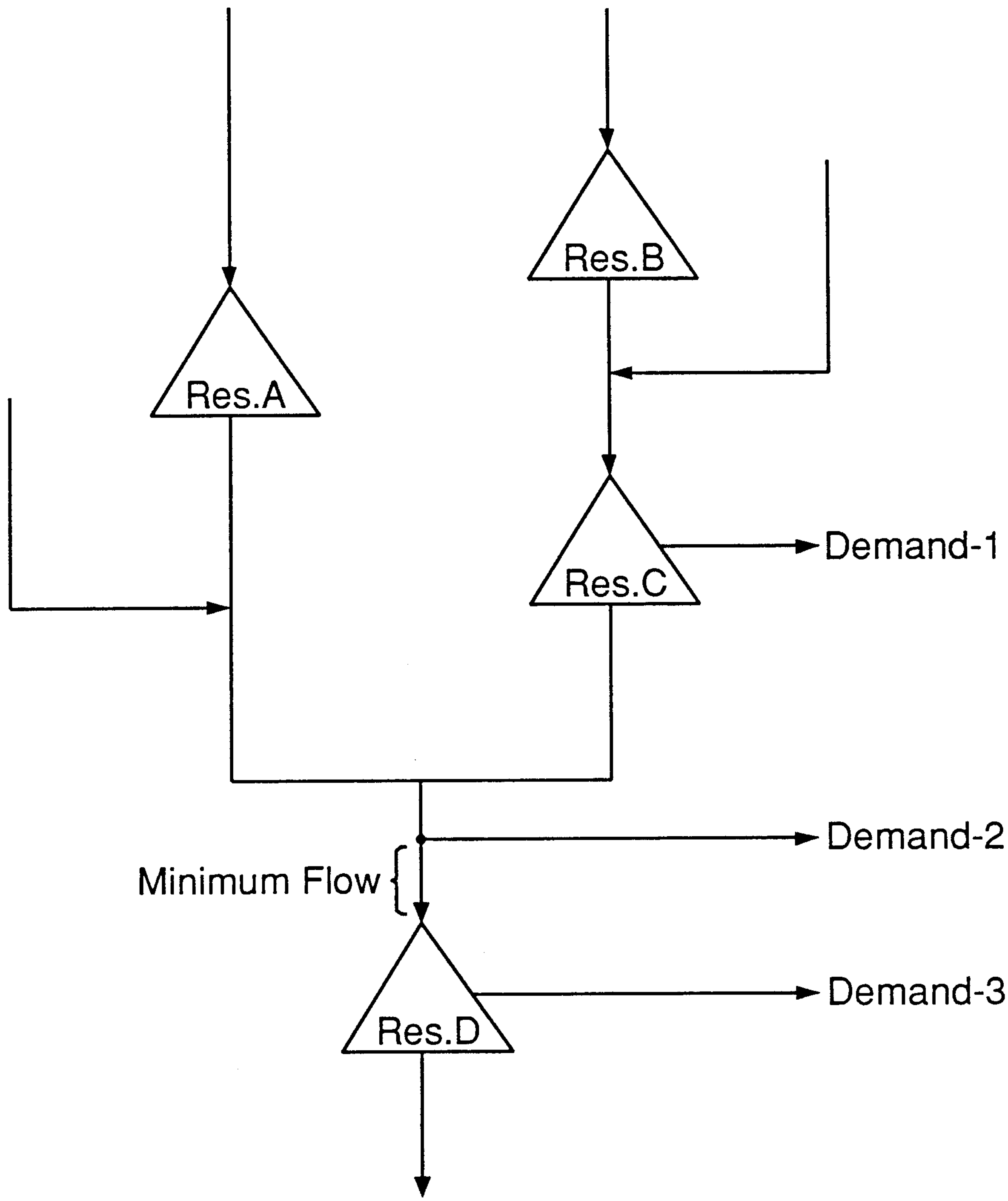

Figure 9. Multiple Reservoir System - Case Study.

computer resources. The intention here, however, is to develop a DSS which best demonstrates the use of the framework.

A PC computer based spreadsheet is an ideal hardware/software environment to illustrate the development of the demonstration DSS since this environment is available to most Colorado reservoir operators. The spreadsheet incorporates the basic development tools of data input, computations, automatic procedures, and a graphics interface. The spreadsheet allows the visual interpretation of data, and information in tabular or graphic formats as required for demonstration purposes. In addition, automating procedures using cell formulas and macro programs can be easily illustrated. LOTUS® 1-2-3, was selected to build the entire decision support system.

As required by the framework, the developed DSS is divided into three major elements:

1. Operator interface
2. Information management
3. System simulation.

Each element is further divided into sections or modules for efficient computations and integration. The three major elements are broken down as follows:

1. Operator interface
    a. Operations work sheet
    b. Exchange potential table
    c. Decision graphics

2. Information management

   a. Real-time data section

   b. Water rights section

   c. Constraints/Factors section

3. System simulation

   a. Natural flow computations section

   b. Out-flow hydrograph section

   c. Exchange potentials section.

Figure 10 depicts a schematic of the DSS. The following discussion explains each of the elements and sections of the developed DSS.

Operator Interface

The operator interface allows an operator to interact with the DSS in a prescribed fashion. It is a set of procedures that react in a fixed manner based on an operator's input. Various computations are made automaticly or upon the operator's request. The results of these computations are displayed in tabular and graphic formats depending on the operator's desire. The basic components or automatic procedures of the operator interface are described below.

Operations Work Sheet. Figure 11 shows the Operations Work Sheet at a given time for the case study reservoir system depicted earlier in Figure 9. As required by the systems approach, all of the information related to the elements or physical features of the reservoir subsystem are

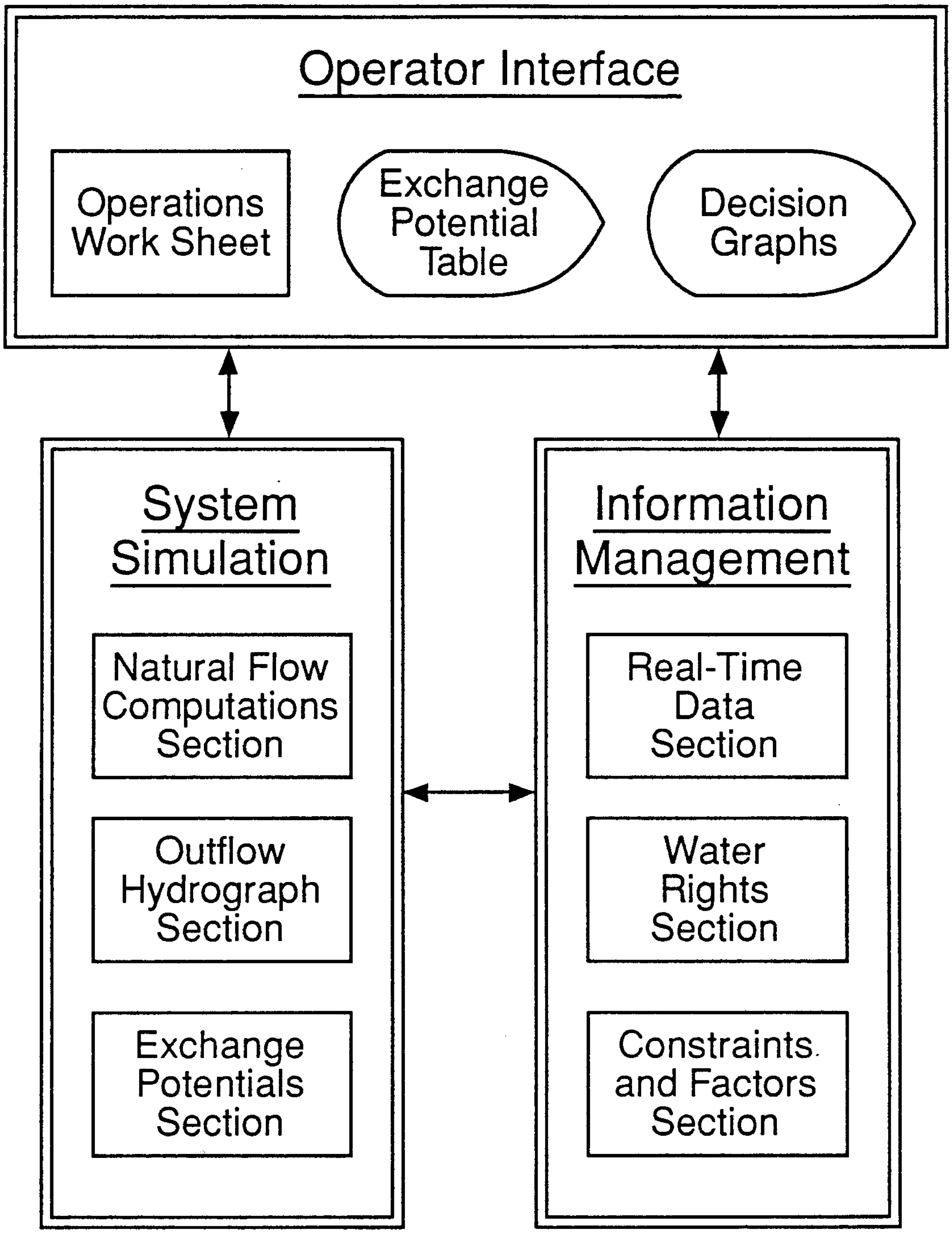

Figure 10. Decision Support System Schematic.

OPERATIONS WORK SHEET (flows in CFS)

***************************	CURRENT	CHANGE TO	SUGGESTED	MAX	MIN/WR	****
RESERVOIR A NATURAL INFLOW	37.6	37.6	---	---	---	DATE
RIVER OUTFLOW	32.0	32.0	0.0	1000	0	24
						TIME
RESERVOIR B NATURAL INFLOW	422.0	422.0	---	---	---	12
RIVER OUTFLOW	431.8	431.8	0.0	800	0	****
RESERVOIR C NATURAL INFLOW	463.2	463.2	---	---	---	
RIVER OUTFLOW	391.7	391.7	240.0	2000	240	
DEMAND AT 1	471.0	471.0	---	900	28	
DEMAND AT 2	186.0	186.0	---	150	100	
MINIMUM FLOW IN REACH 2-D	272.7	---	---	---	50	
RESERVOIR D NATURAL INFLOW	364.0	364.0	---	---	---	
RIVER OUTFLOW	217.0	217.0	1238.5	3000	1239	
DEMAND AT 3	47.0	47.0	---	150	45	
RIVER CALL	1870	1870	---	---	---	

[ALT I] INPUT DATA[ALT R] RES.ACCT.*[ALT O] OPERATE*[ALT E] EXCH.INFO.

Figure 11. Decision Support System Operator Interface.

displayed in this work sheet. For decision making, it is important that an operator is able to view the entire system at once. This is especially important since each of the features interact with one another and a change at one feature can change one or more other features. In addition to the physical features of the system, the other key information listed is the Water Commissioner information in the form of a river call. As explained in Chapter III, the river call is obtained from a Water Commissioner in real-time.

The specific items of information needed for the decisions required to operate the case study reservoir system are as follows:

1. Natural flow and river outflow for reservoirs A, B, C and D.

2. Demands 1,2 and 3.

3. Minimum flow in river reach from demand 2 to reservoir D

4. River call.

For each of these features, the decision variables are listed as identified by the column headings. These values are as follows:

1. Current value

2. Change To value

3. Suggested value

4. Maximum value

5. Minimum or water rights amount.

These values are automatically generated from the DSS using spreadsheet cell equations as shown in Appendix A. For example, the minimum reservoir river outflow values within the system are computed based on the requirements of the reach of river to the next structure. If a minimum flow is required in this reach of river, the value in the "MIN/WR" column is set at the minimum flow requirement. If a diversion with a water right is below the reservoir, this value is added to the minimum flow value. Another and important computation is the Reservoir D river outflow "SUGGESTED" value which represents the subsystem outflow. This value is computed by averaging the forecasted 24 hours of the required outflow hydrograph.

An operator can create a future scenario or forecast by changing any value in the "CHANGE TO" column and view the results not only in the work sheet but in one of several graphical formats which will be shown in the implementation. This process can continue until the operator is satisfied with the results. The viewing of the decision graphs is automatic or can be operator initiated depending on if the OPERATE program is running.

The Operations Work Sheet is controlled by Program OPERATE shown in Appendix B. This program initially sets the "CHANGE TO" and "SUGGESTED" values in the Operations Work Sheet. If the operator chooses to change any of these values, this program steps through the work sheet asking for the reservoir, demand, and river call information. If the operator chooses, spreadsheet commands can also be used.

An important part of the OPERATE program is Subroutine SUGGEST. Subroutine SUGGEST compares exchange potentials, as discussed previously in Chapter IV, between reservoirs, with current natural inflow at each reservoir. It then determines how much of the inflow at each reservoir can be stored, and how much flow to release based on a given operations policy. These values are the "SUGGESTED" values listed in the Operations Work Sheet. This subroutine obtains the exchange potential values from the computations exchange table in the System Simulation element of the DSS. The primary purpose of this table is for computations as will be discussed below under System Simulation, but for information purposes, this table can be viewed at-will from the Operations Work Sheet by an operator.

For demonstration purposes, the logic in Subroutine SUGGEST is set to one policy which is the most common in use. The principle used is to keep water as high in the system as possible, and only release water out of a reservoir to meet required immediate down-stream water rights and minimum flows. In reality, this routine could be variable where different scenarios could be set based on time of year or other possible controlling factors.

Information Management

The information management element of the DSS stores and controls the movement of information to the other sections of the DSS. The spreadsheet approach dictates that the information be stored in tables. The exchange of information is handled using cell equations and macro routines. The following discussion describes the three sections used in the information management element of the DSS.

Real-Time Data Section. The real-time data section of the DSS consists of a data table and data transfer program. The data table represents a window of data transferred from a real-time data acquisition system. The transfer program simulates the automatic transfer of data from a data acquisition system to the DSS real-time data section data table.

The data table structure is set up such that the columns within the table represent the specific data being transferred such as reservoir data, diversion data, and river call for the system. The rows within the table represent the total number of time increments of data transferred from the data acquisition system. The number of rows in the data table or window of data is determined by the required computations of the system. For example, if the current time is 8 am and the DSS requires 24 hours of hourly data, there will be 24 rows in the table. The top row in the table represents data from 7 am yesterday and the bottom row represents 8 am data today.

The amount of data in the Real-Time Data Table needed by the DSS is based on the number of real-time data collection points in the system, the time increment of that data available from the data acquisition system, and the Water Commissioner set river travel time from the upper most reservoir to the lowest. For example, the case study total travel time from the most up-stream reservoir to the most down-stream reservoir is 18 hours and one hour data reporting increments are available from the data acquisition system. The resulting Real-Time Data Table will have 18 rows.

The number of columns in the Real-Time Data Table depends on the number of reservoirs and diversion points in the system. Each reservoir must have two columns representing storage and river outflow. Some reservoirs also have direct diversions. The order in which the reservoirs and diversions are listed in the data table is the most up-stream reservoir on the left side of the table and continuing right to the most down-stream reservoir. This defines the spatial relationship of the system and allows for easy river routing as will be explained in the Natural Flow Computations Section of the DSS. The first column in the data table represents the river call provided in real-time by the Water Commissioner.

A macro program, Program INPUT listed in Appendix B, simulates the automatic transfer of real-time data from a data acquisition system to the DSS. Since this is a demonstration DSS, the program asks the operator for the current date and time rather than automatically running every time increment. Once the date and time are known, the program computes a date and time which represent the travel time from the most up-stream reservoir to the most down-stream. For example, if the travel time from the most up-stream structure to the most down-stream structure is 18 hours, the current date is May 25, and the current time is 12 noon, the computed date and time would be 24 and 7 pm respectively. After this date and time are computed, a look-up table is used to determine the position in the real-time data files to start reading data. For demonstration purposes, rather than accessing data directly from a real-time data acquisition system, each reservoir storage, reservoir river outflow, diversion point, demand, and river call are represented by data files.

Water Rights Section. This section of the Information Management element of the DSS consists of a storage rights accounting program, and a Water Rights Table. The Water Rights Table lists all the water rights for the system diversion and storage structures. For each water right, the following information is listed in the table:

1. Structure
2. Administration number

3. Adjusted administration number

4. Amount

5. Units

6. Cumulative total.

This table assumes that all water rights decrees within the system can be tabulated or quantified. The structure represents the decreed structure of the water right. Each feature of the system to be operated represents a structure and will be listed in this table. The administration number represents the relative diversion priority between water rights. The adjustment value represents an adjusted administration number used by the storage accounting program to set a water right in or out of priority to legally divert water. The amount value represents the volume or rate of flow associated with each right. The units value defines the units of the amount value. The total value represents the accumulative water rights amount for a structure.

A reservoir storage rights accounting program, listed in Appendix B, uses the adjusted administration number to curtail reservoir storage if a storage decree has legally filled for the season. In the normal operations of a reservoir, an operator must know when a reservoir storage right is legally filled and no mater what the seniority of the storage right, it must be legally curtailed if there is a river call. The reservoir accounting program is used to simulate this process. The principle used in this program is to query the operator for each reservoir to find out if the storage rights for each reservoir are filled. If they are, the program sets the adjusted administration number for each storage right filled to represent a very junior priority. Therefore, when the river call is set by the Water Commissioner, these storage rights will be out of priority and not allowed to divert water.

Constraints/Factors Section. This section of the Information Management element consists of a table which sets all the parameters needed by the DSS. The following parameters are used for the case study:

1. River section loss coefficients
2. Maximum and minimum reservoir storage capacities
3. Maximum reservoir outlet capacities
4. Maximum diversion capacities
5. Minimum flow requirements in river sections
6. River section flow times
7. Evaporation rates for each reservoir
8. Conversion factors.

The Constraints/Factors Table represents values which do not change in real-time and are therefore protected from being altered easily. In the event that a parameter needs to be changed, an operator must manually go through the steps required by the spreadsheet commands. For the case study, certain parameters such as evaporation rates and river section loss coefficients, are set constant rather than allowing them to vary over time. As explained in Chapter III, the evaporation values used today are generally monthly and the river section loss coefficients are fixed by Water Commissioners. Therefore, these values don't vary in real-time by definition. However, if an operator desires, these values can be changed as is the case for the monthly evaporation rates.

System Simulation

This element is the heart of the DSS. It represents the reservoir system to be operated in numerical terms and allows the operator to ask "what if" questions without actually altering the real reservoir system. As explained in Chapter IV, this element of the DSS is composed of required computations, which are divided into three sections as described below.

Natural Flow Computations Section. The natural flow computations are the core of the System Simulation. They use real-time data plus computed and forecasted values to reconstruct natural flows. A computation table is used which accesses real-time data from the Real-Time Data Table and forecasted or operator set values from the Operations Work Sheet. The table and corresponding cell equations are shown in Appendix A.

The columns in the computation table represent information pertaining to river calls, reservoirs, and diversions on the river system. The rows represent the number of time increments from the Real-Time Data Table plus a number of rows for a forecast period. As in the real-time data section, the current time (listed as "C" under the day column) as well as a number of rows representing the most recent past data are included. One day or 24 forecast rows, based on the desired forecast period, are also included below the current window of data. These rows start where the day is listed as "F".

The geography of the system is represented by the order of the structures, reservoirs and diversions, listed across the top of the table. They are arranged in order from the most up-stream on the left to the most down-stream on the right. Listed under each structure, are real-time data and computed values. Under each reservoir is the basic information of inflow, outflow and storage. Inflow is separated into total, from up-stream, and natural. Outflow is divided into evaporation, diversion, and river outflow. Storage includes storage volume and change in storage volume. Under a diversion, the basic information consists of flow above the diversion, diversion flow, and flow below the diversion.

Using cell equations, real-time data are automatically transferred from the Real-Time Data Table to the appropriate columns and rows of the Natural Flow Computation Table every time real-time data is updated. Once the real-time data is transferred to the computation table, calculation of natural flow begins. From the real-time data, change in storage, total inflow, and below diversion flow are computed by the mass balance equations described in Chapter IV. The up-stream inflow under reservoirs, however, requires river routing as part of the computations.

An empirical method of river routing is required by the Water Commissioners as explained in Chapter III. This method lends itself to the spreadsheet approach as shown in the cell equations in Appendix A. Two factors are needed to compute the up-stream inflow; lag or travel time and river loss amount. For example, to compute the up-stream inflow using the natural flow computation table and cell equations, obtain the release from an up-stream reservoir or below flow from an up-stream diversion by moving up the number of rows representing the lag time from the Constraints/Factors Table. This flow is then multiplied by the appropriate loss coefficient from the Constraints/Factors Table to obtain up-stream inflow at the present reservoir.

Once the up-stream inflow is known, the natural flow can be computed. This process proceeds from the most up-stream reservoir to the most down-stream reservoir in a sequential fashion. The natural flow computations are automatic whenever real-time data is updated in the DSS.

The rows starting at "F" in the natural flow computation table represent forecasted values for decision purposes in the operator interface. Rather than using real-time data in this section, Program OPERATE or the operator provide forecasted values. These data consist of river call, reservoir natural inflow, reservoir river outflow, and demand at diversion points. The change in storages, storage volumes, and the below diversion flows are then computed. This process is performed by cell equations and is shown in Appendix A. River routing as described above is used to compute up-stream inflows.

Outflow Hydrograph Section. This section uses the natural inflows computed in the natural flow section, and water rights from the Water Rights Table, to compute legal diversions at each reservoir and diversion point. The most down-stream structure river outflow represents the system required outflow hydrograph. As in the natural flows segment of the DSS, a computation table is used where structures are listed across the top and time is represented by each row. There is a current time segment and a forecast segment as in the natural flow section, but for the outflow hydrograph section of the System Simulation element, both time segments use the same equations. Routing is accomplished exactly like the natural flow section where an empirical formulation is used.

The cell equations used in this section are listed in Appendix A. Water rights that can legally divert are determined from the Water Rights Table using the current river call listed in the natural flow section. This is done by using the river call as an index to look up water rights in the water rights table for each diversion. Only those water rights in the table with adjusted administration numbers less than or equal to the river call are selected. At each time period (or row) and at each reservoir or diversion point, the accumulated water rights are entered in the appropriate reservoir or demand rights column and row. Inflow at a structure is computed by obtaining the inflow from the natural flow section and adding to that the routed inflow from the up-stream structure. Once the inflow and water rights are known, the outflow is computed by subtracting the water rights from the inflow. Computations are performed real-time, whenever real-time data is updated, and proceed left to right or up-stream to down-stream. Outflow from the most down-stream structure represents the reservoir subsystem outflow hydrograph as described in Chapter IV.

Exchange Potential Section. This section of the system simulation element computes in real-time the exchange potentials between each reservoir. A computation table is again used and the cell equations are based on the equations described in Chapter IV. The cell equations used for the exchange potential computation table are listed in Appendix A. As described above under the Operations Work Sheet, an operator can view this table for decision making, but cannot change any values. All computations are performed automatically whenever real-time data is updated or an operator enters forecast data.

Decision Support System Implementation

The purpose of implementing the developed DSS on a case study is to illustrate the applicability of using the proposed DSS framework for the operation of a typical Colorado reservoir system. The two items of most interest to a potential user of this DSS are the setup and operation of the DSS. Therefore, once the DSS is setup, several scenarios will be run to demonstrate the operation of the DSS. In order to provide some measure as to the value of using this DSS, a historic manual operation is compared to the same operation using the proposed DSS. But, the real measure of the value of this system is whether it will be used by reservoir operators.

Case Study Definition

The case study is composed of four reservoirs and three diversions as depicted earlier in Figure 9. The reservoir and diversion configuration is based on present typical large scale raw water supply collection systems in Colorado. Reservoirs in series and parallel with multiple diversions and a minimum river flow section present probably a worst case problem in which to implement and operate the proposed DSS.

Physical parameters related to the reservoirs, diversions and river system are listed in Table 1. Water rights related to the reservoirs and diversions are listed in Table 2. Real-time data used in this demonstration were obtained from actual reservoirs and diversions in Colorado. Using the State Engineer's Satellite Data Collection System, twenty days of hourly data were randomly selected from a

Table 1

Case Study Physical System Parameters

RESERVOIRS

RESERVOIR	CAPACITY		OUTLET	EVAP.
	MAXIMUM	MINIMUM	MAXIMUM	MONTHLY
A	80,000 AF	10,000 AF	1000 CFS	5 CFS
B	71,000 AF	15,000 AF	800 CFS	3 CFS
C	60,000 AF	10,000 AF	2000 CFS	6 CFS
D	50,000 AF	20,000 AF	3000 CFS	11 CFS

RIVER SECTIONS

SECTION	LOSS	LAG	MINIMUM FLOW
A - D	0.04 %	10 HOURS	0
B - C	0.025 %	12 HOURS	0
C - 2	0.015 %	4 HOURS	0
2 - D	0.01 %	2 HOURS	50 CFS

Table 2

Case Study Water Rights

STORAGE RIGHTS

RESERVOIR	ADMINISTRATION NUMBER	AMOUNT
A	1926.0000	80,000 AF
B	1889.0000	30,700 AF
	1900.0000	40,300 AF
C	1962.0000	60,000 AF
D	1977.0000	50,000 AF

DIRECT FLOW RIGHTS

DEMAND	ADMINISTRATION NUMBER	AMOUNT
1	1863.0000	28.0 CFS
	1874.0000	32.0 CFS
	1892.0000	72.0 CFS
	1899.0000	95.0 CFS
	1905.0000	10.0 CFS
	1929.0000	15.0 CFS
	1943.0000	40.0 CFS
	1954.0000	50.0 CFS
2	1869.0000	100.0 CFS
	1930.0000	25.0 CFS
	1960.0000	25.0 CFS
3	1868.0000	45.0 CFS

representative period during the irrigation season. These data were set up as data files representing river calls, reservoir storage, reservoir outflow, and diversion files. The data from the real-time data acquisition system was manually corrected for out-of-range and missing data.

DSS Setup

The geographic information was used to set up the columns in the Real-Time Data Table, Natural Flow Computations Table and the Outflow Hydrograph Table, as explained in the DSS development. The columns for these tables represent information for four reservoirs and three diversions as shown in the schematic of the system in Figure 9. Based on one hour real-time data increments, the number of rows required in the DSS as explained in the development is 42, 18 for past conditions and 24 for the future forecast. But, for demonstration purposes and based on my experience, the number of rows or time increments in the DSS is set at 72 in order to allow 2 days of past information.

The demonstration DSS requires that automated macros, cell equations, and the operator interface section be adjusted to represent this particular case study. For example, the case study is a parallel river system and the cell equations in the Natural Flow section representing upstream inflow into Reservoir D include outflows from Reservoir A and Diversion 2, with appropriate routing terms as explained previously. The macro programs are adjusted to handle 4 reservoirs, 3 diversions and 48 hours of real-time data. The Operations Work Sheet is set up to represent the system information available for decision making.

Once the programing changes are completed, the DSS columns set up to represent the system geographicly, and the cell equations adjusted, the system constraints and water rights are manually entered. The demonstration DSS is now ready to use.

DSS Operation

The first step to operate the DSS is to bring up the Operations Work Sheet. This is done automatically when the DSS spreadsheet is loaded or can be accomplished by running the start macro by pressing [ALT]S. The next step is to obtain real-time data by running the input macro, Program INPUT. This is performed by pressing [ALT]I. Program INPUT asks the operator for current day and time. For this example, day 24 and time 12 is selected. Appendix C lists the Real-Time Data Table for this date and time. Before the natural flows, outflow hydrograph, and suggested values can be computed, the reservoir accounting program must be run.

The reservoir accounting program is run by pressing [ALT]R. This program queries the operator for each reservoir and each storage right, asking the operator if the storage right has been filled. The operator answers either yes or no. For this date and time, Reservoir B storage right with administration number 1889 is filled. Table 3 lists the DSS Water Rights Table showing the adjusted administration numbers corresponding to this situation. Note that the Reservoir B adjusted administration number, "ADJUST.," is 2000, which indicates this storage right will not be in priority unless there is no call on the river system.

Finally Program OPERATE is run to automatically compute Current, Change To, and Suggested values in the Operations Work Sheet. This is done by pressing [ALT]O. Appendix C shows the Natural Flow and Outflow Hydrograph sections of the DSS for this day and time. Figure 12 depicts the Operations Work Sheet for this date with no operator changes. Figures 13 through 18 show the resulting decision graphs for this date and time without any changes made for the next 24 hours.

Once the operator views the available information provide by the DSS Work Sheet and decision graphs, various future scenarios can be examined in order to meet present and future forecasted conditions. For this given date and time, notice from the Operations Work Sheet in Figure 12 that Reservoir D current outflow is 217 cfs, but the required and suggested outflow is 1239 cfs. The river is being shorted from past and current conditions.

Looking at the graph of natural inflows from Figure 14, it is possible that natural inflow to Reservoir C could increase in the next 24 hours based on the past 24 hours of

Table 3

Case Study Water Rights Table With Reservoir B 1889
Administration Number=2000

WATER RIGHTS TABLE

RES./DEMAND	ADM. #	ADJUST.	AMOUNT	UNITS	TOTAL
RES A	1926	1926	80000	AF	80000
B	1889	2000	30700	AF	30700
B	1900	1900	40300	AF	71000
C	1962	1962	60000	AF	60000
D	1977	1977	50000	AF	50000
DEMAND 1	1863	1863	28	CFS	28
1	1874	1874	32	CFS	60
1	1892	1892	72	CFS	132
1	1899	1899	95	CFS	227
1	1905	1905	10	CFS	237
1	1929	1929	15	CFS	252
1	1943	1943	40	CFS	292
1	1954	1954	50	CFS	342
2	1869	1869	100	CFS	100
2	1930	1930	25	CFS	125
2	1960	1960	25	CFS	150
3	1868	1868	45	CFS	45

OPERATIONS WORK SHEET (flows in CFS)

***************************	CURRENT	CHANGE TO	SUGGESTED	MAX	MIN/WR	****
RESERVOIR A NATURAL INFLOW	37.6	37.6	---	---	---	DATE
RIVER OUTFLOW	32.0	32.0	0.0	1000	0	24
						TIME
RESERVOIR B NATURAL INFLOW	422.0	422.0	---	---	---	12
RIVER OUTFLOW	431.8	431.8	0.0	800	0	****
RESERVOIR C NATURAL INFLOW	463.2	463.2	---	---	---	
RIVER OUTFLOW	391.7	391.7	240.0	2000	240	
DEMAND AT 1	471.0	471.0	---	900	28	
DEMAND AT 2	186.0	186.0	---	150	100	
MINIMUM FLOW IN REACH 2-D	272.7	---	---	---	50	
RESERVOIR D NATURAL INFLOW	364.0	364.0	---	---	---	
RIVER OUTFLOW	217.0	217.0	1238.5	3000	1239	
DEMAND AT 3	47.0	47.0	---	150	45	
RIVER CALL	1870	1870	---	---	---	

[ALT I] INPUT DATA[ALT R] RES.ACCT.*[ALT O] OPERATE*[ALT E] EXCH.INFO.

Figure 12. Case Study Operations Work Sheet For Day=24 and Time=12 With No Operator Changed Values.

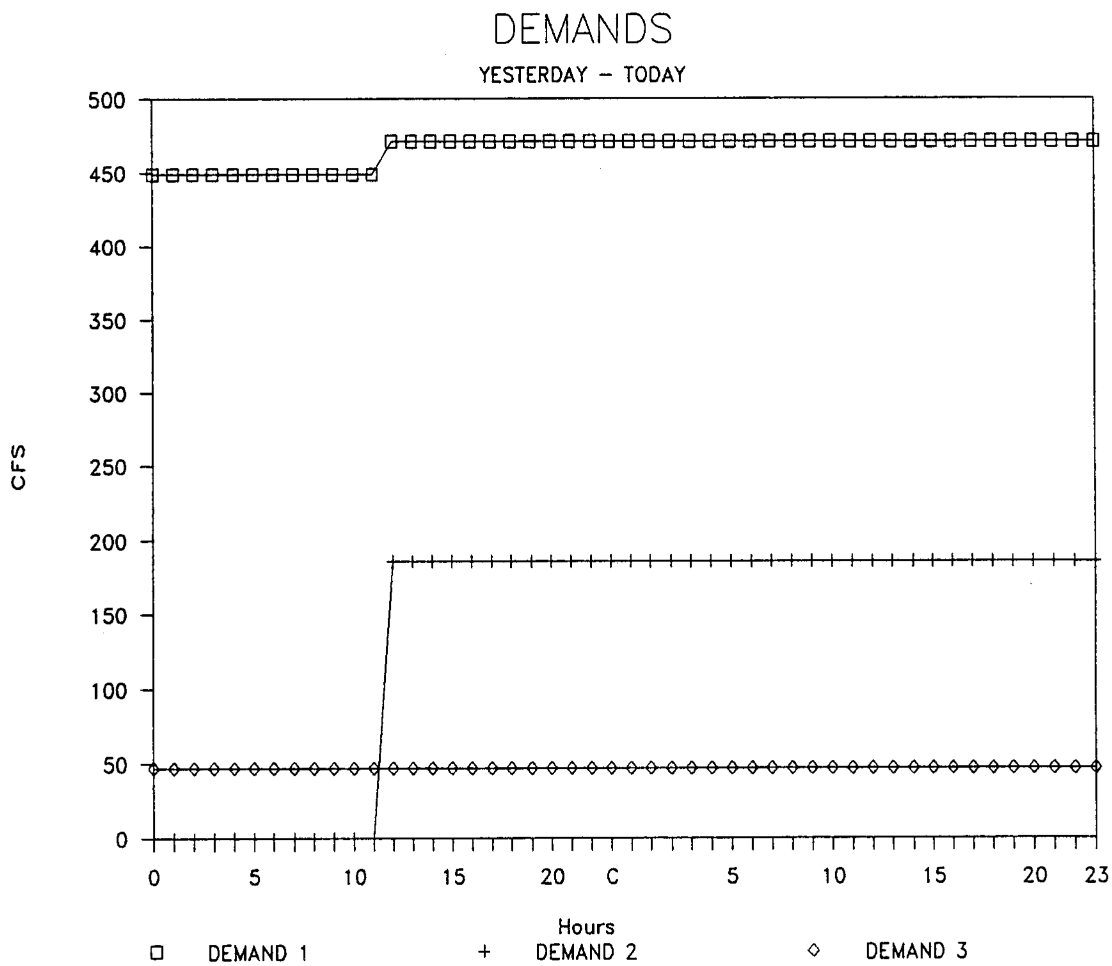

Figure 13. Case Study Demands With No Operator Changed Values.

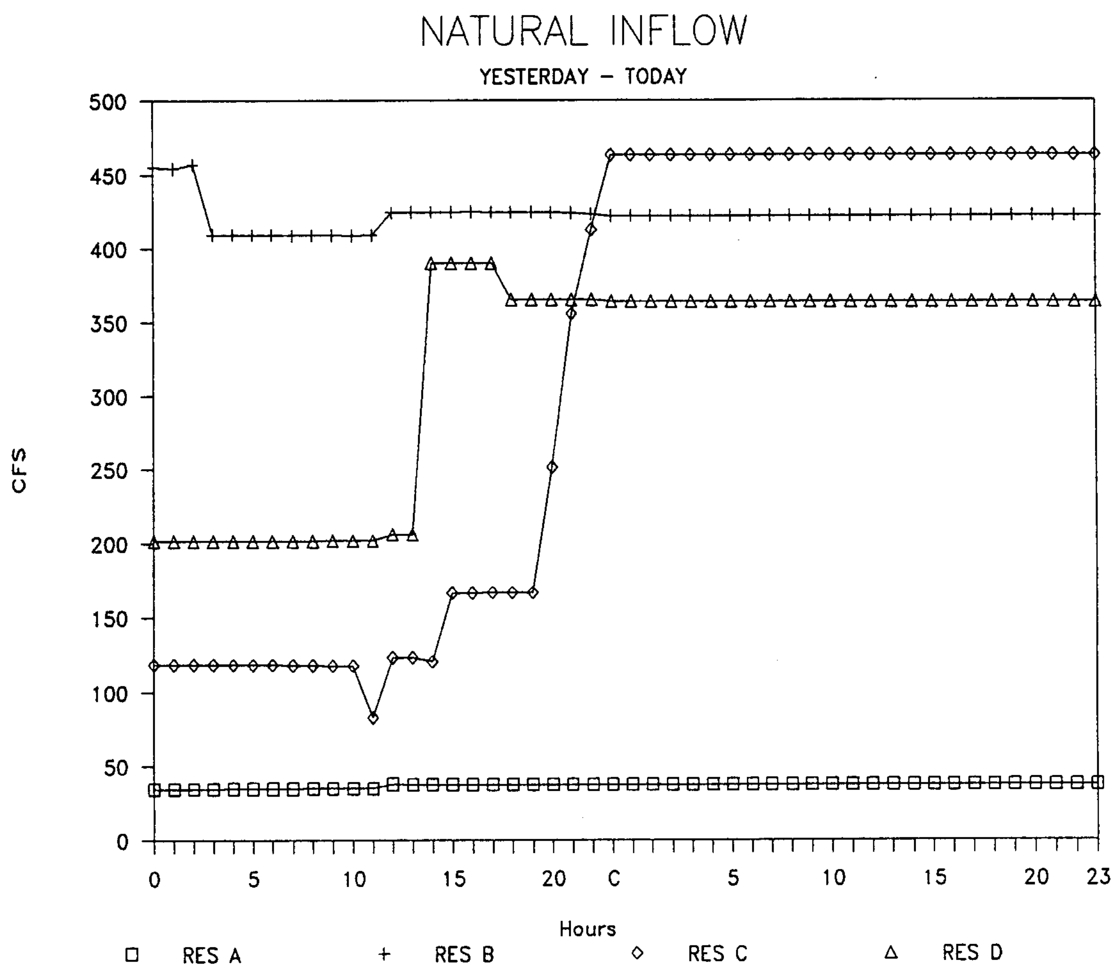

Figure 14. Case Study Natural Inflow With No Operator Changed Values.

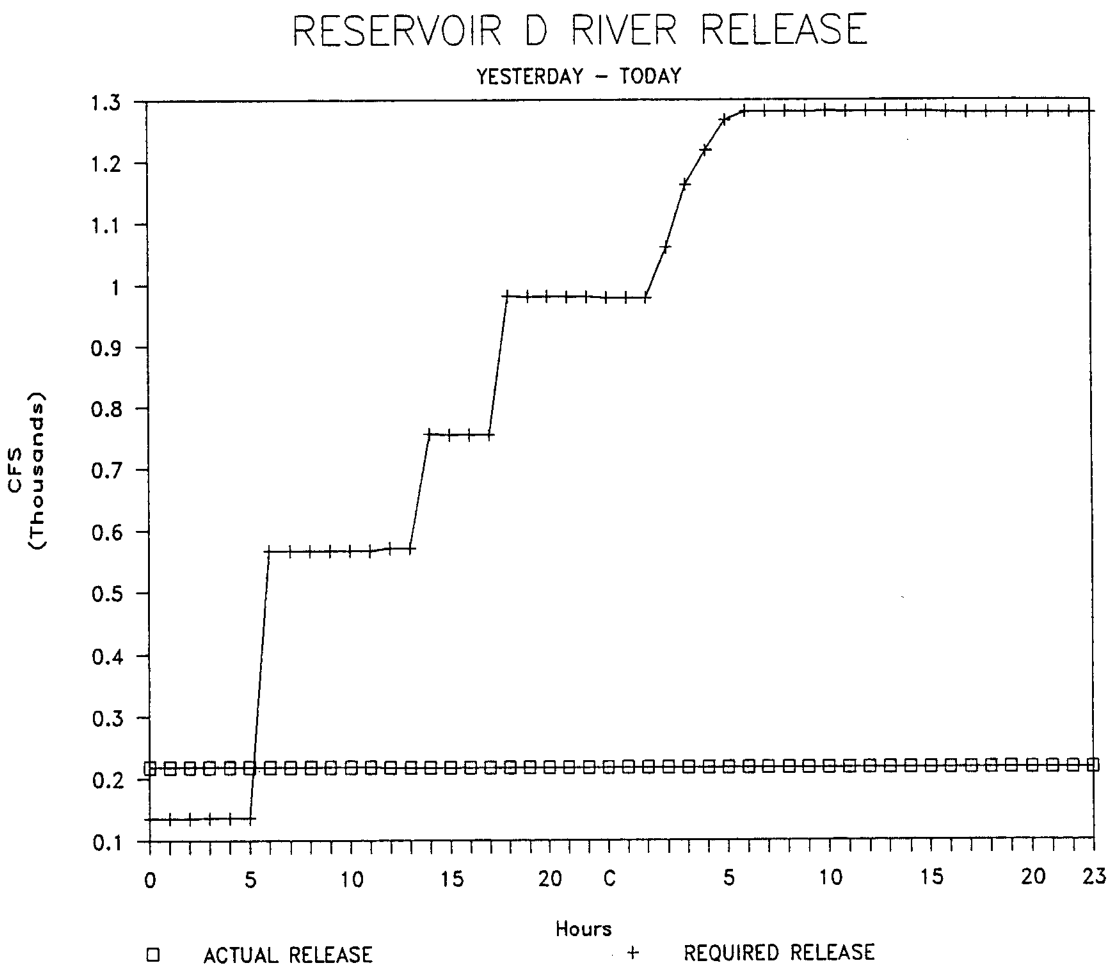

Figure 15. Case Study Reservoir D River Release With No Operator Changed Values.

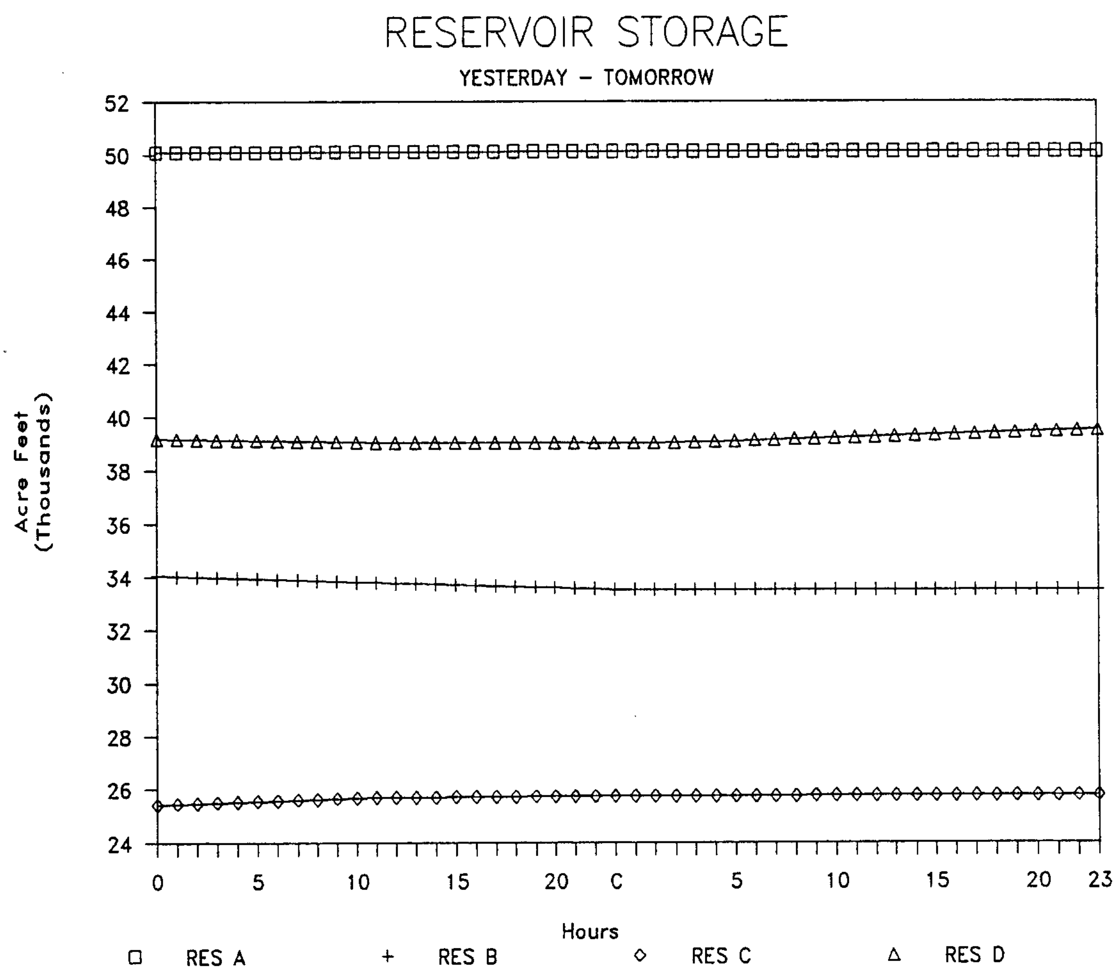

Figure 16. Case Study Reservoir Storage With No Operator Changed Values.

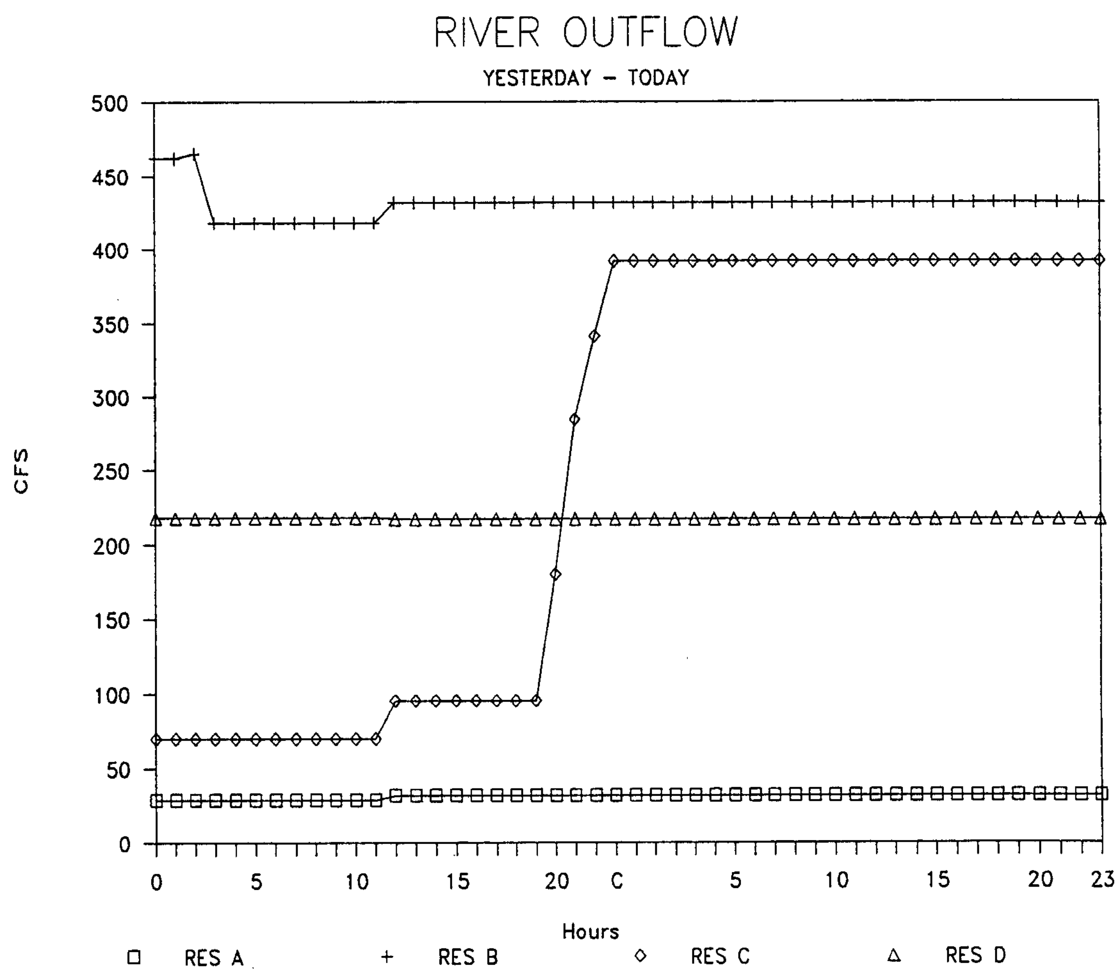

Figure 17. Case Study River Outflow With No Operator Changed Values.

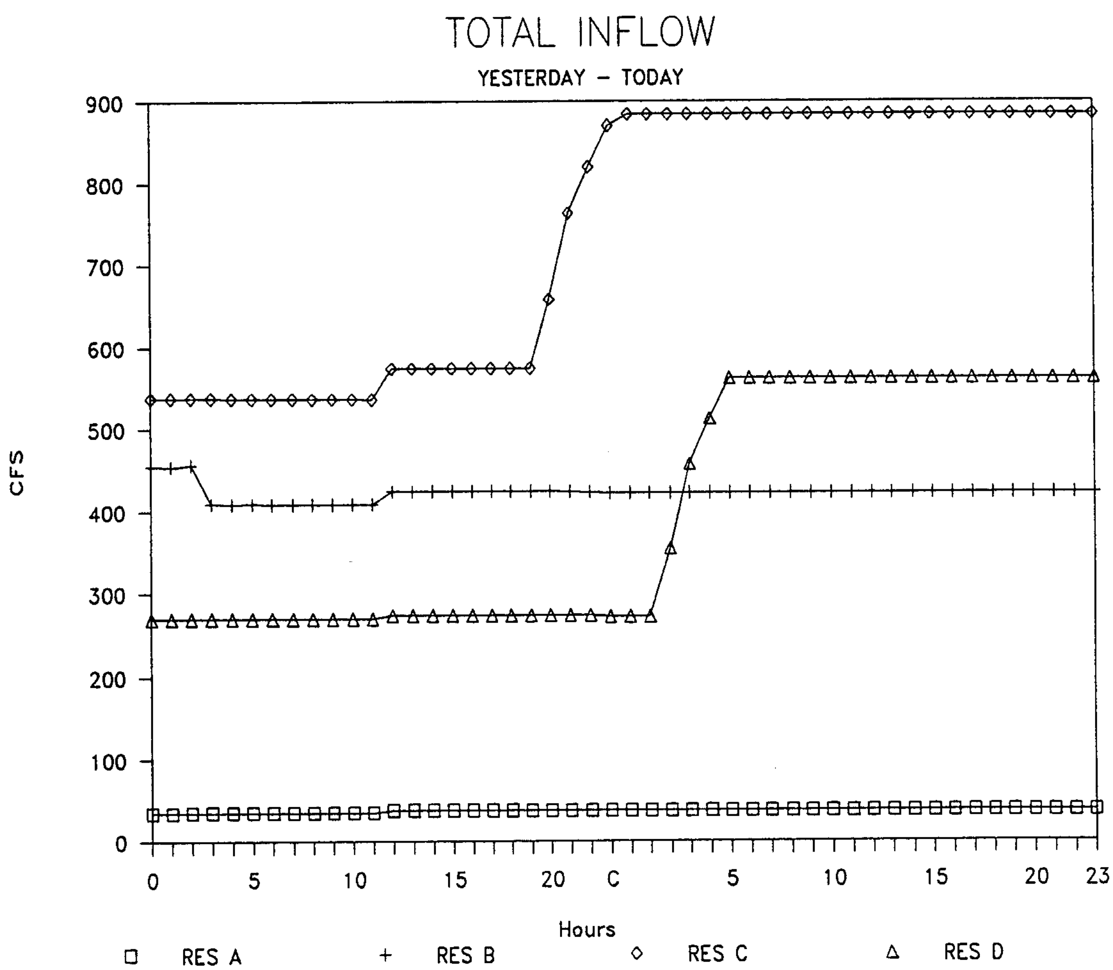

Figure 18. Case Study Total Inflow With No Operator Changed Values.

data, making the river shortage even greater in the future. Figure 13 indicates that Demand 3 is holding fairly constant. Figure 16 indicates that all reservoirs have enough storage remaining for exchanges, and remaining storage capacity to store the current inflow.

Using this information, Reservoir D outflow should be increased to meet present requirements and may have to be increased further to meet future requirements. As a result, one possible future scenario an operator may try is increasing natural inflow to Reservoir C; increasing river outflow from Reservoir D; and decreasing all other reservoir outflows as suggested, to keep water as high in the system as possible.

In order to meet the Outflow Hydrograph requirements from Reservoir D, Program OPERATE is run again. Using the current Operations Work Sheet, Reservoir D outflow is increased to 1250 cfs, slightly more than suggested since the down-stream water rights have been shorted 19 hours as shown in Figure 15, and the inflow to Reservoir C is forecasted to increase. Natural inflow to Reservoir C is increased from 463 to 500 cfs. All other flows are set as suggested. The Operations Work Sheet for this scenario is shown in Figure 19 and the resulting decision graphs for this scenario are depicted in Figures 20 through 25.

As shown in Figure 22, Reservoir D release is still slightly below the required amount. This is because the inflows to the system were increased, in particular at

OPERATIONS WORK SHEET (flows in CFS)

***************************	CURRENT	CHANGE TO	SUGGESTED	MAX	MIN/WR	****
RESERVOIR A NATURAL INFLOW	37.6	37.6	---	---	---	DATE
RIVER OUTFLOW	32.0	0.0	0.0	1000	0	24
						TIME
RESERVOIR B NATURAL INFLOW	422.0	422.0	---	---	---	12
RIVER OUTFLOW	431.8	0.0	0.0	800	0	****
RESERVOIR C NATURAL INFLOW	463.2	500.0	---	---	---	
RIVER OUTFLOW	391.7	240.0	240.0	2000	240	
DEMAND AT 1	471.0	471.0	---	900	28	
DEMAND AT 2	186.0	186.0	---	150	100	
MINIMUM FLOW IN REACH 2-D	272.7	---	---	---	50	
RESERVOIR D NATURAL INFLOW	364.0	364.0	---	---	---	
RIVER OUTFLOW	217.0	1250.0	1238.5	3000	1265	
DEMAND AT 3	47.0	47.0	---	150	45	
RIVER CALL	1870	1870	---	---	---	

[ALT I] INPUT DATA[ALT R] RES.ACCT.*[ALT O] OPERATE*[ALT E] EXCH.INFO.

Figure 19. Case Study Operations Work Sheet For Day=24 and Time=12 With Operator Forecast.

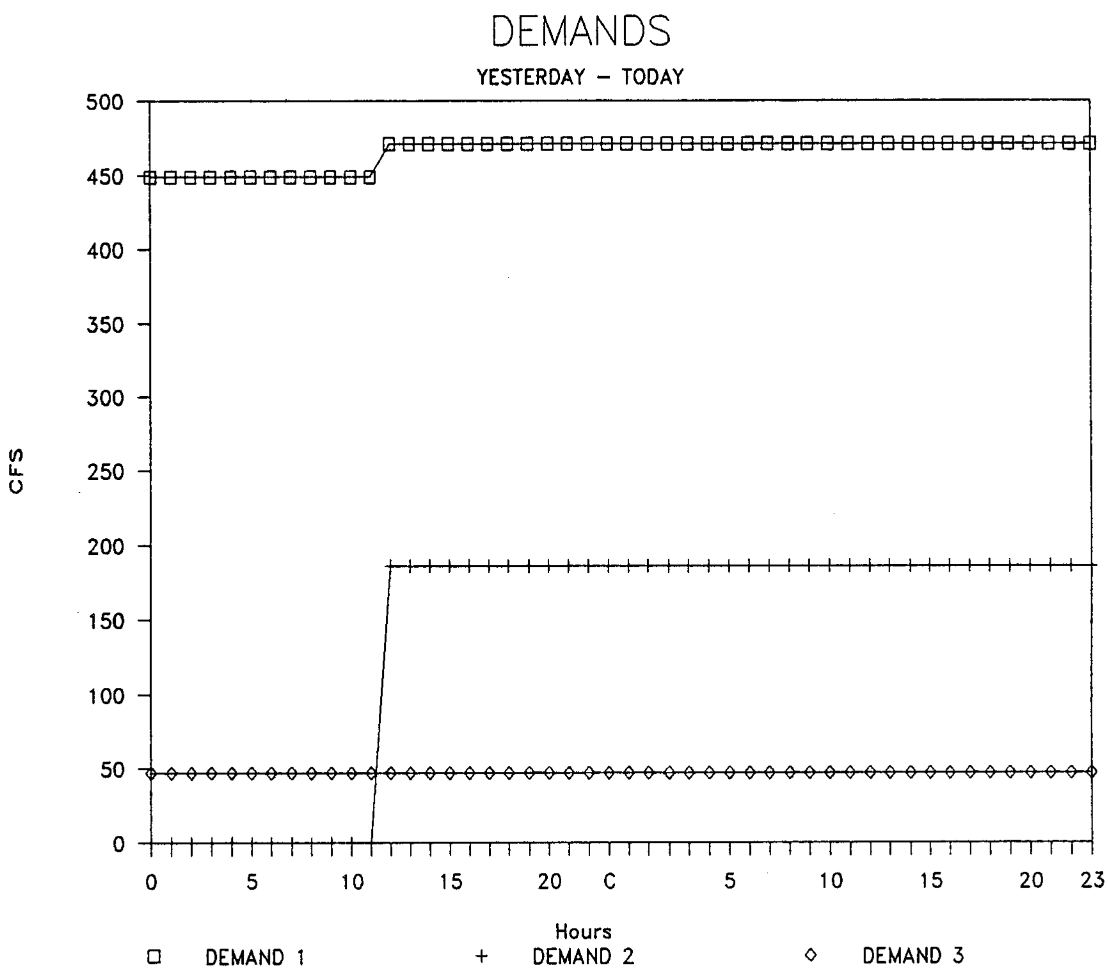

Figure 20. Case Study Demands With Operator Forecast.

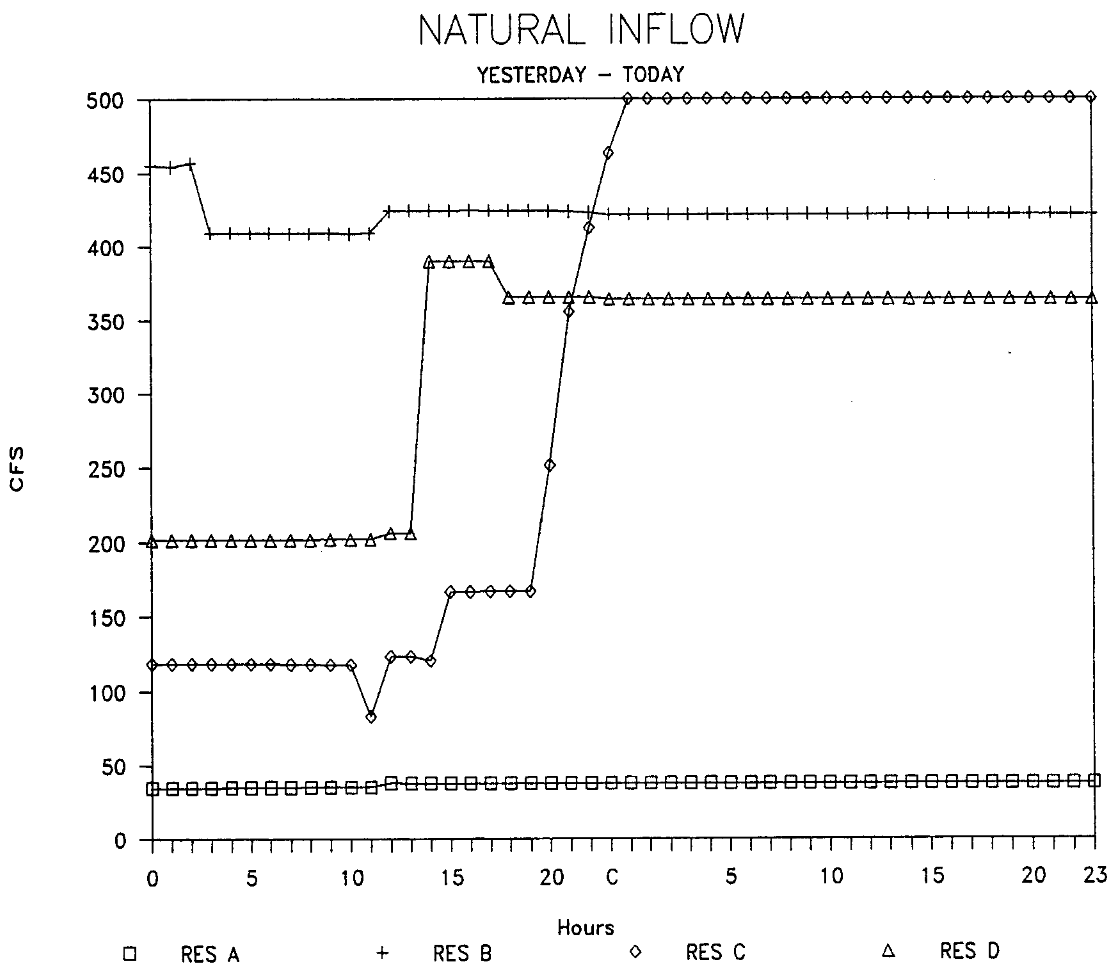

Figure 21. Case Study Natural Inflow With Operator Forecast.

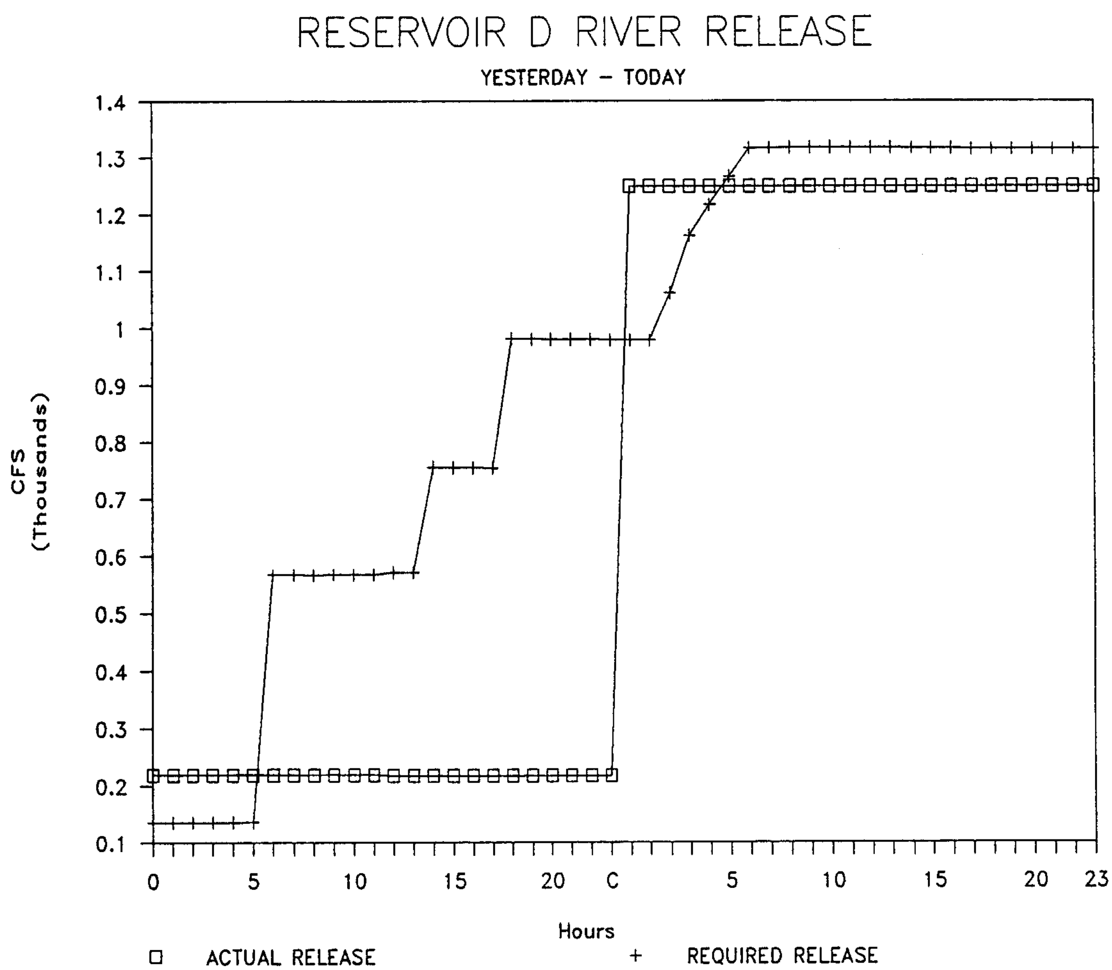

Figure 22. Case Study Reservoir D River Release With Operator Forecast.

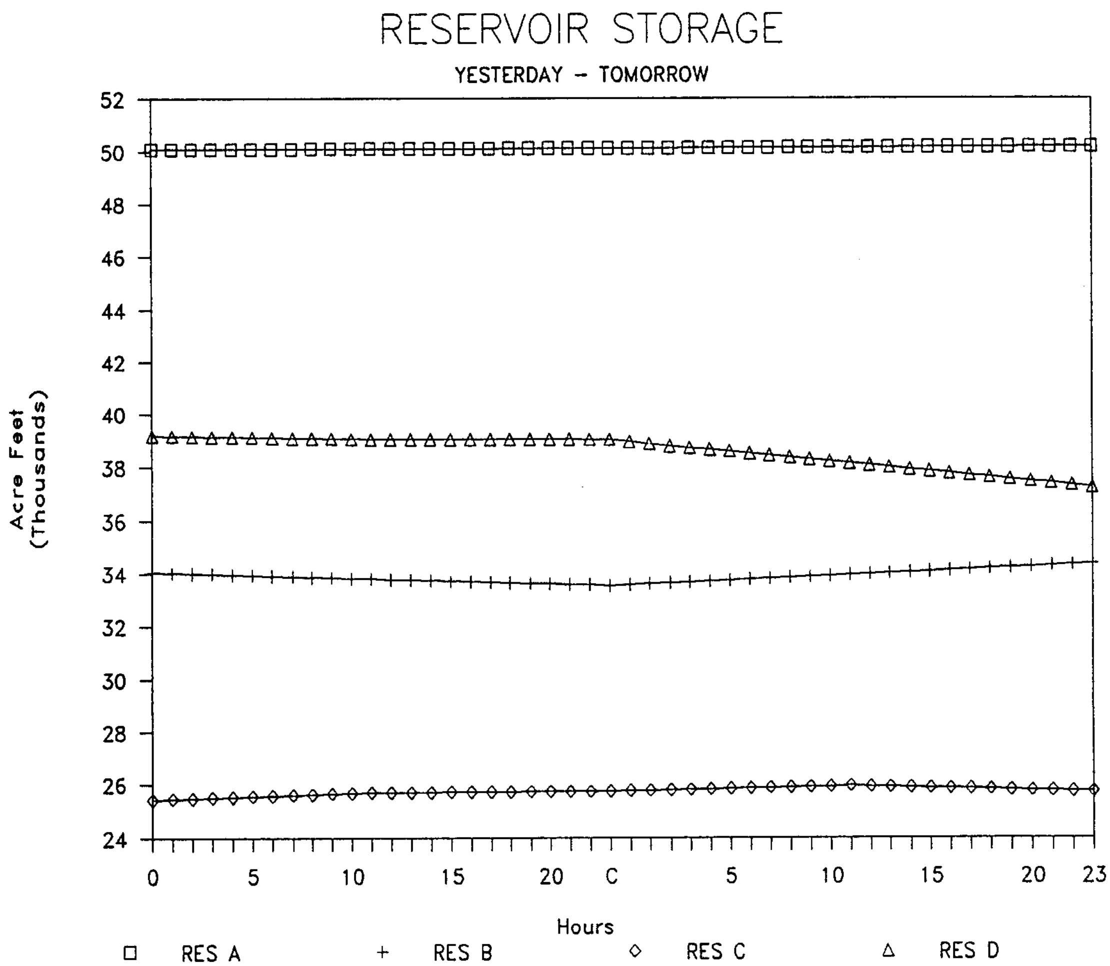

Figure 23. Case Study Reservoir Storage With Operator Forecast.

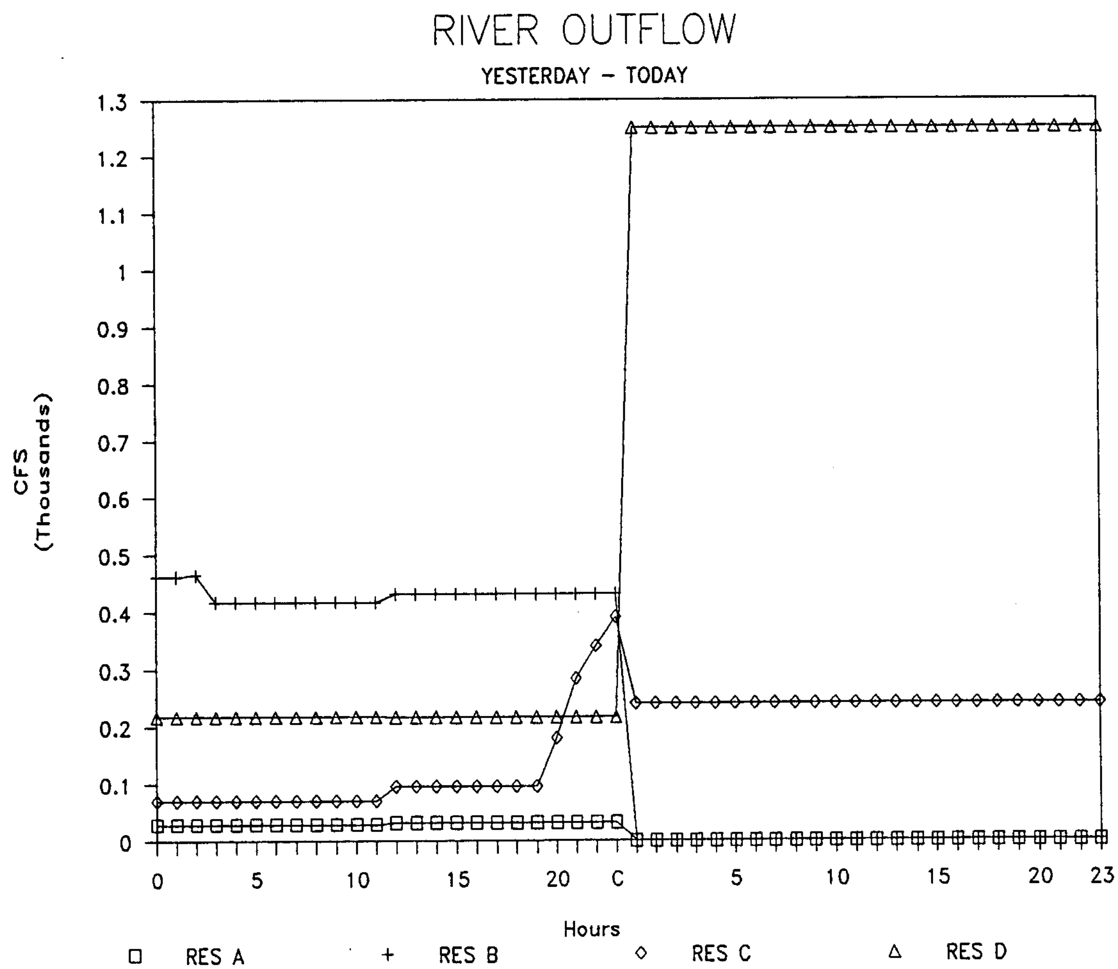

Figure 24. Case Study River Outflow With Operator Forecast.

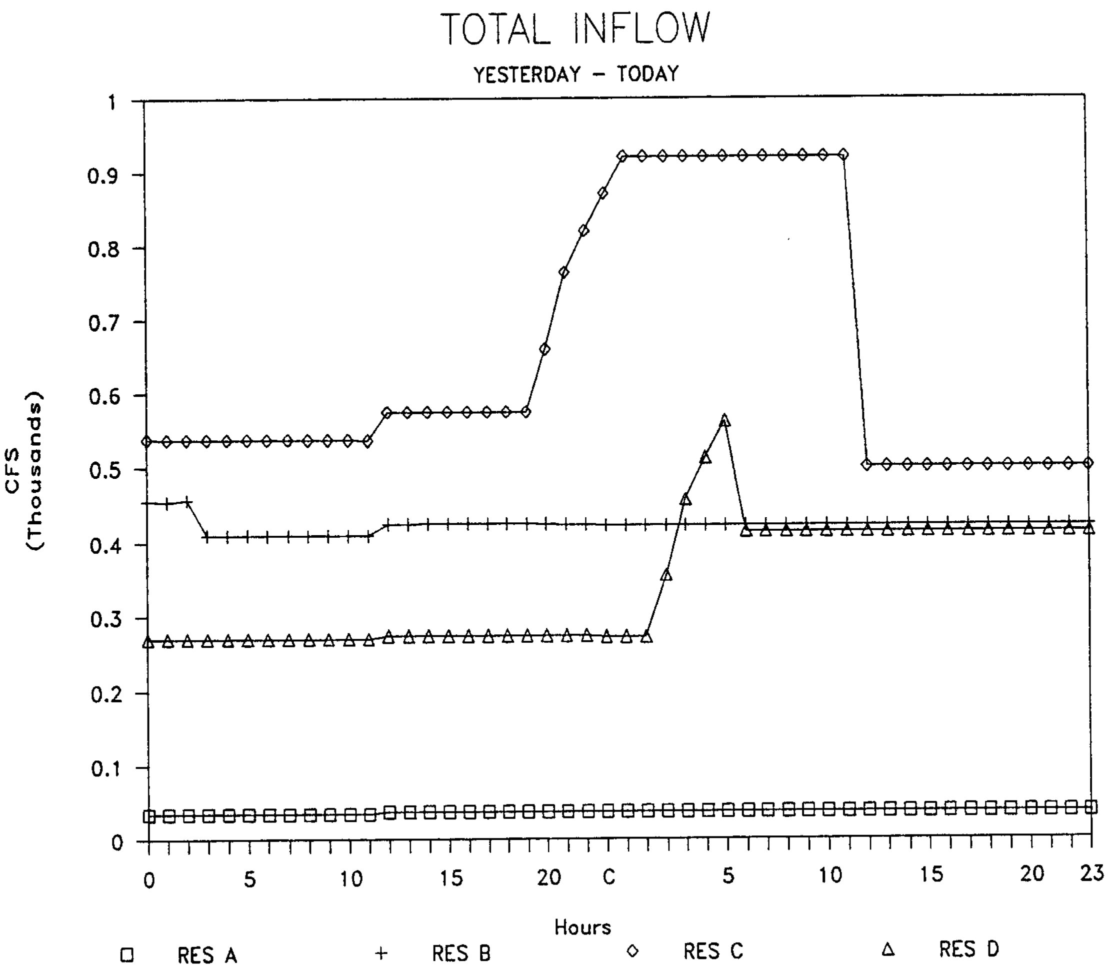

Figure 25. Case Study Total Inflow With Operator Forecast.

Reservoir C. If the operator feels the increased inflow is a realistic situation, he would probably run Program OPERATE again to increase the outflow at Reservoir D without increasing the inflow to Reservoir C. If the results of this new scenario are acceptable to the operator, he can then relay this information to gate control systems or dam tenders. If the results are unacceptable, this scenario process is repeated until the operator is satisfied with the outcome.

In reviewing all of the decision graphs for this scenario, Figure 23, would alert an operator to the fact that Reservoir D storage is starting to decrease and should be closely watched over the next few days. Knowing ahead of time if water from up-stream reservoirs is needed to maintain a minimum pool elevation at a lower reservoir is critical due to the time required for water to travel from an up-stream reservoir to the lower reservoir. At least for the next 24 hours, this does not appear to be a problem.

If this DSS would have been running in the past, the large required outflow change at Reservoir D would probably not have occurred. But, if a large reservoir release is required, as in this scenario, several outflow changes from Reservoir D, rather than one large one, might be desirable. These outflow changes could be preset through control systems at this time and future real-time data would verify these outflow changes. At the same time, the DSS would recommend refinements to these outflows in real-time if the required outflow hydrograph values are not being met.

When the operator is satisfied with the results of a scenario or future forecasted conditions, he can move to the next time step by running the input program. The operator would use the same scenario process as above. A real-time DSS would automatically run and process information every hour.

Real-Time Implementation

If this DSS is implemented in real-time and running automatically, the operator does not have to operate the DSS at each time increment to make system adjustments. The DSS could automatically recommend reservoir and diversion outflows according to the suggested values. Reservoir outflow automation could be connected to the DSS and automatically adjust gates every hour according to the DSS recommendations. Since the operator has supervisory control, he could view the DSS whenever appropriate according to his schedule or any other criteria, and make changes as desired.

Subroutine SUGGEST of the DSS Program OPERATE could be set according to operations criteria predetermined based on seasonal forecasts and special situation criteria such as an emergency. This allows the real-time operations to be automatic and manageable by an operator. The DSS is totally flexible to meet operational and water rights criteria which insures that system demand requirements are being met and that there is no injury to senior water rights.

<u>Historic vs. Proposed Operations</u>

To demonstrate the proposed DSS operations effect on current operations, the DSS was set up to simulate real-time operations where real-time data is transferred to the DSS automatically. In order to match typical current operator time spent on operations, the proposed DSS was set up to allow operator input only once every 24 hours. The 20 day period of real-time data was used as the period for comparison. Figure 26 shows the results of the 20 day run which compares Reservoir D actual river outflow to the DSS proposed or required river outflow.

As shown in Figure 26, down-stream water rights are being injured because Reservoir D releases are not meeting the required outflow. Currently, most operators do not know what natural river flows are in real-time, and therefore river outflow at Reservoir D is generally set only once a day based on past inflow conditions. In this case the water being stored out of priority or not being released to down-steam water users, is being stored in an owe-the-river account to be released at a later date.

The proposed DSS computes natural flows at all reservoirs, and required system outflow at Reservoir D, based on the river call being met at all times. This insures that an owe-the-river or administration account in

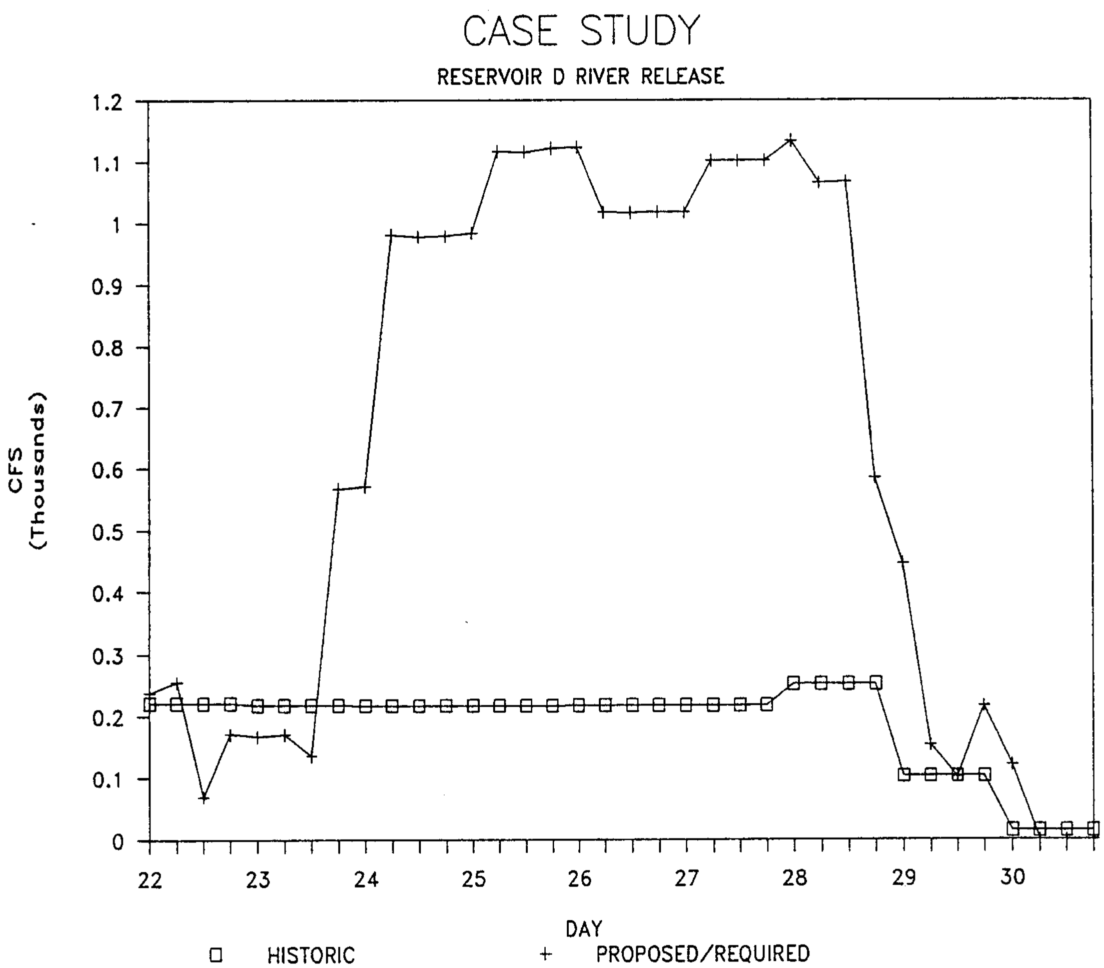

Figure 26. Case Study Reservoir D Historic vs. Proposed Operations.

Reservoir D does not develop if the outflow is adjusted to meet the required outflows from the system outflow hydrograph. The present method only meets yesterday's river call in an average or volumetric sense as explained in Chapter III.

If Reservoir D outflow increased according to the proposed DSS, more than likely the river call would have been more junior, since additional water would have been available down-stream. As a result, the true operations picture would be somewhat different than projected in this example. The reservoir operator could have possibly diverted or stored more water legally than historic conditions allowed and down-stream water rights would not have been injured.

In summary, this chapter demonstrated how the proposed framework in Chapter IV could be used to develop and implement a DSS for reservoir operations in Colorado. Although a hypothetical case study was used, the DSS setup and operations of this system represents a very realistic situation. Certain aspects of the operations process were simulated, but based on my experience, represent a small problem for the true real-time implementation of the proposed methodology.

CHAPTER VI

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

Summary

Using a systems engineering approach to analyze current reservoir operations practices in Colorado, a formalized and routinized procedure was developed to operate multiple reservoirs in a real-time reservoir operations environment according to the Doctrine of Prior Appropriation. Based on the latest decision support system technology, a framework for a decision support system (DSS) was then developed which integrated the reservoir operations procedure with real-time data acquisition into a real-time computer based environment. Using the framework, a demonstration DSS was developed and implemented for a typical multiple Colorado reservoir system.

As required by the framework, the demonstration DSS was divided into three major elements:

1. Operator interface
2. Information management
3. System simulation.

Each element was further divided into modules required to overcome the current real-time reservoir operations problems. The three major elements were broken down as follows:

1. Operator interface
    a. Operations work sheet
    b. Exchange potential table
    c. Decision graphics
2. Information management
    a. Real-time data section
    b. Water rights section
    c. Constraints/Factors section
3. System simulation
    a. Natural flow computations section
    b. Out-flow hydrograph section
    c. Exchange potentials section.

The theory behind each of these modules was developed and then implemented in a demonstration DSS on a case study using a PC spreadsheet environment.

Conclusions

This study was motivated based on 15 years of personal experiences in actually operating reservoirs, being in charge of reservoir operations, and "hands-on" working with various reservoir operators throughout Colorado for this study. The study is therefore unique in that the researcher also represents the practitioner who would use the results of this research. As a result, certain assumptions, judgments, and conclusions are based on this experience and should reflect those of other reservoir operators in Colorado.

The research established that two major problems exist today regarding real-time reservoir operations in Colorado:

1. The existing manual procedures used by reservoir operators can no longer handle today's problems caused by the complex and increasing number of water rights.

2. Presently developed computer based decision support systems for reservoir operations are not being used by operators.

The analysis of these problems revealed that reservoir operators are unwilling or unable to use the current technology to overcome their problems because the developed DSS's todate do not integrate a water rights system nor automatically use their real-time data acquisition systems.

The results of this research established that the demonstration DSS used to implement the proposed framework was able to overcome these problems. In addition, the demonstration DSS was shown to more equitably distribute water according to the Prior Appropriation Doctrine of water rights. Although a hypothetical case study was used and certain aspects of the operations process were simulated, these represent relatively small problems for the true implementation of this methodology. Because the basis of the framework is a procedure developed from currently accepted operations practices in Colorado, the proposed framework has a very good chance of being implemented.

The proposed demonstration DSS did not require that today's reservoir operator would have to be a computer programmer or engineer to understand and use. Based on the hardware and software selected for the demonstration DSS, most operators today have access and possess the knowledge to use PC computers and spreadsheet software. Those operators that are more advanced can take advantage of their technology when implementing the proposed framework.

The key concepts that resulted from this study are the systems approach to the development of a formalized real-time reservoir operations procedure, the reconstruction in real-time of natural flows at all points in the reservoir system based on current and past real-time data, and the development in real-time of the required system outflow hydrograph. These concepts allowed several common operations problems to be solved in a relatively simple manner. Probably the most important operations problem resolved was that of determining the legally required outflow from the reservoir system in real-time so that down-stream water rights would not be injured. The second major operations problem solved was the determination of exchanges and transfers in real-time which alleviated potential injury to senior water rights.

The proposed framework solved these problems by first creating a strictly legal reservoir subsystem to determine the required subsystem outflow. Secondly, by meeting the required subsystem outflows, the elements of the subsystem could be operated independently from the river system to determine exchanges and transfers as desired. These tasks were performed in real-time whenever real-time data was updated in the DSS.

As demonstrated, the problem of integrating real-time reservoir operations with water rights decisions is very complex and system specific. However, the proposed decision framework is generic and can be used on any reservoir system which operates according to the Prior Appropriation Doctrine of water rights. The primary concern here was using available technology, in particular real-time data collection systems, to make decisions in real-time. This study demonstrated by simulation that the proposed decision framework could adequately integrate information from an automated real-time data collection system in real-time to operate reservoirs according to a water rights system.

Recommendations and Potential for Further Research

Based on the research performed in this study and the demonstration of the methodology, the following recommendations are suggested:

1. Although today's requirements for real-time reservoir operations do not dictate advanced simulation technology, the use of advanced techniques could be made available to a reservoir operator. Several techniques could be included in a DSS and made accessible to a reservoir operator based on his selection. As regulations and

requirements change, new techniques could be implemented as easy as pushing a button to select a desired technique. Some examples of these techniques might be kinematic river routing, reservoir storage routing, measured reservoir evaporation and loss factors in real-time, and short term forecasting methods.

2. Using today's software windows technology, the development of a state-of-the-art operator interface could be produced that would be generic in nature. In order to be used by today's reservoir operator, this package would have to be easy to setup and integrate with the proposed framework elements.

3. The introduction of artificial intelligence techniques in the operator interface could provide further research. Although the real-time operation of a multiple reservoir system is an ill-structured real-world problem that requires human expertise, this study formalized the reservoir operations process into a sequential and arithmetical procedure. If the operator's decision process when using this procedure was studied, a possible expert system or knowledge based operator interface could be used to integrate this man-machine interaction into the operator interface in the DSS. Based on my experience, however, this would be a very difficult to make generic, since a good deal of the operations decision process is based on the specific geography of the reservoir and river systems, and the river call regime.

4. Based on the systems approach, this framework has the potential to be integrated basin wide. In particular, this methodology could possibly be used to develop a computer based DSS for Water Commissioners to regulate entire river systems.

5. A prototype DSS using the proposed decision framework should be developed for a specific reservoir system and field tested. In order to not reveal operations policies, this work would probably have to be done by a reservoir system owner.

6. The integration and addition of modules to the framework which provide reservoir system water accounting and required State Engineer diversion records accounting should be considered. This is probably the most important next step in resolving reservoir operations - regulations problems in Colorado today.

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APPENDIX A

DECISION SUPPORT SYSTEM CELL EQUATIONS

Table A-1

Decision Support System Operator Interface.

```
         OPERATIONS WORK SHEET                    (flows in CFS)

         ********************* CURRENT CHANGE TO SUGGESTED  MAX MIN/WR ****
    [ 6] RES. A NATURAL INFLOW |                                       DATE
    [ 7]            RIVER OUTFLOW |
                                                                       TIME
    [ 9] RES. B NATURAL INFLOW |
    [10]            RIVER OUTFLOW |                                    ****

    [12] RES. C NATURAL INFLOW |
    [13]            RIVER OUTFLOW |
    [14] DEMAND AT 1           |    [FF]      [FG]      [FH]  [FI]  [FJ]

    [16] DEMAND AT 2           |
    [17] MIN. FLOW REACH 2-D   |

    [19] RES. D NATURAL INFLOW |
    [20]            RIVER OUTFLOW |
    [21] DEMAND AT 3           |
    [22] RIVER CALL            |

    [ALT I] INPUT DATA*[ALT R] RES.ACCT.*[ALT O] OPERATE*[ALT E] EXCH.INFO.
```

[12] = Row Number

[FH] = Column

Table A-2

Decision Support System Operations Interface Equations

CELL	EQUATION
FF6:	+$BJ$59
FF7:	+$BN$59
FI7:	+$RESA_MAX_OUT
FF9:	+$BT$59
FF10:	+$BX$59
FI10:	+$RESB_MAX_OUT
FF12:	+$CD$59
FF13:	+$CI$59
FI13:	+$RESC_MAX_OUT
FJ13:	+$DP$60
FF14:	+$CH$59
FI14:	+$DIV1_MAX
FJ14:	+$DO60
FF16:	+$CL$59
FI16:	+$DIV2_MAX
FJ16:	+$DT60
FF17:	+$CQ$59
FJ17:	+$MF2_D
FF19:	+$CS$59
FF20:	+$CX$59
FI20:	+$RESD_MAX_OUT
FJ20:	@SUM($DZ$60..$DZ$83)/24
FF21:	+$CW$59
FI21:	+$DIV3_MAX
FJ21:	+$DY60
FF22:	+$BF$59

Table A-3

Decision Support System Real-Time Data Table

DAY	T	RIVER CALL	RES A STOR	RES A RIVER	RES B STOR	RES B RIVER
-2	0					
	1					
	2					
	3					
	.					
	.					
	.					
-1	23	[V]	[W]	[X]	[Y]	[Z]
	0					
	1					
	2					
	3					
	.					
	.					
	.					
C	23					

DAY	T	RES C STOR	RES C DEM-1	RES C RIVER	DEM-2	RES D STOR	RES D DEM-3	RES D RIVER
-2	0							
	1							
	2							
	3							
	.							
	.							
	.							
-1	23	[AA]	[AB]	[AC]	[AD]	[AE]	[AF]	[AG]
	0							
	1							
	2							
	3							
	.							
	.							
	.							
C	23							

[Y] = Column

Table A-4 (Part 1)

Decision Support System Natural Flow Computations Table

DAY	T	RIVER CALL	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	RESERVOIR A DELTA-S	RESERVOIR A STOR (AF)	EVAP.	OUTFLOW RIVER
-1	0								
	1								
	2								
	3								
	.								
	.								
	.								
C	23	[BF]	[BH]	[BI]	[BJ]	[BK]	[BL]	[BM]	[BN]
F	0								
	1								
	2								
	3								
	.								
	.								
	.								
	23								

[BK] = Column

Table A-4 (Part 2)

Decision Support System Natural Flow Computations Table

		RESERVOIR B						
DAY	T	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	DELTA-S	STOR (AF)	EVAP.	OUTFLOW RIVER
-1	0							
	1							
	2							
	3							
	.							
	.							
	.							
C	23	[BR]	[BS]	[BT]	[BU]	[BV]	[BW]	[BX]
F	0							
	1							
	2							
	3							
	.							
	.							
	.							
	23							

[BU] = Column

Table A-4 (Part 3)

Decision Support System Natural Flow Computations Table

RESERVOIR C

DAY	T		INFLOW		DELTA-S	STOR	EVAP.	OUTFLOW	
		TOTAL	UPSTRM	NATURAL				DEM-1	RIVER
-1	0								
	1								
	2								
	3								
	.								
	.								
	.								
C	23	[CB]	[CC]	[CD]	[CE]	[CF]	[CG]	[CH]	[CI]
F	0								
	1								
	2								
	3								
	.								
	.								
	.								
	23								

[CE] = Column

Table A-4 (Part 4)

Decision Support System Natural Flow Computations Table

DAY	T	DEMAND ABOVE FLOW	DEMAND DEM-2	DEMAND BELOW FLOW
-1	0			
	1			
	2			
	3			
	.			
	.			
	.			
C	23	[CK]	[CL]	[CM]
F	0			
	1			
	2			
	3			
	.			
	.			
	.			
	23			

[CL] = Column

Table A-4 (Part 5)

Decision Support System Natural Flow Computations Table

RESERVOIR D

DAY	T	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	DELTA-S	STOR	EVAP.	OUTFLOW DEM-3	OUTFLOW RIVER
-1	0								
	1								
	2								
	3								
	.								
	.								
	.								
C	23	[CQ]	[CR]	[CS]	[CT]	[CU]	[CV]	[CW]	[CX]
F	0								
	1								
	2								
	3								
	.								
	.								
	.								
	23								

[CU] = Column

Table A-5

Decision Support System Natural Flow Equations

COLUMN	EQUATION
BF59:	@VALUE(V59)
BH59:	+BK59+BM59+BN59
BJ59:	+BH59-BI59
BK59:	(BL59-BL58)/$CONV
BL59:	@VALUE(W59)
BM59:	+$EVAP_A
BN59:	@VALUE(X59)
BR59:	+BU59+BW59+BX59
BT59:	+BR59-BS59
BU59:	(BV59-BV58)/$CONV
BV59:	@VALUE(Y59)
BW59:	+$EVAP_B
BX59:	@VALUE(Z59)
CB59:	+CE59+CG59+CH59+CI59
CC59:	+BX47*(1-$LB-C)
CD59:	+CB59-CC59
CE59:	(CF59-CF58)/$CONV
CF59:	@VALUE(AA59)
CG59:	+$EVAP_C
CH59:	@VALUE(AB59)
CI59:	@VALUE(AC59)
CK59:	+CI55*(1-$LC-2)
CL59:	@VALUE(AD59)
CM59:	@MAX(+CK59-CL59,0)
CQ59:	+CT59+CV59+CW59+CX59
CR59:	+CM57*(1-$L2_D)
CS59:	+CQ59-CR59
CT59:	(CU59-CU58)/$CONV
CU59:	@VALUE(AE59)
CV59:	+$EVAP_D
CW59:	@VALUE(AF59)
CX59:	@VALUE(AG59)

All column equations the same above Row 59 - "C"

Table A-6

Decision Support System Forecast Flow Equations

COLUMN	EQUATION
BF60:	+$CALL
BH60:	+BI60+BJ60
BJ60:	+$RESA_INF
BK60:	+BH60-BM60-BN60
BL60:	+BL59+($CONV/24*BK60)
BM60:	+$EVAP_A
BN60:	+$RESA_OUT
BR60:	+BS60+BT60
BT60:	+$RESB_INF
BU60:	+BR60-BW60-BX60
BV60:	+BV59+($CONV/24*BU60)
BW60:	+$EVAP_B
BX60:	+$RESB_OUT
CB60:	+CC60+CD60
CC60:	+BX48*(1-$LB-C)
CD60:	+$RESC_INF
CE60:	+CB60-CG60-CH60-CI60
CF60:	+CF59+(CE60*$CONV/24)
CG60:	+$EVAP_C
CH60:	+$DEM_1
CI60:	+$RESC_OUT
CK60:	+CI56*(1-$LC-2)
CL60:	+$DEM_2
CM60:	+CK60-CL60
CQ60:	+CR60+CS60
CR60:	+CM58*(1-$L2_D)
CS60:	+$RESD_INF
CT60:	+CQ60-CV60-CW60-CX60
CU60:	+CU59+(CT60*$CONV/24)
CV60:	+$EVAP_D
CW60:	+$DEM_3
CX60:	+$RESD_OUT

All column equations the same below Row 60 - "F"

Table A-7 (Part 1)

Decision Support System Outflow Hydrograph Computations Table

DAY	T	RESERVOIR A INFLOW	RESERVOIR A RIGHTS (STORG)	RESERVOIR A OUTFLOW	RESERVOIR B INFLOW	RESERVOIR B RIGHTS (STORG)	RESERVOIR B OUTFLOW
-1	0						
	1						
	2						
	3						
	.						
	.						
	.						
C	23	[DE]	[DF]	[DG]	[DI]	[DJ]	[DK]
F	0						
	1						
	2						
	3						
	.						
	.						
	.						
	23						

[DI] = Column

Table A-7 (Part 2)

Decision Support System Outflow Hydrograph Computations Table

DAY	T	RESERVOIR C				
		INFLOW	RIGHTS (STORG)	RIGHTS (DEM-1)	REQ'D OUTFLOW	OUTFLOW
-1	0					
	1					
	2					
	3					
	.					
	.					
	.					
C	23	[DM]	[DN]	[DO]	[DP]	[DQ]
F	0					
	1					
	2					
	3					
	.					
	.					
	.					
	23					

[DP] = Column

Table A-7 (Part 3)

Decision Support System Outflow Hydrograph Comutations Table

DAY	T	DEMAND ABOVE FLOW	DEMAND DEM-2	DEMAND BELOW FLOW	RESERVOIR D INFLOW	RESERVOIR D RIGHTS (STORG)	RESERVOIR D RIGHTS (DEM-2)	RESERVOIR D OUTFLOW
-1	0							
	1							
	2							
	3							
	.							
	.							
	.							
C	23	[DS]	[DT]	[DU]	[DW]	[DX]	[DY]	[DZ]
F	0							
	1							
	2							
	3							
	.							
	.							
	.							
	23							

[DX] = Column

Table A-8

Decision Support System Outflow Hydrograph Equations

COLUMN	EQUATION
DE59:	+BJ59
DF59:	@IF($BF59<$AP$47,0,DE59)
DG59:	+DE59-DF59
DI59:	+BT59
DJ59:	@IF($BF59<$AP$49,@IF($BF59<$AP$48,0,DI59),DI59)
DK59:	+DI59-DJ59
DM59:	+DK47*(1-$LB-C)+CD59
DN59:	@IF($BF59<$AP$50,0,DM59-DO59)
DO59:	@MIN(@VLOOKUP($BF59,$AP$52..$AS$59,3),$CH59)
DP59:	(DT59+$MF2_D)*(1+$LC-2)+($MF2_D*$L2_D)
DQ59:	+DM59-DN59-DO59+DP59
DS59:	+DQ55*(1-$LC-2)
DT59:	@MIN(@VLOOKUP($BF59,$AP$60..$AS$62,3),$CL59)
DU59:	+DS59-DT59
DW59:	+DU57*(1-$L2_D)+CS59
DX59:	@IF($BF59<$AP$51,0,DW59-DY59)
DY59:	@MIN(@IF(BF59<$AP$63,0,$AS$63),$CW12)
DZ59:	+DW59-DX59-DY59

Column equations the same for all rows

Table A-9

Decision Support System Exchange Table

*** EXCHANGE POTENTIALS ***

	RESERVOIR	REMAIN. CAPACITY (af)	EXCHANGE IN POTENTIAL (cfs)	USABLE STORAGE (af)	EXCHANGE OUT POTENTIAL (cfs)
[34]	A				
[35]	B	[FF]	[FG]	[FH]	[FJ]
[36]	C				
[37]	D				

EXCHANGE BETWEEN RES.

	RES-IN		RES-OUT	MAXIMUM AMOUNT (cfs)	ACCUM AMT. (cfs)	EXCH. OUT TOTAL/RES. res.	(cfs)
[42]	A	TO	B			B	
[43]		TO	C				
[44]		TO	D	[FH]	[FI]	[FJ]	[FK]
[45]	B	TO	A				
[46]		TO	C			C	
[47]		TO	D				
[48]	C	TO	A			A	
[49]		TO	D			D	

[42] = Row Number

[FG] = Column

Table A-10

Decision Support System Exchange Table Equations

CELL	EQUATION
FF34:	+$RESAMAX-$BL$59
FG34:	@MIN($FF$34/2,$FF$6-$FJ$7)
FH34:	+$BL$59-$RESAMIN
FJ34:	@MIN($FH$34/2,$RESA_MAX_OUT-$FJ$7)
FF35:	+$RESBMAX-$BV$59
FG35:	@MIN($FF$35/2,$FF$9-$FJ$10)
FH35:	+$BV$59-$RESBMIN
FJ35:	@MIN($FH$35/2,$RESB_MAX_OUT-$FJ$10)
FF36:	+$RESCMAX-$CF$59
FG36:	@MIN($FF$36/2,$FF$12-$FJ$13)
FH36:	+$CF$59-$RESCMIN
FJ36:	@MIN($FH$36/2,$RESC_MAX_OUT-$FJ$13)
FF37:	+$RESDMAX-$CU$59
FG37:	@MIN($FF$37/2,$FF$19-$FJ$20)
FH37:	+$CU$59-$RESDMIN
FJ37:	@MIN($FH$37/2,$RESD_MAX_OUT-$FJ$20)
FH42:	@MIN($RESA_EXI,$RESB_EXO)
FI42:	+FH42
FK42:	+FH42
FH43:	@MIN($RESA_EXI,$RESC_EXO)
FI43:	+FI42+FH43
FH44:	@MIN($RESA_EXI,$RESD_EXO)
FI44:	+FI43+FH44
FH45:	@MIN($RESB_EXI,$RESA_EXO)
FI45:	+FH45
FH46:	@MIN($RESB_EXI,$RESC_EXO)
FI46:	+FI45+FH46
FK46:	+FH43+FH46
FH47:	@MIN($RESB_EXI,$RESD_EXO)
FI47:	+FI46+FH47
FH48:	@MIN($RESC_EXI,$RESA_EXO)
FI48:	+FH48
FK48:	+FH45+FH48
FH49:	@MIN($RESC_EXI,$RESD_EXO)
FI49:	+FI48+FH49
FK49:	+FH44+FH47+FH49

APPENDIX B

DECISION SUPPORT SYSTEM PROGRAMS

Table B-1

Program OPERATE

```
        \O      {INDICATE OPER}
                {PANELOFF}
                {GOTO}FC4~
                {GETLABEL "DO YOU WANT TO SEE PAST 24 HOUR DATA WITH
PROJECTIONS ? (Y or N) ",ANS}
                {IF ANS="Y"}{BRANCH $GRAPHS}
     START      {LET RESA_INF,+$BJ$59}
                {LET RESA_OUT,+$BN$59}
                {LET RESB_INF,+$BT$59}
                {LET RESB_OUT,+$BX$59}
                {LET RESC_INF,+$CD$59}
                {LET RESC_OUT,+$CI$59}
                {LET DEM_1,+$CH$59}
                {LET DEM_2,+$CL$59}
                {LET RESD_INF,+$CS$59}
                {LET RESD_OUT,+$CX$59}
                {LET DEM_3,+$CW$59}
                {LET CALL,+$BF$59}
                {SUGGEST}
                {GETLABEL "DO YOU WANT TO CHANGE INFLOWS OR OUTFLOWS
                ?(Y or N)  ",ANS}~
                {IF ANS="N"}{BRANCH $GRAPHS}
                {GETNUMBER "ENTER RESERVOIR A NATURAL INFLOW IN CFS
                FOR NEXT 24 HOURS ",RESA_INF}
                {CALC}
                {GETNUMBER "ENTER RESERVOIR A RELEASE IN CFS FOR NEXT
                24 HOURS ",RESA_OUT}
                {CALC}
                {GETNUMBER "ENTER RESERVOIR B NATURAL INFLOW IN CFS
                FOR NEXT 24 HOURS ",RESB_INF}
                {CALC}
                {GETNUMBER "ENTER RESERVOIR B RELEASE IN CFS FOR NEXT
                24 HOURS ",RESB_OUT}
                {CALC}
                {GETNUMBER "ENTER RESERVOIR C NATURAL INFLOW IN CFS
                FOR NEXT 24 HOURS ",RESC_INF}
                {CALC}
                {GETNUMBER "ENTER RESERVOIR C RELEASE IN CFS FOR NEXT
                24 HOURS ",RESC_OUT}
                {CALC}
                {GETNUMBER "ENTER DEMAND AT 1 IN CFS FOR NEXT 24 HOURS
                ",DEM_1}
                {CALC}
                {GETNUMBER "ENTER DEMAND AT 2 IN CFS FOR NEXT 24 HOURS
                ",DEM_2}
                {CALC}
                {GETNUMBER "ENTER RESERVOIR D NATURAL INFLOW IN CFS
                FOR NEXT 24 HOURS ",RESD_INF}
                {CALC}
                {GETNUMBER "ENTER RESERVOIR D RELEASE IN CFS FOR NEXT
                24 HOURS ",RESD_OUT}
                {CALC}
                {GETNUMBER "ENTER DEMAND AT 3 IN CFS FOR NEXT 24 HOURS
                ",DEM_3}
                {CALC}
                {GETNUMBER "ENTER RIVER CALL ",CALL}
                {CALC}
```

Table B-1 (Continued)

```
    GRAPHS          {MENUCALL TOPMENU}
                    {BRANCH $GRAPHS}
      DONE          {INDICATE READY}
                    {QUIT}


    TOPMENU         STORAGENAT-INFINFLOW OUTFLOWDEMANDSRESD_RECONTINUQUIT
                    ReservoNaturalTotal iReservoDemandsReservoContinuStop
                    this hour's operations

{BRANCH{BRANCH{BRANCH{BRANCH{BRANCH{BRANCH{BRANCH{BRANCH EK91}


    RES STORAGE     /GNURES_STORAGE~
                    Q~

    NATURAL INFLOW/GNUNATURAL_INFLOW~
                    Q~

    TOTAL INFLOW    /GNUTOTAL_INFLOW~
                    Q~

    RIVER OUTFLOW /GNURIVER_OUTFLOW~
                    Q~

    DEMANDS         /GNUDEMANDS~
                    Q~

    RESD REQ        /GNURESD_REQ~
                    Q~

    CONTINUE        {BRANCH $START}

    QUIT            {BRANCH $DONE}


    SUGGEST         {CALC}
                    {LET $FH$7,$FF$6-(@MIN($RESA_EXI,$FI$44))}
                    {LET $FH$10,$FF$9-(@MIN($RESB_EXI,$FI$47))}
                    {LET $FH$13,$FF$12-(@MIN($RESC_EXI,$FI$49))}
                    {LET $FH$20,$FJ$20}
                    {CALC}
                    {RETURN}


            \E      {INDICATE EXCH}
                    {PANELOFF}
                    {GOTO}FC30~
                    {MENUBRANCH EXMENU}


            EXMENU WORK SHOPERATE
                   Return Run Operate Program
                   {BRANCH{BRANCH EK130}


            GOTO W {INDICATE READY}
                   {GOTO}FC4~
```

Table B-1 (Continued)

```
GOTO O {INDICATE READY}
       {BRANCH EK8}
```

Table B-2

Program INPUT

```
  \I {INDICATE INPUT}
     {WINDOWSOFF}
     {PANELOFF}
     {GETNUMBER "ENTER CURRENT DAY (23-31 only) ",DAY}~
     {LET $TODAY,$DAY}
     {GETNUMBER "ENTER CURRENT TIME (0-23 only) ",TIME}~
     {LET $NOW,$TIME}
     {FOR COUNTER,1,48,1,LOOP}


LOOP {IF TIME=0}{LET DAY,DAY-1}
     {LET TIME,TIME-1}
     {IF TIME<0}{LET TIME,23}


     {LET D_T,(DAY+TIME/24)+.0001}
     {CALC}~
     {SUB_CALL}
     {SUB_RESA_S}
     {SUB_RESA_R}
     {SUB_RESB_S}
     {SUB_RESB_R}
     {SUB_RESC_S}
     {SUB_RESC_R}
     {SUB_RESC_D}
     {SUB_DEM_2}
     {SUB_RESD_S}
     {SUB_RESD_R}
     {SUB_RESD_D}
     {INDICATE_READY}
```

POSITION TABLE

Hour	d.h	Position
0	21	0
1	21.041	14
2	21.083	28
3	21.125	42
4	21.166	56
5	21.208	70
6	21.25	84
7	21.291	98
8	21.333	112
9	21.375	126
10	21.416	140
11	21.458	154
12	21.5	168
13	21.541	182
14	21.583	196
15	21.625	210
16	21.666	224
17	21.708	238
18	21.75	252
19	21.791	266
20	21.833	280
21	21.875	294
22	21.916	308
23	0.0416	14

Table B-2 (Continued)

```
          0 0.0833     28
          1  0.125     42
          .      .      .
          .      .      .
          .      .      .
         23 31.958   3682

SUB_CALL       {OPEN CALL.DAT,R}
               {SETPOS POSITION}
               {READLN V12}
               {READLN V13}
                    .
                    .
                    .
               {READLN V59}
               {CALC}~
               {CLOSE}
               {RETURN}

SUB_RESA_S     {OPEN RESA-S.DAT,R}
               {SETPOS POSITION}
               {READLN W12}
               {READLN W13}
                    .
                    .
                    .
               {READLN W59}
               {CALC}~
               {CLOSE}
               {RETURN}

SUB_RESA_R     {OPEN RESA-R.DAT,R}
               {SETPOS POSITION}
               {READLN X12}
               {READLN X13}
                    .
                    .
                    .
               {READLN X59}
               {CALC}~
               {CLOSE}
               {RETURN}

SUB_RESB_S     {OPEN RESB-S.DAT,R}
               {SETPOS POSITION}
               {READLN Y12}
               {READLN Y13}
                    .
                    .
                    .
               {READLN Y59}
               {CALC}~
               {CLOSE}
               {RETURN}
```

Table B-2 (Continued)

```
SUB_RESB_R     {OPEN RESB-R.DAT,R}
               {SETPOS POSITION}
               {READLN Z12}
               {READLN Z13}
                    .
                    .
                    .
               {READLN Z59}
               {CALC}~
               {CLOSE}
               {RETURN}

SUB_RESC_S     {OPEN RESC-S.DAT,R}
               {SETPOS POSITION}
               {READLN AA12}
               {READLN AA13}
                    .
                    .
                    .
               {READLN AA59}
               {CALC}~
               {CLOSE}
               {RETURN}

SUB_RESC_R     {OPEN RESC-R.DAT,R}
               {SETPOS POSITION}
               {READLN AC12}
               {READLN AC13}
                    .
                    .
                    .
               {READLN AC59}
               {CALC}~
               {CLOSE}
               {RETURN}

SUB_RESC_D     {OPEN DEM-1.DAT,R}
               {SETPOS POSITION}
               {READLN AB12}
               {READLN AB13}
                    .
                    .
                    .
               {READLN AB59}
               {CALC}~
               {CLOSE}
               {RETURN}

SUB_DEM_2      {OPEN DEM-2.DAT,R}
               {SETPOS POSITION}
               {READLN AD12}
               {READLN AD13}
                    .
                    .
                    .
```

Table B-2 (Continued)

```
                {READLN AD59}
                {CALC}~
                {CLOSE}
                {RETURN}

SUB_RESD_S      {OPEN RESD-S.DAT,R}
                {SETPOS POSITION}
                {READLN AE12}
                {READLN AE13}
                     .
                     .
                     .
                {READLN AE59}
                {CALC}~
                {CLOSE}
                {RETURN}

SUB_RESD_R      {OPEN RESD-R.DAT,R}
                {SETPOS POSITION}
                {READLN AG12}
                {READLN AG13}
                     .
                     .
                     .
                {READLN AG59}
                {CALC}~
                {CLOSE}
                 {RETURN}

SUB_RESD_D      {OPEN DEM-3.DAT,R}
                {SETPOS POSITION}
                {READLN AF12}
                {READLN AF13}
                     .
                     .
                     .
                {READLN AF59}
                {CALC}~
                {CLOSE}
                {RETURN}
```

Table B-3

Program STORAGE RIGHTS ACCOUNTING

```
\R      {INDICATE RES}
        {WINDOWSOFF}
        {PANELOFF}
        /CAN47..AN51~AP47..AP51~
        {LET ANSO,"N"}
        {GETLABEL "IS RESERVOIR A FILLED (Y or N)? ",ANSO}
        {IF ANSO="Y"}{LET AP47,2000}
        {LET ANSO,"N"}
        {GETLABEL "IS RESERVOIR B FIRST FILLED (Y or N)? ",ANSO}
        {IF ANSO="Y"}{LET AP48,2000}
        {LET ANSO,"N"}
        {GETLABEL "IS RESERVOIR B SECOND FILLED (Y or N)? ",ANSO}
        {IF ANSO="Y"}{LET AP49,2000}
        {LET ANSO,"N"}
        {GETLABEL "IS RESERVOIR C FILLED (Y or N)? ",ANSO}
        {IF ANSO="Y"}{LET AP50,2000}
        {LET ANSO,"N"}
        {GETLABEL "IS RESERVOIR D FILLED (Y or N)? ",ANSO}
        {IF ANSO="Y"}{LET AP51,2000}
        {LET ANSO,"N"}
        {INDICATE READY}
```

Table B-4

Decision Support System List Of Variables

VARIABLE	CELL
ANS	EH9
ANS0	AN70
A_EX	EH100
B_EX	EH101
CALL	FG22
CONV	AP14
COUNTER	G13
C_EX	EH102
DAY	G11
DEM_1	FG14
DEM_2	FG16
DEM_3	FG21
DIV1_MAX	AQ27
DIV2_MAX	AQ28
DIV3_MAX	AQ29
DONE	EK54
D_T	G14
EVAP_A	AP35
EVAP_B	AP36
EVAP_C	AP37
EVAP_D	AP38
EXMENU	EK118
GRAPHS	EK52
HOUR_INC	G10
L2_D	AP18
LA-D	AP15
LB-C	AP16
LC-2	AP17
LOOP	Q15
MF2_D	AP30
NOW	G17
POSITION	G15
RESAMAX	AQ19
RESAMIN	AR19
RESA_EXI	FG34
RESA_EXO	FJ34
RESA_INF	FG6
RESA_MAX_OUT	AQ23
RESA_OUT	FG7
RESBMAX	AQ20
RESBMIN	AR20
RESB_EXI	FG35
RESB_EXO	FJ35
RESB_INF	FG9
RESB_MAX_OUT	AQ24
RESB_OUT	FG10

Table B-4 (Continued)

RESCMAX	AQ21
RESCMIN	AR21
RESC_EXI	FG36
RESC_EXO	FJ36
RESC_INF	FG12
RESC_MAX_OUT	AQ25
RESC_OUT	FG13
RESDMAX	AQ22
RESDMIN	AR22
RESD_EXI	FG37
RESD_EXO	FJ37
RESD_INF	FG19
RESD_MAX_OUT	AQ26
RESD_OUT	FG20
START	EK13
SUB_CALL	K35
SUB_DEM_2	W91
SUB_RESA_R	K147
SUB_RESA_S	K91
SUB_RESB_R	Q35
SUB_RESB_S	K203
SUB_RESC_D	Q203
SUB_RESC_R	Q147
SUB_RESC_S	Q91
SUB_RESD_D	Z91
SUB_RESD_R	W203
SUB_RESD_S	W147
SUGGEST	EK97
TIME	G12
TODAY	G16
TOPMENU	EK60
\0	Q8
\E	EK110
\I	I8
\O	EK8
\R	AQ70
\S	Q8

APPENDIX C

CASE STUDY DECISION SUPPORT SYSTEM SECTIONS

Table C-1 (Part 1)

Case Study Real-Time Data Table For Day=24 and Time=12

DAY	T	RIVER CALL	RES A STOR	RES A RIVER	RES B STOR	RES B RIVER
-2	0	1898.00	50044.00	27.00	34530.04	422.49
	1	1898.00	50044.97	27.00	34512.55	422.49
	2	1898.00	50045.94	27.00	34495.05	422.49
	3	1898.00	50046.91	27.00	34476.42	422.49
	4	1898.00	50047.94	27.00	34456.64	465.66
	5	1898.00	50049.39	27.00	34435.34	459.50
	6	1898.00	50050.88	27.00	34412.90	459.50
	7	1898.00	50052.49	27.00	34389.70	459.50
	8	1898.00	50054.18	27.00	34366.12	459.50
	9	1898.00	50056.04	27.00	34341.78	459.50
	10	1898.00	50058.04	27.00	34317.44	459.50
	11	1898.00	50060.04	27.00	34292.72	459.50
	12	1885.00	50061.50	29.00	34273.78	429.54
	13	1885.00	50062.93	29.00	34255.14	429.54
	14	1885.00	50064.32	29.00	34236.20	429.54
	15	1885.00	50065.68	29.00	34217.56	429.54
	16	1885.00	50067.01	29.00	34198.91	429.54
	17	1885.00	50068.31	29.00	34180.26	429.54
	18	1885.00	50069.57	29.00	34162.20	429.54
	19	1885.00	50070.80	29.00	34144.14	429.54
	20	1885.00	50072.00	29.00	34126.08	429.54
	21	1885.00	50073.21	29.00	34107.43	429.54
	22	1885.00	50074.47	29.00	34088.49	429.54
	23	1885.00	50075.73	29.00	34068.39	465.09
-1	0	1885.00	50076.96	29.00	34048.00	462.21
	1	1885.00	50078.19	29.00	34026.44	462.21
	2	1885.00	50079.48	29.00	34004.00	465.09
	3	1885.00	50080.82	29.00	33980.99	418.00
	4	1885.00	50082.24	29.00	33957.68	418.00
	5	1885.00	50083.80	29.00	33934.67	418.00
	6	1885.00	50085.47	29.00	33911.36	418.00
	7	1885.00	50087.31	29.00	33887.76	418.00
	8	1885.00	50089.27	29.00	33864.16	418.00
	9	1885.00	50091.35	29.00	33840.56	418.00
	10	1885.00	50093.43	29.00	33816.38	418.00
	11	1885.00	50095.50	29.00	33792.78	418.00
	12	1870.00	50097.07	32.00	33771.74	431.83
	13	1870.00	50098.61	32.00	33750.96	431.83
	14	1870.00	50100.12	32.00	33730.44	431.83
	15	1870.00	50101.57	32.00	33709.92	431.83
	16	1870.00	50102.99	32.00	33689.91	431.83
	17	1870.00	50104.35	32.00	33669.39	431.83
	18	1870.00	50105.69	32.00	33648.87	431.83
	19	1870.00	50107.00	32.00	33628.35	431.83
	20	1870.00	50108.28	32.00	33607.31	431.83
	21	1870.00	50109.56	32.00	33585.48	431.83
	22	1870.00	50110.81	32.00	33562.10	431.83
C	23	1870.00	50112.03	32.00	33536.65	431.83

Table C-1 (Part 2)

Case Study Real-Time Data Table For Day=24 and Time=12

DAY	T	RES C STOR	RES C DEM-1	RES C RIVER	DEM-2
-2	0	25011.28	467.00	64.91	0.00
	1	25024.04	467.00	64.91	0.00
	2	25036.70	467.00	64.91	0.00
	3	25049.25	467.00	64.91	0.00
	4	25061.70	467.00	64.91	0.00
	5	25074.46	467.00	64.91	0.00
	6	25087.64	467.00	64.91	0.00
	7	25100.82	467.00	64.91	0.00
	8	25113.99	467.00	64.91	0.00
	9	25127.17	467.00	64.91	0.00
	10	25140.35	467.00	64.91	0.00
	11	25154.17	467.00	64.91	0.00
	12	25174.65	449.00	69.91	0.00
	13	25195.29	449.00	69.91	0.00
	14	25216.09	449.00	69.91	0.00
	15	25236.89	449.00	69.91	0.00
	16	25258.33	449.00	69.91	0.00
	17	25280.57	449.00	69.91	0.00
	18	25303.28	449.00	69.91	0.00
	19	25326.64	449.00	69.91	0.00
	20	25350.48	449.00	69.91	0.00
	21	25374.48	449.00	69.91	0.00
	22	25398.48	449.00	69.91	0.00
	23	25423.43	449.00	69.91	0.00
-1	0	25448.23	449.00	69.91	0.00
	1	25472.87	449.00	69.91	0.00
	2	25497.51	449.00	69.91	0.00
	3	25521.99	449.00	69.91	0.00
	4	25546.31	449.00	69.91	0.00
	5	25570.46	449.00	69.91	0.00
	6	25594.46	449.00	69.91	0.00
	7	25618.14	449.00	69.91	0.00
	8	25641.50	449.00	69.91	0.00
	9	25664.54	449.00	69.91	0.00
	10	25687.25	449.00	69.91	0.00
	11	25709.65	449.00	69.91	0.00
	12	25713.23	471.00	95.25	186.00
	13	25716.84	471.00	95.25	186.00
	14	25720.52	471.00	95.25	186.00
	15	25724.33	471.00	95.25	186.00
	16	25728.24	471.00	95.25	186.00
	17	25732.25	471.00	95.25	186.00
	18	25736.34	471.00	95.25	186.00
	19	25740.47	471.00	95.25	186.00
	20	25744.60	471.00	179.74	186.00
	21	25748.72	471.00	284.20	186.00
	22	25752.82	471.00	341.04	186.00
C	23	25756.88	471.00	391.74	186.00

Table C-1 (Part 3)

Case Study Real-Time Data Table For Day=24 and Time=12

DAY	T	RES D STOR	RES D DEM-3	RES D RIVER
-2	0	39477.14	46.00	221.00
	1	39464.73	46.00	221.00
	2	39452.66	46.00	221.00
	3	39440.60	46.00	221.00
	4	39428.53	46.00	221.00
	5	39416.46	46.00	221.00
	6	39404.40	46.00	221.00
	7	39392.33	46.00	221.00
	8	39380.26	46.00	221.00
	9	39368.20	46.00	221.00
	10	39356.13	46.00	221.00
	11	39344.07	46.00	221.00
	12	39332.49	47.00	218.00
	13	39320.90	47.00	218.00
	14	39309.32	47.00	218.00
	15	39297.74	47.00	218.00
	16	39286.16	47.00	218.00
	17	39274.58	47.00	218.00
	18	39263.00	47.00	218.00
	19	39251.09	47.00	218.00
	20	39239.17	47.00	218.00
	21	39227.26	47.00	218.00
	22	39215.35	47.00	218.00
	23	39203.44	47.00	218.00
-1	0	39191.53	47.00	218.00
	1	39179.61	47.00	218.00
	2	39167.70	47.00	218.00
	3	39155.79	47.00	218.00
	4	39143.88	47.00	218.00
	5	39131.96	47.00	218.00
	6	39120.05	47.00	218.00
	7	39108.14	47.00	218.00
	8	39096.23	47.00	218.00
	9	39084.65	47.00	218.00
	10	39073.07	47.00	218.00
	11	39061.49	47.00	218.00
	12	39060.05	47.00	217.00
	13	39058.61	47.00	217.00
	14	39057.17	47.00	217.00
	15	39055.74	47.00	217.00
	16	39054.30	47.00	217.00
	17	39052.86	47.00	217.00
	18	39051.43	47.00	217.00
	19	39049.99	47.00	217.00
	20	39048.55	47.00	217.00
	21	39047.12	47.00	217.00
	22	39045.64	47.00	217.00
C	23	39041.16	47.00	217.00

Table C-2 (Part 1)

Case Study Natural Flow Section For Day=24 and Time=12

DAY	T	RIVER CALL	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	RESERVOIR A DELTA-S	RESERVOIR A STOR (AF)	RESERVOIR A EVAP.	RESERVOIR A OUTFLOW RIVER
-2	0	1898					50044.0	5.0	27.0
	1	1898	32.5		32.5	0.5	50045.0	5.0	27.0
	2	1898	32.5		32.5	0.5	50045.9	5.0	27.0
	3	1898	32.5		32.5	0.5	50046.9	5.0	27.0
	4	1898	32.5		32.5	0.5	50047.9	5.0	27.0
	5	1898	32.7		32.7	0.7	50049.4	5.0	27.0
	6	1898	32.8		32.8	0.8	50050.9	5.0	27.0
	7	1898	32.8		32.8	0.8	50052.5	5.0	27.0
	8	1898	32.9		32.9	0.9	50054.2	5.0	27.0
	9	1898	32.9		32.9	0.9	50056.0	5.0	27.0
	10	1898	33.0		33.0	1.0	50058.0	5.0	27.0
	11	1898	33.0		33.0	1.0	50060.0	5.0	27.0
	12	1885	34.7		34.7	0.7	50061.5	5.0	29.0
	13	1885	34.7		34.7	0.7	50062.9	5.0	29.0
	14	1885	34.7		34.7	0.7	50064.3	5.0	29.0
	15	1885	34.7		34.7	0.7	50065.7	5.0	29.0
	16	1885	34.7		34.7	0.7	50067.0	5.0	29.0
	17	1885	34.7		34.7	0.7	50068.3	5.0	29.0
	18	1885	34.6		34.6	0.6	50069.6	5.0	29.0
	19	1885	34.6		34.6	0.6	50070.8	5.0	29.0
	20	1885	34.6		34.6	0.6	50072.0	5.0	29.0
	21	1885	34.6		34.6	0.6	50073.2	5.0	29.0
	22	1885	34.6		34.6	0.6	50074.5	5.0	29.0
	23	1885	34.6		34.6	0.6	50075.7	5.0	29.0
-1	0	1885	34.6		34.6	0.6	50077.0	5.0	29.0
	1	1885	34.6		34.6	0.6	50078.2	5.0	29.0
	2	1885	34.7		34.7	0.7	50079.5	5.0	29.0
	3	1885	34.7		34.7	0.7	50080.8	5.0	29.0
	4	1885	34.7		34.7	0.7	50082.2	5.0	29.0
	5	1885	34.8		34.8	0.8	50083.8	5.0	29.0
	6	1885	34.8		34.8	0.8	50085.5	5.0	29.0
	7	1885	34.9		34.9	0.9	50087.3	5.0	29.0
	8	1885	35.0		35.0	1.0	50089.3	5.0	29.0
	9	1885	35.0		35.0	1.0	50091.4	5.0	29.0
	10	1885	35.0		35.0	1.0	50093.4	5.0	29.0
	11	1885	35.0		35.0	1.0	50095.5	5.0	29.0
	12	1870	37.8		37.8	0.8	50097.1	5.0	32.0
	13	1870	37.8		37.8	0.8	50098.6	5.0	32.0
	14	1870	37.8		37.8	0.8	50100.1	5.0	32.0
	15	1870	37.7		37.7	0.7	50101.6	5.0	32.0
	16	1870	37.7		37.7	0.7	50103.0	5.0	32.0
	17	1870	37.7		37.7	0.7	50104.4	5.0	32.0
	18	1870	37.7		37.7	0.7	50105.7	5.0	32.0
	19	1870	37.7		37.7	0.7	50107.0	5.0	32.0
	20	1870	37.6		37.6	0.6	50108.3	5.0	32.0
	21	1870	37.6		37.6	0.6	50109.6	5.0	32.0
	22	1870	37.6		37.6	0.6	50110.8	5.0	32.0
C	23	1870	37.6		37.6	0.6	50112.0	5.0	32.0
F	0	1870	37.6		37.6	0.6	50112.1	5.0	32.0
	1	1870	37.6		37.6	0.6	50112.1	5.0	32.0
	2	1870	37.6		37.6	0.6	50112.2	5.0	32.0

Table C-2 (Part 1) (Continued)

DAY T	RIVER CALL	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	RESERVOIR A DELTA-S	RESERVOIR A STOR (AF)	EVAP.	OUTFLOW RIVER
3	1870	37.6		37.6	0.6	50112.2	5.0	32.0
4	1870	37.6		37.6	0.6	50112.3	5.0	32.0
5	1870	37.6		37.6	0.6	50112.3	5.0	32.0
6	1870	37.6		37.6	0.6	50112.4	5.0	32.0
7	1870	37.6		37.6	0.6	50112.4	5.0	32.0
8	1870	37.6		37.6	0.6	50112.5	5.0	32.0
9	1870	37.6		37.6	0.6	50112.5	5.0	32.0
10	1870	37.6		37.6	0.6	50112.6	5.0	32.0
11	1870	37.6		37.6	0.6	50112.6	5.0	32.0
12	1870	37.6		37.6	0.6	50112.7	5.0	32.0
13	1870	37.6		37.6	0.6	50112.7	5.0	32.0
14	1870	37.6		37.6	0.6	50112.8	5.0	32.0
15	1870	37.6		37.6	0.6	50112.8	5.0	32.0
16	1870	37.6		37.6	0.6	50112.9	5.0	32.0
17	1870	37.6		37.6	0.6	50112.9	5.0	32.0
18	1870	37.6		37.6	0.6	50113.0	5.0	32.0
19	1870	37.6		37.6	0.6	50113.0	5.0	32.0
20	1870	37.6		37.6	0.6	50113.1	5.0	32.0
21	1870	37.6		37.6	0.6	50113.1	5.0	32.0
22	1870	37.6		37.6	0.6	50113.2	5.0	32.0
23	1870	37.6		37.6	0.6	50113.3	5.0	32.0

Table C-2 (Part 2)

Case Study Natural Flow Section For Day=24 and Time=12

RESERVOIR B

DAY	T	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	DELTA-S	STOR (AF)	EVAP.	OUTFLOW RIVER
-2	0					34530.0	3.0	422.5
	1	416.7		416.7	-8.8	34512.6	3.0	422.5
	2	416.7		416.7	-8.8	34495.1	3.0	422.5
	3	416.1		416.1	-9.4	34476.4	3.0	422.5
	4	458.7		458.7	-10.0	34456.6	3.0	465.7
	5	451.8		451.8	-10.7	34435.3	3.0	459.5
	6	451.2		451.2	-11.3	34412.9	3.0	459.5
	7	450.8		450.8	-11.7	34389.7	3.0	459.5
	8	450.6		450.6	-11.9	34366.1	3.0	459.5
	9	450.2		450.2	-12.3	34341.8	3.0	459.5
	10	450.2		450.2	-12.3	34317.4	3.0	459.5
	11	450.0		450.0	-12.5	34292.7	3.0	459.5
	12	423.0		423.0	-9.5	34273.8	3.0	429.5
	13	423.1		423.1	-9.4	34255.1	3.0	429.5
	14	423.0		423.0	-9.5	34236.2	3.0	429.5
	15	423.1		423.1	-9.4	34217.6	3.0	429.5
	16	423.1		423.1	-9.4	34198.9	3.0	429.5
	17	423.1		423.1	-9.4	34180.3	3.0	429.5
	18	423.4		423.4	-9.1	34162.2	3.0	429.5
	19	423.4		423.4	-9.1	34144.1	3.0	429.5
	20	423.4		423.4	-9.1	34126.1	3.0	429.5
	21	423.1		423.1	-9.4	34107.4	3.0	429.5
	22	423.0		423.0	-9.5	34088.5	3.0	429.5
	23	458.0		458.0	-10.1	34068.4	3.0	465.1
-1	0	454.9		454.9	-10.3	34048.0	3.0	462.2
	1	454.3		454.3	-10.9	34026.4	3.0	462.2
	2	456.8		456.8	-11.3	34004.0	3.0	465.1
	3	409.4		409.4	-11.6	33981.0	3.0	418.0
	4	409.2		409.2	-11.8	33957.7	3.0	418.0
	5	409.4		409.4	-11.6	33934.7	3.0	418.0
	6	409.2		409.2	-11.8	33911.4	3.0	418.0
	7	409.1		409.1	-11.9	33887.8	3.0	418.0
	8	409.1		409.1	-11.9	33864.2	3.0	418.0
	9	409.1		409.1	-11.9	33840.6	3.0	418.0
	10	408.8		408.8	-12.2	33816.4	3.0	418.0
	11	409.1		409.1	-11.9	33792.8	3.0	418.0
	12	424.2		424.2	-10.6	33771.7	3.0	431.8
	13	424.4		424.4	-10.5	33751.0	3.0	431.8
	14	424.5		424.5	-10.3	33730.4	3.0	431.8
	15	424.5		424.5	-10.3	33709.9	3.0	431.8
	16	424.7		424.7	-10.1	33689.9	3.0	431.8
	17	424.5		424.5	-10.3	33669.4	3.0	431.8
	18	424.5		424.5	-10.3	33648.9	3.0	431.8
	19	424.5		424.5	-10.3	33628.4	3.0	431.8
	20	424.2		424.2	-10.6	33607.3	3.0	431.8
	21	423.8		423.8	-11.0	33585.5	3.0	431.8
	22	423.0		423.0	-11.8	33562.1	3.0	431.8
C	23	422.0		422.0	-12.8	33536.7	3.0	431.8
F	0	422.0		422.0	-12.8	33535.6	3.0	431.8
	1	422.0		422.0	-12.8	33534.5	3.0	431.8
	2	422.0		422.0	-12.8	33533.5	3.0	431.8

Table C-2 (Part 2)(Continued)

RESERVOIR B

DAY T	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	DELTA-S	STOR (AF)	EVAP.	OUTFLOW RIVER
3	422.0		422.0	-12.8	33532.4	3.0	431.8
4	422.0		422.0	-12.8	33531.3	3.0	431.8
5	422.0		422.0	-12.8	33530.3	3.0	431.8
6	422.0		422.0	-12.8	33529.2	3.0	431.8
7	422.0		422.0	-12.8	33528.2	3.0	431.8
8	422.0		422.0	-12.8	33527.1	3.0	431.8
9	422.0		422.0	-12.8	33526.0	3.0	431.8
10	422.0		422.0	-12.8	33525.0	3.0	431.8
11	422.0		422.0	-12.8	33523.9	3.0	431.8
12	422.0		422.0	-12.8	33522.9	3.0	431.8
13	422.0		422.0	-12.8	33521.8	3.0	431.8
14	422.0		422.0	-12.8	33520.7	3.0	431.8
15	422.0		422.0	-12.8	33519.7	3.0	431.8
16	422.0		422.0	-12.8	33518.6	3.0	431.8
17	422.0		422.0	-12.8	33517.6	3.0	431.8
18	422.0		422.0	-12.8	33516.5	3.0	431.8
19	422.0		422.0	-12.8	33515.4	3.0	431.8
20	422.0		422.0	-12.8	33514.4	3.0	431.8
21	422.0		422.0	-12.8	33513.3	3.0	431.8
22	422.0		422.0	-12.8	33512.3	3.0	431.8
23	422.0		422.0	-12.8	33511.2	3.0	431.8

Table C-2 (Part 3)

Case Study Natural Flow Section For Day=24 and Time=12

RESERVOIR C

DAY	T	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	DELTA-S	STOR	EVAP.	OUTFLOW DEM-1	OUTFLOW RIVER
-2	0					25011.3	6.0	467.0	64.9
	1					25024.0	6.0	467.0	64.9
	2					25036.7	6.0	467.0	64.9
	3					25049.3	6.0	467.0	64.9
	4					25061.7	6.0	467.0	64.9
	5					25074.5	6.0	467.0	64.9
	6					25087.6	6.0	467.0	64.9
	7					25100.8	6.0	467.0	64.9
	8					25114.0	6.0	467.0	64.9
	9					25127.2	6.0	467.0	64.9
	10					25140.4	6.0	467.0	64.9
	11					25154.2	6.0	467.0	64.9
	12	535.2	411.9	123.3	10.3	25174.7	6.0	449.0	69.9
	13	535.3	411.9	123.4	10.4	25195.3	6.0	449.0	69.9
	14	535.4	411.9	123.5	10.5	25216.1	6.0	449.0	69.9
	15	535.4	411.9	123.5	10.5	25236.9	6.0	449.0	69.9
	16	535.7	454.0	81.7	10.8	25258.3	6.0	449.0	69.9
	17	536.1	448.0	88.1	11.2	25280.6	6.0	449.0	69.9
	18	536.4	448.0	88.3	11.4	25303.3	6.0	449.0	69.9
	19	536.7	448.0	88.7	11.8	25326.6	6.0	449.0	69.9
	20	536.9	448.0	88.9	12.0	25350.5	6.0	449.0	69.9
	21	537.0	448.0	89.0	12.1	25374.5	6.0	449.0	69.9
	22	537.0	448.0	89.0	12.1	25398.5	6.0	449.0	69.9
	23	537.5	448.0	89.5	12.6	25423.4	6.0	449.0	69.9
-1	0	537.4	418.8	118.6	12.5	25448.2	6.0	449.0	69.9
	1	537.3	418.8	118.5	12.4	25472.9	6.0	449.0	69.9
	2	537.3	418.8	118.5	12.4	25497.5	6.0	449.0	69.9
	3	537.3	418.8	118.5	12.3	25522.0	6.0	449.0	69.9
	4	537.2	418.8	118.4	12.3	25546.3	6.0	449.0	69.9
	5	537.1	418.8	118.3	12.2	25570.5	6.0	449.0	69.9
	6	537.0	418.8	118.2	12.1	25594.5	6.0	449.0	69.9
	7	536.8	418.8	118.0	11.9	25618.1	6.0	449.0	69.9
	8	536.7	418.8	117.9	11.8	25641.5	6.0	449.0	69.9
	9	536.5	418.8	117.7	11.6	25664.5	6.0	449.0	69.9
	10	536.4	418.8	117.6	11.4	25687.3	6.0	449.0	69.9
	11	536.2	453.5	82.7	11.3	25709.7	6.0	449.0	69.9
	12	574.1	450.7	123.4	1.8	25713.2	6.0	471.0	95.3
	13	574.1	450.7	123.4	1.8	25716.8	6.0	471.0	95.3
	14	574.1	453.5	120.6	1.9	25720.5	6.0	471.0	95.3
	15	574.2	407.6	166.6	1.9	25724.3	6.0	471.0	95.3
	16	574.2	407.6	166.7	2.0	25728.2	6.0	471.0	95.3
	17	574.3	407.6	166.7	2.0	25732.3	6.0	471.0	95.3
	18	574.3	407.6	166.8	2.1	25736.3	6.0	471.0	95.3
	19	574.3	407.6	166.8	2.1	25740.5	6.0	471.0	95.3
	20	658.8	407.6	251.3	2.1	25744.6	6.0	471.0	179.7
	21	763.3	407.6	355.7	2.1	25748.7	6.0	471.0	284.2
	22	820.1	407.6	412.6	2.1	25752.8	6.0	471.0	341.0
C	23	870.8	407.6	463.2	2.0	25756.9	6.0	471.0	391.7
F	0	884.3	421.0	463.2	15.5	25758.2	6.0	471.0	391.7
	1	884.3	421.0	463.2	15.5	25759.4	6.0	471.0	391.7
	2	884.3	421.0	463.2	15.5	25760.7	6.0	471.0	391.7

Table C-2 (Part 3) (Continued)

RESERVOIR C

DAY T	INFLOW TOTAL	INFLOW UPSTRM	INFLOW NATURAL	DELTA-S	STOR	EVAP.	OUTFLOW DEM-1	OUTFLOW RIVER
3	884.3	421.0	463.2	15.5	25762.0	6.0	471.0	391.7
4	884.3	421.0	463.2	15.5	25763.3	6.0	471.0	391.7
5	884.3	421.0	463.2	15.5	25764.6	6.0	471.0	391.7
6	884.3	421.0	463.2	15.5	25765.9	6.0	471.0	391.7
7	884.3	421.0	463.2	15.5	25767.1	6.0	471.0	391.7
8	884.3	421.0	463.2	15.5	25768.4	6.0	471.0	391.7
9	884.3	421.0	463.2	15.5	25769.7	6.0	471.0	391.7
10	884.3	421.0	463.2	15.5	25771.0	6.0	471.0	391.7
11	884.3	421.0	463.2	15.5	25772.3	6.0	471.0	391.7
12	884.3	421.0	463.2	15.5	25773.6	6.0	471.0	391.7
13	884.3	421.0	463.2	15.5	25774.8	6.0	471.0	391.7
14	884.3	421.0	463.2	15.5	25776.1	6.0	471.0	391.7
15	884.3	421.0	463.2	15.5	25777.4	6.0	471.0	391.7
16	884.3	421.0	463.2	15.5	25778.7	6.0	471.0	391.7
17	884.3	421.0	463.2	15.5	25780.0	6.0	471.0	391.7
18	884.3	421.0	463.2	15.5	25781.3	6.0	471.0	391.7
19	884.3	421.0	463.2	15.5	25782.6	6.0	471.0	391.7
20	884.3	421.0	463.2	15.5	25783.8	6.0	471.0	391.7
21	884.3	421.0	463.2	15.5	25785.1	6.0	471.0	391.7
22	884.3	421.0	463.2	15.5	25786.4	6.0	471.0	391.7
23	884.3	421.0	463.2	15.5	25787.7	6.0	471.0	391.7

Table C-2 (Part 4)

Case Study Natural Flow Section For Day=24 and Time=12

DAY	T	ABOVE FLOW	DEMAND DEM-2	BELOW FLOW
-2	0		0.0	
	1		0.0	
	2		0.0	
	3		0.0	
	4		0.0	
	5		0.0	
	6		0.0	
	7		0.0	
	8		0.0	
	9		0.0	
	10		0.0	
	11		0.0	
	12		0.0	
	13		0.0	
	14		0.0	
	15		0.0	
	16	68.9	0.0	68.9
	17	68.9	0.0	68.9
	18	68.9	0.0	68.9
	19	68.9	0.0	68.9
	20	68.9	0.0	68.9
	21	68.9	0.0	68.9
	22	68.9	0.0	68.9
	23	68.9	0.0	68.9
-1	0	68.9	0.0	68.9
	1	68.9	0.0	68.9
	2	68.9	0.0	68.9
	3	68.9	0.0	68.9
	4	68.9	0.0	68.9
	5	68.9	0.0	68.9
	6	68.9	0.0	68.9
	7	68.9	0.0	68.9
	8	68.9	0.0	68.9
	9	68.9	0.0	68.9
	10	68.9	0.0	68.9
	11	68.9	0.0	68.9
	12	68.9	186.0	0.0
	13	68.9	186.0	0.0
	14	68.9	186.0	0.0
	15	68.9	186.0	0.0
	16	93.8	186.0	0.0
	17	93.8	186.0	0.0
	18	93.8	186.0	0.0
	19	93.8	186.0	0.0
	20	93.8	186.0	0.0
	21	93.8	186.0	0.0
	22	93.8	186.0	0.0
C	23	93.8	186.0	0.0
F	0	177.0	186.0	0.0
	1	279.9	186.0	93.9
	2	335.9	186.0	149.9

Table C-2 (Part 4) (Continued)

DAY T	ABOVE FLOW	DEMAND DEM-2	BELOW FLOW
3	385.9	186.0	199.9
4	385.9	186.0	199.9
5	385.9	186.0	199.9
6	385.9	186.0	199.9
7	385.9	186.0	199.9
8	385.9	186.0	199.9
9	385.9	186.0	199.9
10	385.9	186.0	199.9
11	385.9	186.0	199.9
12	385.9	186.0	199.9
13	385.9	186.0	199.9
14	385.9	186.0	199.9
15	385.9	186.0	199.9
16	385.9	186.0	199.9
17	385.9	186.0	199.9
18	385.9	186.0	199.9
19	385.9	186.0	199.9
20	385.9	186.0	199.9
21	385.9	186.0	199.9
22	385.9	186.0	199.9
23	385.9	186.0	199.9

Table C-2 (Part 5)

Case Study Natural Flow Section For Day=24 and Time=12

RESERVOIR D

DAY	T	INFLOW TOTAL	UPSTRM	NATURAL	DELTA-S	STOR	EVAP.	OUTFLOW DEM-3	RIVER
-2	0					39477.1	11.0	46.0	221.0
	1					39464.7	11.0	46.0	221.0
	2					39452.7	11.0	46.0	221.0
	3					39440.6	11.0	46.0	221.0
	4					39428.5	11.0	46.0	221.0
	5					39416.5	11.0	46.0	221.0
	6					39404.4	11.0	46.0	221.0
	7					39392.3	11.0	46.0	221.0
	8					39380.3	11.0	46.0	221.0
	9					39368.2	11.0	46.0	221.0
	10					39356.1	11.0	46.0	221.0
	11					39344.1	11.0	46.0	221.0
	12					39332.5	11.0	47.0	218.0
	13					39320.9	11.0	47.0	218.0
	14					39309.3	11.0	47.0	218.0
	15					39297.7	11.0	47.0	218.0
	16					39286.2	11.0	47.0	218.0
	17					39274.6	11.0	47.0	218.0
	18	270.2	68.2	202.0	-5.8	39263.0	11.0	47.0	218.0
	19	270.0	68.2	201.8	-6.0	39251.1	11.0	47.0	218.0
	20	270.0	68.2	201.8	-6.0	39239.2	11.0	47.0	218.0
	21	270.0	68.2	201.8	-6.0	39227.3	11.0	47.0	218.0
	22	270.0	68.2	201.8	-6.0	39215.4	11.0	47.0	218.0
	23	270.0	68.2	201.8	-6.0	39203.4	11.0	47.0	218.0
-1	0	270.0	68.2	201.8	-6.0	39191.5	11.0	47.0	218.0
	1	270.0	68.2	201.8	-6.0	39179.6	11.0	47.0	218.0
	2	270.0	68.2	201.8	-6.0	39167.7	11.0	47.0	218.0
	3	270.0	68.2	201.8	-6.0	39155.8	11.0	47.0	218.0
	4	270.0	68.2	201.8	-6.0	39143.9	11.0	47.0	218.0
	5	270.0	68.2	201.8	-6.0	39132.0	11.0	47.0	218.0
	6	270.0	68.2	201.8	-6.0	39120.1	11.0	47.0	218.0
	7	270.0	68.2	201.8	-6.0	39108.1	11.0	47.0	218.0
	8	270.0	68.2	201.8	-6.0	39096.2	11.0	47.0	218.0
	9	270.2	68.2	202.0	-5.8	39084.7	11.0	47.0	218.0
	10	270.2	68.2	202.0	-5.8	39073.1	11.0	47.0	218.0
	11	270.2	68.2	202.0	-5.8	39061.5	11.0	47.0	218.0
	12	274.3	68.2	206.1	-0.7	39060.1	11.0	47.0	217.0
	13	274.3	68.2	206.1	-0.7	39058.6	11.0	47.0	217.0
	14	274.3	0.0	390.2	-0.7	39057.2	11.0	47.0	217.0
	15	274.3	0.0	390.2	-0.7	39055.7	11.0	47.0	217.0
	16	274.3	0.0	390.2	-0.7	39054.3	11.0	47.0	217.0
	17	274.3	0.0	390.2	-0.7	39052.9	11.0	47.0	217.0
	18	274.3	0.0	365.5	-0.7	39051.4	11.0	47.0	217.0
	19	274.3	0.0	365.5	-0.7	39050.0	11.0	47.0	217.0
	20	274.3	0.0	365.5	-0.7	39048.6	11.0	47.0	217.0
	21	274.3	0.0	365.5	-0.7	39047.1	11.0	47.0	217.0
	22	274.3	0.0	365.5	-0.7	39045.6	11.0	47.0	217.0
C	23	272.7	0.0	364.0	-2.3	39041.2	11.0	47.0	217.0
F	0	272.7	0.0	364.0	-2.3	39041.0	11.0	47.0	217.0
	1	272.7	0.0	364.0	-2.3	39040.8	11.0	47.0	217.0
	2	355.1	0.0	364.0	80.1	39047.4	11.0	47.0	217.0

Table C-2 (Part 5) (Continued)

RESERVOIR D

DAY T	INFLOW TOTAL	UPSTRM	NATURAL	DELTA-S	STOR	EVAP.	OUTFLOW DEM-3	RIVER
3	457.0	93.0	364.0	182.0	39062.5	11.0	47.0	217.0
4	512.4	148.4	364.0	237.4	39082.1	11.0	47.0	217.0
5	561.9	197.9	364.0	286.9	39105.8	11.0	47.0	217.0
6	561.9	197.9	364.0	286.9	39129.5	11.0	47.0	217.0
7	561.9	197.9	364.0	286.9	39153.2	11.0	47.0	217.0
8	561.9	197.9	364.0	286.9	39176.9	11.0	47.0	217.0
9	561.9	197.9	364.0	286.9	39200.6	11.0	47.0	217.0
10	561.9	197.9	364.0	286.9	39224.3	11.0	47.0	217.0
11	561.9	197.9	364.0	286.9	39248.0	11.0	47.0	217.0
12	561.9	197.9	364.0	286.9	39271.7	11.0	47.0	217.0
13	561.9	197.9	364.0	286.9	39295.4	11.0	47.0	217.0
14	561.9	197.9	364.0	286.9	39319.1	11.0	47.0	217.0
15	561.9	197.9	364.0	286.9	39342.9	11.0	47.0	217.0
16	561.9	197.9	364.0	286.9	39366.6	11.0	47.0	217.0
17	561.9	197.9	364.0	286.9	39390.3	11.0	47.0	217.0
18	561.9	197.9	364.0	286.9	39414.0	11.0	47.0	217.0
19	561.9	197.9	364.0	286.9	39437.7	11.0	47.0	217.0
20	561.9	197.9	364.0	286.9	39461.4	11.0	47.0	217.0
21	561.9	197.9	364.0	286.9	39485.1	11.0	47.0	217.0
22	561.9	197.9	364.0	286.9	39508.8	11.0	47.0	217.0
23	561.9	197.9	364.0	286.9	39532.5	11.0	47.0	217.0

Table C-3 (Part 1)

Case Study Outflow Hydrograph For Day=24 and Time=12

DAY	T	RESERVOIR A INFLOW	RESERVOIR A RIGHTS (STORG)	RESERVOIR A OUTFLOW	RESERVOIR B INFLOW	RESERVOIR B RIGHTS (STORG)	RESERVOIR B OUTFLOW
-2	0	0.0	0.0	0.0	0.0	0.0	0.0
	1	32.5	0.0	32.5	416.7	416.7	0.0
	2	32.5	0.0	32.5	416.7	416.7	0.0
	3	32.5	0.0	32.5	416.1	416.1	0.0
	4	32.5	0.0	32.5	458.7	458.7	0.0
	5	32.7	0.0	32.7	451.8	451.8	0.0
	6	32.8	0.0	32.8	451.2	451.2	0.0
	7	32.8	0.0	32.8	450.8	450.8	0.0
	8	32.9	0.0	32.9	450.6	450.6	0.0
	9	32.9	0.0	32.9	450.2	450.2	0.0
	10	33.0	0.0	33.0	450.2	450.2	0.0
	11	33.0	0.0	33.0	450.0	450.0	0.0
	12	34.7	0.0	34.7	423.0	0.0	423.0
	13	34.7	0.0	34.7	423.1	0.0	423.1
	14	34.7	0.0	34.7	423.0	0.0	423.0
	15	34.7	0.0	34.7	423.1	0.0	423.1
	16	34.7	0.0	34.7	423.1	0.0	423.1
	17	34.7	0.0	34.7	423.1	0.0	423.1
	18	34.6	0.0	34.6	423.4	0.0	423.4
	19	34.6	0.0	34.6	423.4	0.0	423.4
	20	34.6	0.0	34.6	423.4	0.0	423.4
	21	34.6	0.0	34.6	423.1	0.0	423.1
	22	34.6	0.0	34.6	423.0	0.0	423.0
	23	34.6	0.0	34.6	458.0	0.0	458.0
-1	0	34.6	0.0	34.6	454.9	0.0	454.9
	1	34.6	0.0	34.6	454.3	0.0	454.3
	2	34.7	0.0	34.7	456.8	0.0	456.8
	3	34.7	0.0	34.7	409.4	0.0	409.4
	4	34.7	0.0	34.7	409.2	0.0	409.2
	5	34.8	0.0	34.8	409.4	0.0	409.4
	6	34.8	0.0	34.8	409.2	0.0	409.2
	7	34.9	0.0	34.9	409.1	0.0	409.1
	8	35.0	0.0	35.0	409.1	0.0	409.1
	9	35.0	0.0	35.0	409.1	0.0	409.1
	10	35.0	0.0	35.0	408.8	0.0	408.8
	11	35.0	0.0	35.0	409.1	0.0	409.1
	12	37.8	0.0	37.8	424.2	0.0	424.2
	13	37.8	0.0	37.8	424.4	0.0	424.4
	14	37.8	0.0	37.8	424.5	0.0	424.5
	15	37.7	0.0	37.7	424.5	0.0	424.5
	16	37.7	0.0	37.7	424.7	0.0	424.7
	17	37.7	0.0	37.7	424.5	0.0	424.5
	18	37.7	0.0	37.7	424.5	0.0	424.5
	19	37.7	0.0	37.7	424.5	0.0	424.5
	20	37.6	0.0	37.6	424.2	0.0	424.2
	21	37.6	0.0	37.6	423.8	0.0	423.8
	22	37.6	0.0	37.6	423.0	0.0	423.0
C	23	37.6	0.0	37.6	422.0	0.0	422.0
F	0	37.6	0.0	37.6	422.0	0.0	422.0
	1	37.6	0.0	37.6	422.0	0.0	422.0
	2	37.6	0.0	37.6	422.0	0.0	422.0
	3	37.6	0.0	37.6	422.0	0.0	422.0

Table C-3 (Part 1) (Continued)

DAY T	RESERVOIR A INFLOW	RESERVOIR A RIGHTS (STORG)	RESERVOIR A OUTFLOW	RESERVOIR B INFLOW	RESERVOIR B RIGHTS (STORG)	RESERVOIR B OUTFLOW
4	37.6	0.0	37.6	422.0	0.0	422.0
5	37.6	0.0	37.6	422.0	0.0	422.0
6	37.6	0.0	37.6	422.0	0.0	422.0
7	37.6	0.0	37.6	422.0	0.0	422.0
8	37.6	0.0	37.6	422.0	0.0	422.0
9	37.6	0.0	37.6	422.0	0.0	422.0
10	37.6	0.0	37.6	422.0	0.0	422.0
11	37.6	0.0	37.6	422.0	0.0	422.0
12	37.6	0.0	37.6	422.0	0.0	422.0
13	37.6	0.0	37.6	422.0	0.0	422.0
14	37.6	0.0	37.6	422.0	0.0	422.0
15	37.6	0.0	37.6	422.0	0.0	422.0
16	37.6	0.0	37.6	422.0	0.0	422.0
17	37.6	0.0	37.6	422.0	0.0	422.0
18	37.6	0.0	37.6	422.0	0.0	422.0
19	37.6	0.0	37.6	422.0	0.0	422.0
20	37.6	0.0	37.6	422.0	0.0	422.0
21	37.6	0.0	37.6	422.0	0.0	422.0
22	37.6	0.0	37.6	422.0	0.0	422.0
23	37.6	0.0	37.6	422.0	0.0	422.0

Table C-3 (Part 2)

Case Study Outflow Hydrograph For Day=24 and Time=12

RESERVOIR C

DAY	T	INFLOW	RIGHTS (STORG)	RIGHTS (DEM-1)	REQ'D OUTFLOW	OUTFLOW
-2	0		0.0	132.0	51.3	
	1		0.0	132.0	51.3	
	2		0.0	132.0	51.3	
	3		0.0	132.0	51.3	
	4		0.0	132.0	51.3	
	5		0.0	132.0	51.3	
	6		0.0	132.0	51.3	
	7		0.0	132.0	51.3	
	8		0.0	132.0	51.3	
	9		0.0	132.0	51.3	
	10		0.0	132.0	51.3	
	11		0.0	132.0	51.3	
	12	123.3	0.0	60.0	51.3	114.6
	13	123.4	0.0	60.0	51.3	114.6
	14	123.5	0.0	60.0	51.3	114.7
	15	123.5	0.0	60.0	51.3	114.7
	16	81.7	0.0	60.0	51.3	73.0
	17	88.1	0.0	60.0	51.3	79.4
	18	88.3	0.0	60.0	51.3	79.6
	19	88.7	0.0	60.0	51.3	79.9
	20	88.9	0.0	60.0	51.3	80.2
	21	89.0	0.0	60.0	51.3	80.2
	22	89.0	0.0	60.0	51.3	80.2
	23	89.5	0.0	60.0	51.3	80.7
-1	0	531.0	0.0	60.0	51.3	522.3
	1	531.1	0.0	60.0	51.3	522.3
	2	530.9	0.0	60.0	51.3	522.2
	3	531.0	0.0	60.0	51.3	522.3
	4	530.9	0.0	60.0	51.3	522.2
	5	530.8	0.0	60.0	51.3	522.1
	6	531.1	0.0	60.0	51.3	522.3
	7	530.9	0.0	60.0	51.3	522.1
	8	530.7	0.0	60.0	51.3	522.0
	9	530.3	0.0	60.0	51.3	521.5
	10	530.0	0.0	60.0	51.3	521.2
	11	529.2	0.0	60.0	51.3	520.5
	12	567.0	0.0	28.0	240.0	779.0
	13	566.4	0.0	28.0	240.0	778.4
	14	566.0	0.0	28.0	240.0	778.0
	15	565.8	0.0	28.0	240.0	777.8
	16	565.7	0.0	28.0	240.0	777.7
	17	565.9	0.0	28.0	240.0	777.9
	18	565.8	0.0	28.0	240.0	777.8
	19	565.7	0.0	28.0	240.0	777.7
	20	650.1	0.0	28.0	240.0	862.2
	21	754.6	0.0	28.0	240.0	966.6
	22	811.1	0.0	28.0	240.0	1023.2
C	23	862.1	0.0	28.0	240.0	1074.2
F	0	876.9	0.0	28.0	240.0	1088.9
	1	877.0	0.0	28.0	240.0	1089.0
	2	877.1	0.0	28.0	240.0	1089.1
	3	877.1	0.0	28.0	240.0	1089.1

Table C-3 (Part 2) (Continued)

RESERVOIR C

DAY T	INFLOW	RIGHTS (STORG)	RIGHTS (DEM-1)	REQ'D OUTFLOW	OUTFLOW
4	877.4	0.0	28.0	240.0	1089.4
5	877.1	0.0	28.0	240.0	1089.1
6	877.1	0.0	28.0	240.0	1089.1
7	877.1	0.0	28.0	240.0	1089.1
8	876.9	0.0	28.0	240.0	1088.9
9	876.5	0.0	28.0	240.0	1088.5
10	875.7	0.0	28.0	240.0	1087.7
11	874.7	0.0	28.0	240.0	1086.7
12	874.7	0.0	28.0	240.0	1086.7
13	874.7	0.0	28.0	240.0	1086.7
14	874.7	0.0	28.0	240.0	1086.7
15	874.7	0.0	28.0	240.0	1086.7
16	874.7	0.0	28.0	240.0	1086.7
17	874.7	0.0	28.0	240.0	1086.7
18	874.7	0.0	28.0	240.0	1086.7
19	874.7	0.0	28.0	240.0	1086.7
20	874.7	0.0	28.0	240.0	1086.7
21	874.7	0.0	28.0	240.0	1086.7
22	874.7	0.0	28.0	240.0	1086.7
23	874.7	0.0	28.0	240.0	1086.7

Table C-3 (Part 3)

Case Study Outflow Hydrograph For Day=24 and Time=12

DAY	T	DEMAND ABOVE FLOW	DEMAND DEM-2	DEMAND BELOW FLOW	RESERVOIR D INFLOW	RESERVOIR D RIGHTS (STORG)	RESERVOIR D RIGHTS (DEM-2)	RESERVOIR D OUTFLOW
-2	0		100.0			0.0	45.0	
	1		100.0			0.0	45.0	
	2		100.0			0.0	45.0	
	3		100.0			0.0	45.0	
	4		100.0			0.0	45.0	
	5		100.0			0.0	45.0	
	6		100.0			0.0	45.0	
	7		100.0			0.0	45.0	
	8		100.0			0.0	45.0	
	9		100.0			0.0	45.0	
	10		100.0			0.0	45.0	
	11		100.0			0.0	45.0	
	12		100.0			0.0	45.0	
	13		100.0			0.0	45.0	
	14		100.0			0.0	45.0	
	15		100.0			0.0	45.0	
	16	112.8	100.0	12.8		0.0	45.0	
	17	112.9	100.0	12.9		0.0	45.0	
	18	113.0	100.0	13.0	214.7	0.0	45.0	169.7
	19	113.0	100.0	13.0	214.6	0.0	45.0	169.6
	20	71.9	100.0	0.0	214.7	0.0	45.0	169.7
	21	78.2	100.0	0.0	214.7	0.0	45.0	169.7
	22	78.4	100.0	0.0	174.0	0.0	45.0	129.0
	23	78.7	100.0	0.0	180.2	0.0	45.0	135.2
-1	0	79.0	100.0	0.0	180.4	0.0	45.0	135.4
	1	79.0	100.0	0.0	180.8	0.0	45.0	135.8
	2	79.0	100.0	0.0	181.0	0.0	45.0	136.0
	3	79.5	100.0	0.0	181.1	0.0	45.0	136.1
	4	514.4	100.0	414.4	181.1	0.0	45.0	136.1
	5	514.5	100.0	414.5	181.5	0.0	45.0	136.5
	6	514.4	100.0	414.4	612.1	0.0	45.0	567.1
	7	514.4	100.0	414.4	612.2	0.0	45.0	567.2
	8	514.3	100.0	414.3	612.0	0.0	45.0	567.0
	9	514.3	100.0	414.3	612.3	0.0	45.0	567.3
	10	514.5	100.0	414.5	612.2	0.0	45.0	567.2
	11	514.3	100.0	414.3	612.1	0.0	45.0	567.1
	12	514.2	100.0	414.2	616.4	0.0	45.0	571.4
	13	513.7	100.0	413.7	616.3	0.0	45.0	571.3
	14	513.4	100.0	413.4	800.3	0.0	45.0	755.3
	15	512.7	100.0	412.7	799.8	0.0	45.0	754.8
	16	767.3	100.0	667.3	799.5	0.0	45.0	754.5
	17	766.8	100.0	666.8	798.8	0.0	45.0	753.8
	18	766.4	100.0	666.4	1026.2	0.0	45.0	981.2
	19	766.2	100.0	666.2	1025.6	0.0	45.0	980.6
	20	766.1	100.0	666.1	1025.2	0.0	45.0	980.2
	21	766.3	100.0	666.3	1025.0	0.0	45.0	980.0
	22	766.2	100.0	666.2	1024.9	0.0	45.0	979.9
C	23	766.0	100.0	666.0	1023.6	0.0	45.0	978.6
F	0	849.3	100.0	749.3	1023.5	0.0	45.0	978.5
	1	952.1	100.0	852.1	1023.4	0.0	45.0	978.4
	2	1007.8	100.0	907.8	1105.8	0.0	45.0	1060.8
	3	1058.0	100.0	958.0	1207.6	0.0	45.0	1162.6

Table C-3 (Part 3) (Continued)

DAY T	DEMAND ABOVE FLOW	DEMAND DEM-2	DEMAND BELOW FLOW	RESERVOIR D INFLOW	RESERVOIR D RIGHTS (STORG)	RESERVOIR D RIGHTS (DEM-2)	RESERVOIR D OUTFLOW
4	1072.6	100.0	972.6	1262.8	0.0	45.0	1217.8
5	1072.7	100.0	972.7	1312.5	0.0	45.0	1267.5
6	1072.8	100.0	972.8	1326.8	0.0	45.0	1281.8
7	1072.8	100.0	972.8	1327.0	0.0	45.0	1282.0
8	1073.1	100.0	973.1	1327.1	0.0	45.0	1282.1
9	1072.8	100.0	972.8	1327.1	0.0	45.0	1282.1
10	1072.8	100.0	972.8	1327.3	0.0	45.0	1282.3
11	1072.8	100.0	972.8	1327.1	0.0	45.0	1282.1
12	1072.6	100.0	972.6	1327.1	0.0	45.0	1282.1
13	1072.2	100.0	972.2	1327.1	0.0	45.0	1282.1
14	1071.4	100.0	971.4	1326.8	0.0	45.0	1281.8
15	1070.4	100.0	970.4	1326.5	0.0	45.0	1281.5
16	1070.4	100.0	970.4	1325.7	0.0	45.0	1280.7
17	1070.4	100.0	970.4	1324.7	0.0	45.0	1279.7
18	1070.4	100.0	970.4	1324.7	0.0	45.0	1279.7
19	1070.4	100.0	970.4	1324.7	0.0	45.0	1279.7
20	1070.4	100.0	970.4	1324.7	0.0	45.0	1279.7
21	1070.4	100.0	970.4	1324.7	0.0	45.0	1279.7
22	1070.4	100.0	970.4	1324.7	0.0	45.0	1279.7
23	1070.4	100.0	970.4	1324.7	0.0	45.0	1279.7