WATER MANAGEMENT MODEL FOR FRONT RANGE RIVER BASINS

by

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April 1979

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Colorado State University
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Technical Report No. 16

ACKNOWLEDGEMENT

This technical report describes the development of a simulation model for water planning or management in a Front Range river basin or sub-basin. The application of the model is illustrated by two cases.

Cooling water demands for the Rawhide Power Plant in Larimer County are proposed to be met with reusable foreign water from Fort Collins' sewer effluent. The model examines all options in reservoir storage and stream and river exchanges and selects the optimum combination. Vested water rights are always protected.

The second case is management of water releases from storage in high mountain reservoirs in such a way that vested water rights remain undisturbed, while at the same time instream flow demands are more nearly met.

With the new tool, options can be examined by any water owner who may desire to meet a new pattern of water use--irrigation, municipal, industrial, or a combination of two or more of these together in sequential use programs.

The authors offer sincere thanks to Norman A. Evans, Director, Colorado Water Resources Research Institute, for his thoughtful consultation concerning the direction this research has taken. Thanks are also extended to John W. Neutze, Commissioner, Water District 3, for help in interpreting information obtained from the Colorado Water Data Bank.

Special thanks are afforded E. Bruce Jones, President, and Morton W. Bittinger, Vice President, Resource Consultants, Inc., whose help and patience made the Rawhide Case Study possible, and to William W. Hansen for assistance in initially outlining the case study.

This report is made possible by funding support from the Legislative Council of the Colorado General Assembly. The work leading to this report was also supported in part by funds provided by the U. S. Department of the Interior, Office of Water Research and Technology, as authorized by the Water Resources Research Act of 1964, and pursuant to Grant Agreement No. 14-34-0001-8006.

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The Legislative Council
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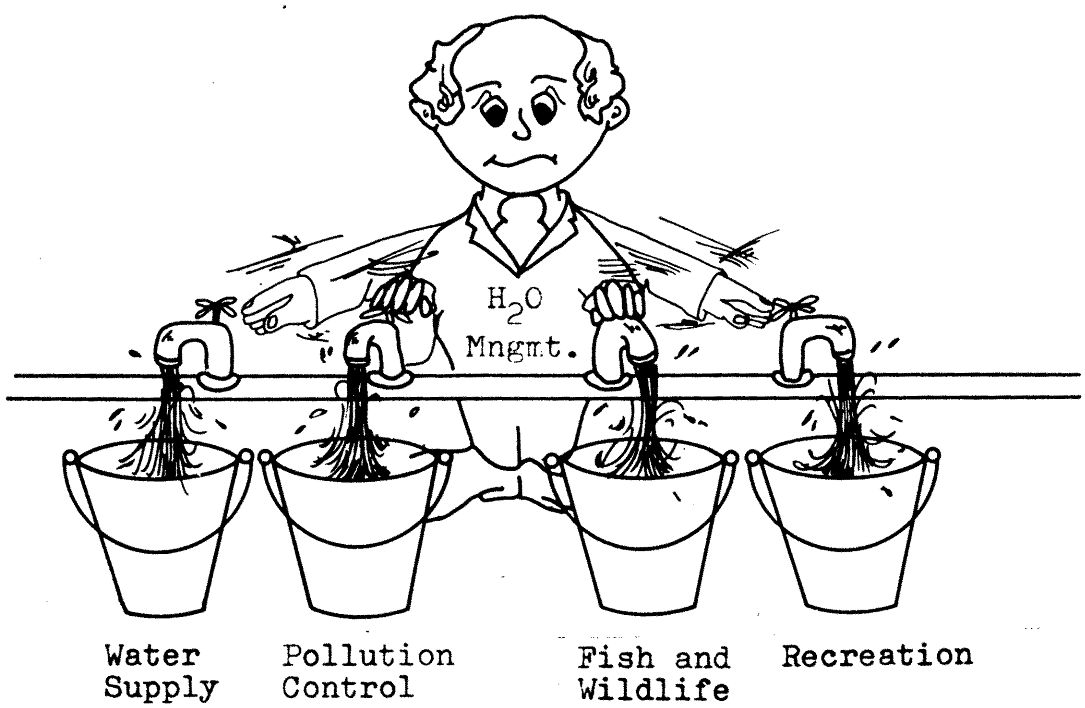
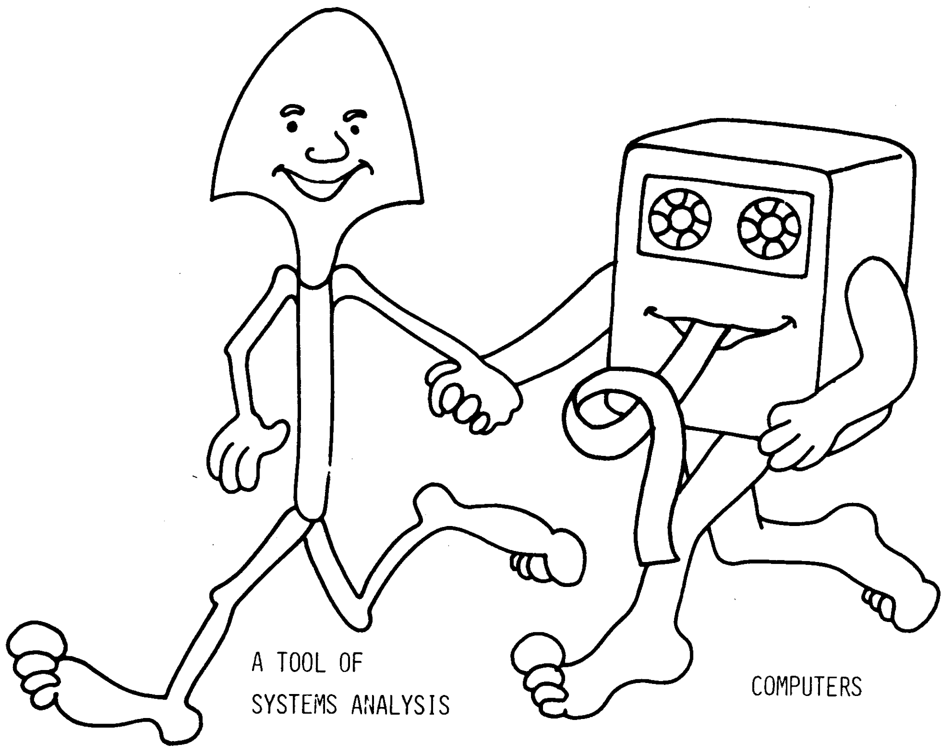
SUMMARY OF RESEARCH RESULTS

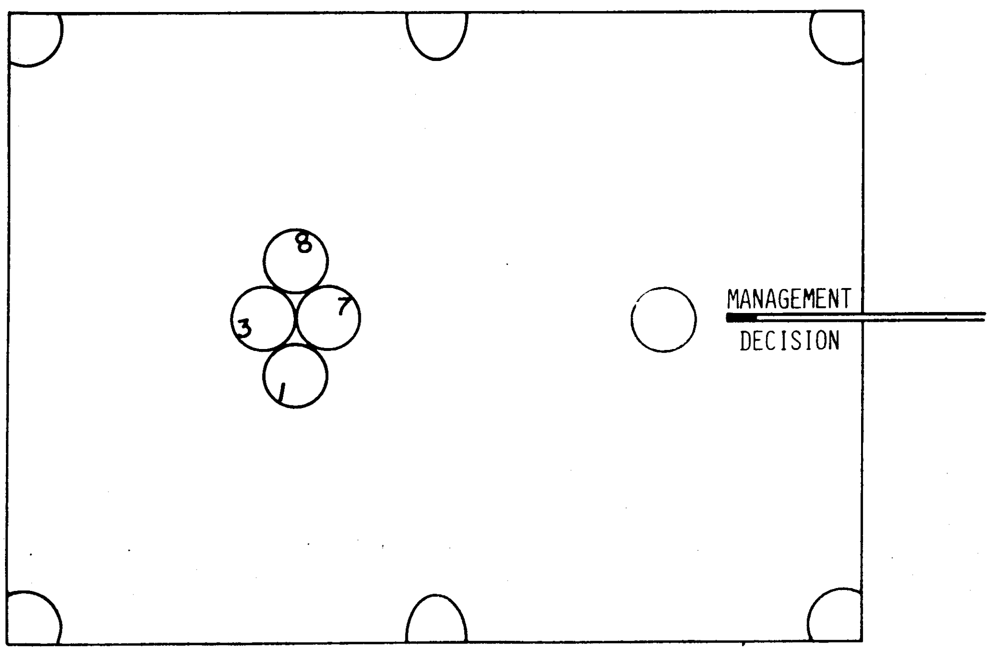
The water supply of Colorado's Front Range is hard pressed to meet ever-increasing demands upon it. The challenge for water managers is to maximize the total beneficial use of our water without injuring the legal rights of individual water users. How do we resolve competitive water demands among municipal, industrial and agricultural uses? How can legitimate instream water requirements related to environmental quality and recreation uses be met? These questions and others pose the dilemma facing public officials and others having planning and management responsibilities and authority.

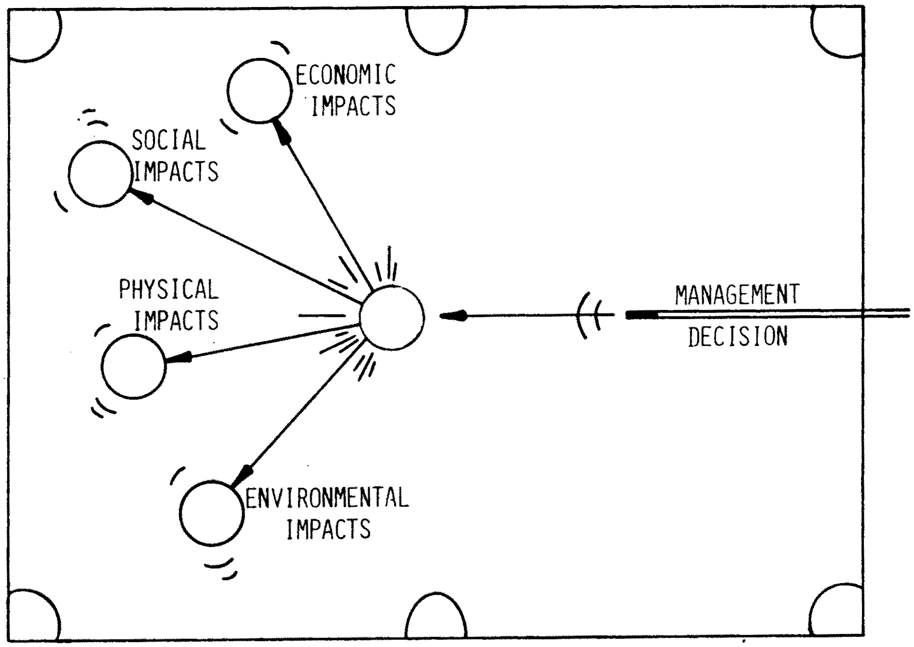


An important tool for analyzing conflicts and trade-offs is simulation. The effectiveness of this tool is directly related to advances in the modern high-speed digital computer. The two really go hand in hand.

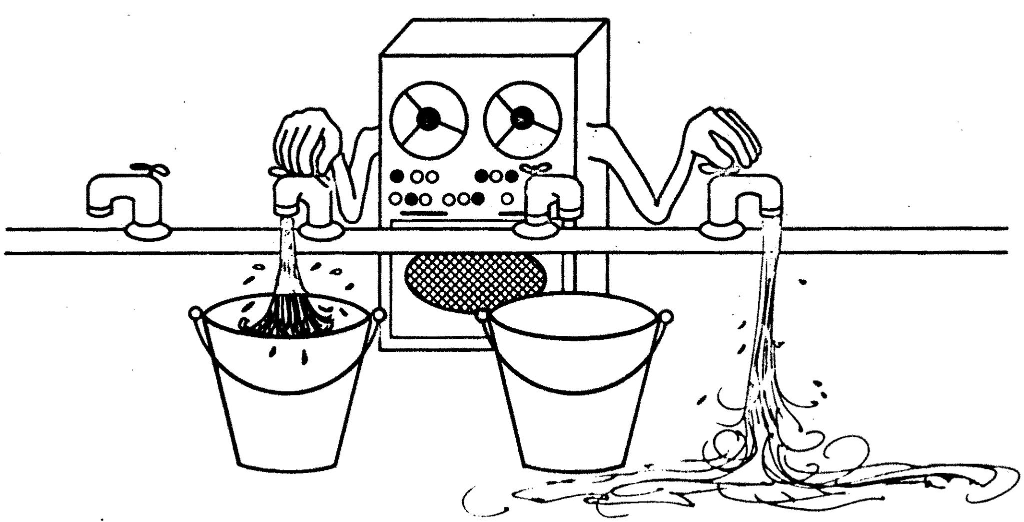


Computer simulation of complex water resource systems gives us a convenient way to quantify some of the important impacts of alternate water management decisions. Computer simulation can help answer *what if* questions and provide decision-makers with important information on the impacts of these decisions.





Obviously, the use of computer simulation must be tempered with the realistic perspective of what it can and cannot do. Computer models can never replace sound judgement, but they can be a tool to enhance it.



Why do we need computer simulation? Because water management problems are growing more and more complex. As an example, Figure S-1 gives a schematic of a portion of the upper Poudre River system. Looking at this we realize that we have to deal with:

1. the physical complexity of interrelated water storage, transport, distribution, treatment, and reuse systems;
2. many possible combinations of reservoir releases which could physically satisfy the final demand;
3. constraints on system operation due to institutional and legal structures governing water rights;
4. the complexity of interaction of surface and groundwater; and
5. potential water quality impacts.

The simulation model that we have synthesized in this project is capable of dealing with all of these problems. The model is based on one that was developed by the Texas Water Development Board, which has been extended and modified in order to make it applicable to the Colorado Front Range.

Two Applications of the Model

The simulation model was used to examine two typical cases in the Front Range. The first case is recreational enhancement of high country storage reservoirs. There are many beautiful high mountain reservoirs that are currently being used for water storage purposes only. Figure S-2 shows Twin Lake reservoir on the South Fork of the Poudre River under severe drawdown conditions. Reservoirs such as these are either closed to the public or are so severely drawn down during the prime recreational season that it is virtually impossible to maintain fisheries or use the reservoirs for recreational purposes. Everyone is aware of the increasing pressures on existing recreational areas as multitudes flock

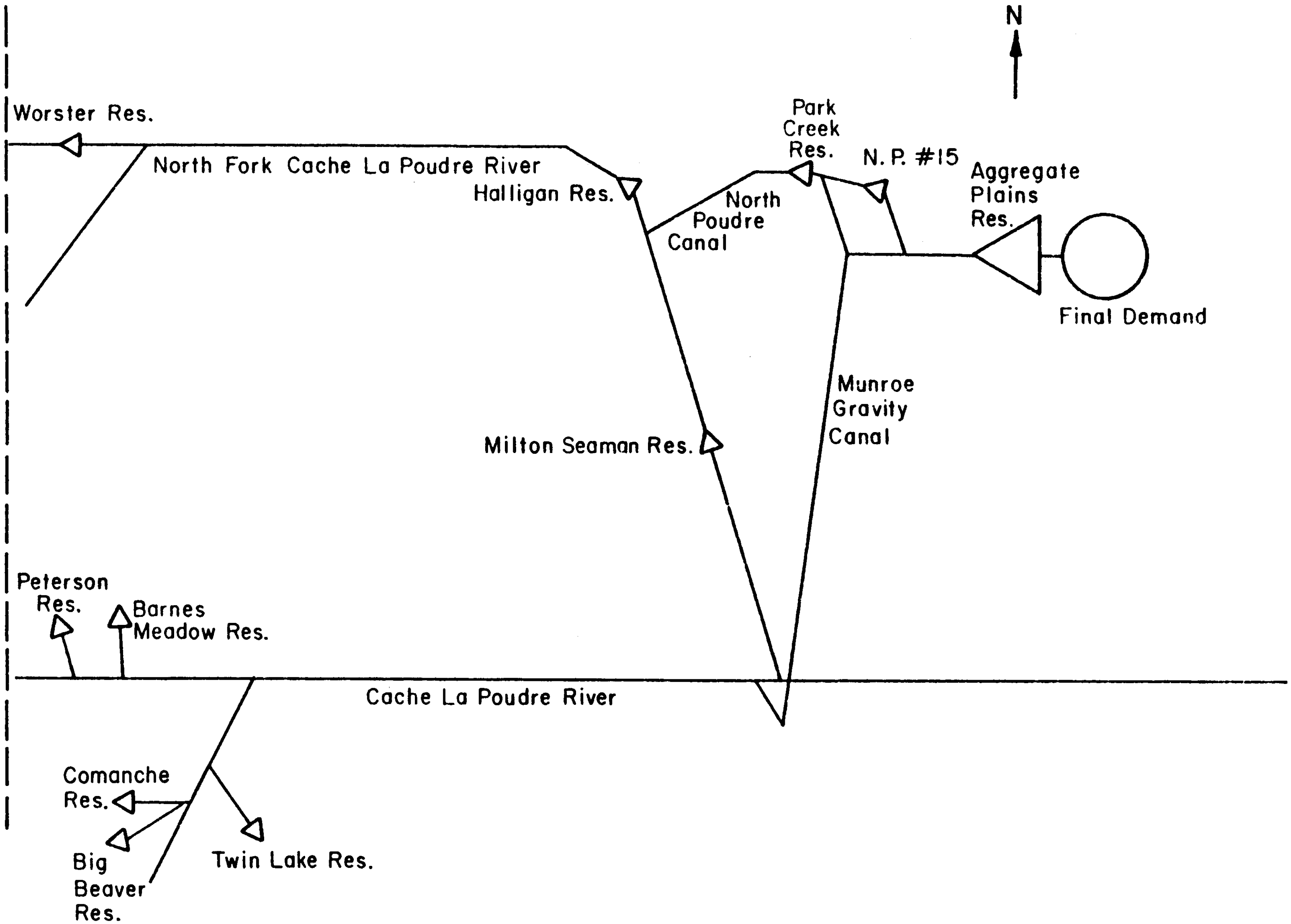


Figure S-1. Schematic of the Upper Poudre River System

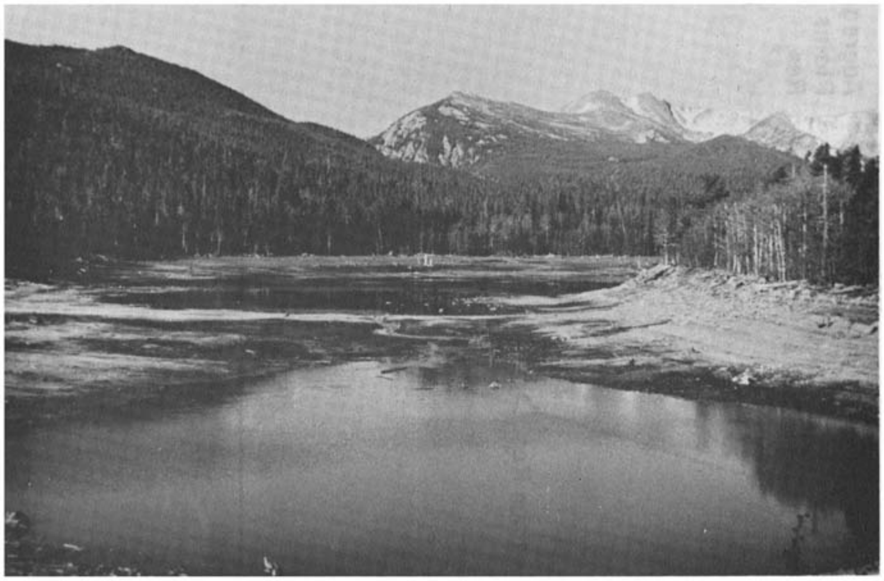


Figure S-2. High Mountain Reservoir in the Upper Poudre River Basin under Severe Drawdown Conditions to the high country during the summer. Some of these high country water supply reservoirs could help relieve that pressure if it could be shown that, under proper control, the primary water supply use of the reservoir would not be damaged.

On the other hand, there are reservoirs at lower elevation on the plains which are much less attractive for recreation. Could these be drawn down first or more severely so that water could remain stored in the high mountain reservoirs for a longer time? Of course, during periods of drought the high mountain reservoirs would necessarily be exhausted as the situation dictated.

Based on input from recreation resource specialists, fishery biologists and water law experts, those reservoirs in the Poudre subbasin that would be most conducive to recreation were identified. A computer simulation of the upper Poudre River basin was then conducted which showed that indeed it was possible to stabilize water levels in these selected reservoirs without any injury to downstream water rights. Figure S-3 displays a graph of Twin Lakes reservoir which shows the historical drawdown pattern compared with what would have been possible during 1972-1975 without injury to downstream water right holders.

For this particular case enhanced recreation would be possible, but in other cases this was not possible.

Instream requirements can easily be considered in the simulation by simply specifying the minimum river flow and observing what effect that has on reservoir levels for recreation while meeting the legal water rights. The computer simulation model can show what tradeoffs need to be made so that the right balance of high mountain and plains reservoir releases can be found.

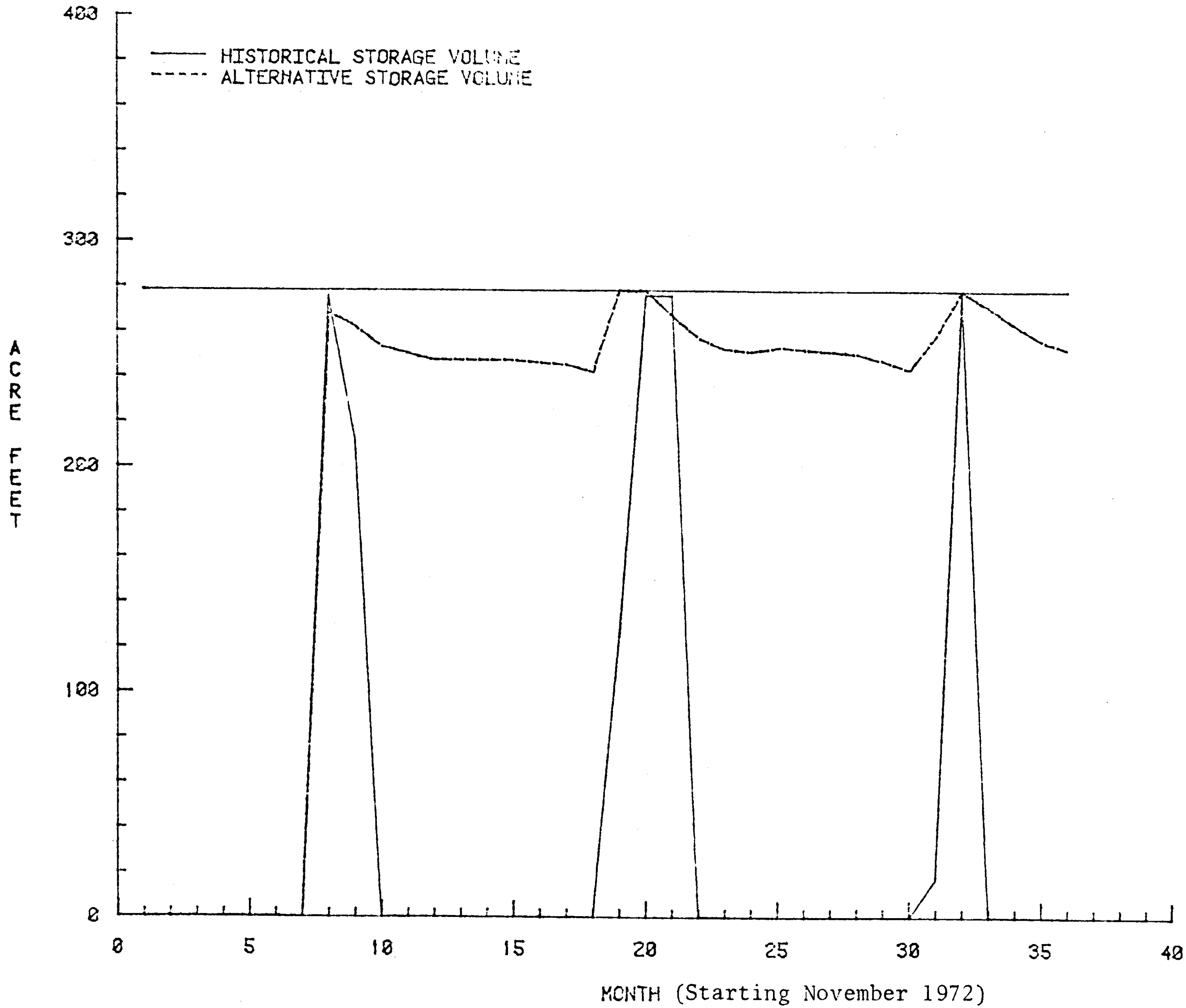


Figure S-3. Twin Lake Reservoir (High Mountain)

An extremely important step in simulation is model calibration. This is where we develop trust in our simulation model to reasonably duplicate the behavior of the real system. If the computer simulation predicts river flows which reasonably match historical records, then we can be confident that it will correctly predict the impacts of various management options. The advantage of a simulation model is that the options can be tested without the expense and disruption of actually trying to implement the management alternative to see how it performs. Figure S-4 shows that this computer simulation model matched historical gaged records of river flow very closely.

The second application is the problem of water supply for the 230 megawatt Rawhide Power Plant north of Fort Collins, Colorado. The PRPA is currently negotiating with the City of Fort Collins and Water Supply and Storage Company to purchase water for a planned 13,000 acre foot cooling pond. This water would be delivered through a series of exchanges based upon effluent from the Fort Collins waste treatment plant. This effluent can be reused by the City because it is imported water from Joe Wright reservoir and Long Draw reservoir. The goal of this simulation model, of course, is to make sure that the cooling pond can be filled and maintained without injury to other water right holders.

The simulation results show that, assuming repetition of the same hydrological sequences that were experienced in the past 25 years, the pond can be filled by 1985 without injury to downstream users, as shown in Figure S-5. Further, the model tells us how to operate the supply system of exchanges to keep the pond full thereafter. An advantage of the computer simulation is that we can test various hydrological sequences that could possibly occur in the future, including extensive drought sequences, and predict how the supply would be affected.

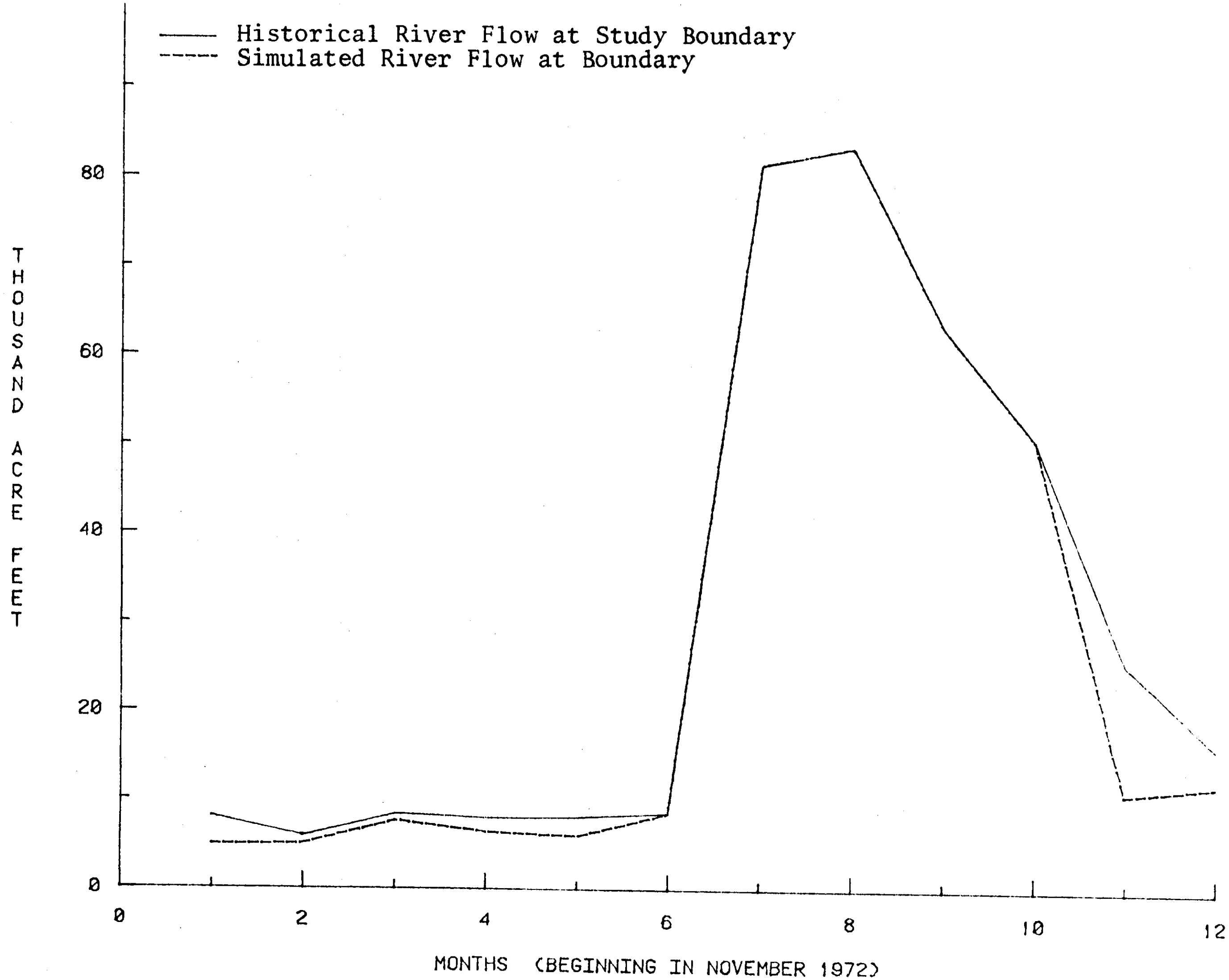


Figure S-4. Computer Simulation Flows vs. Historical Flows after Model Calibration

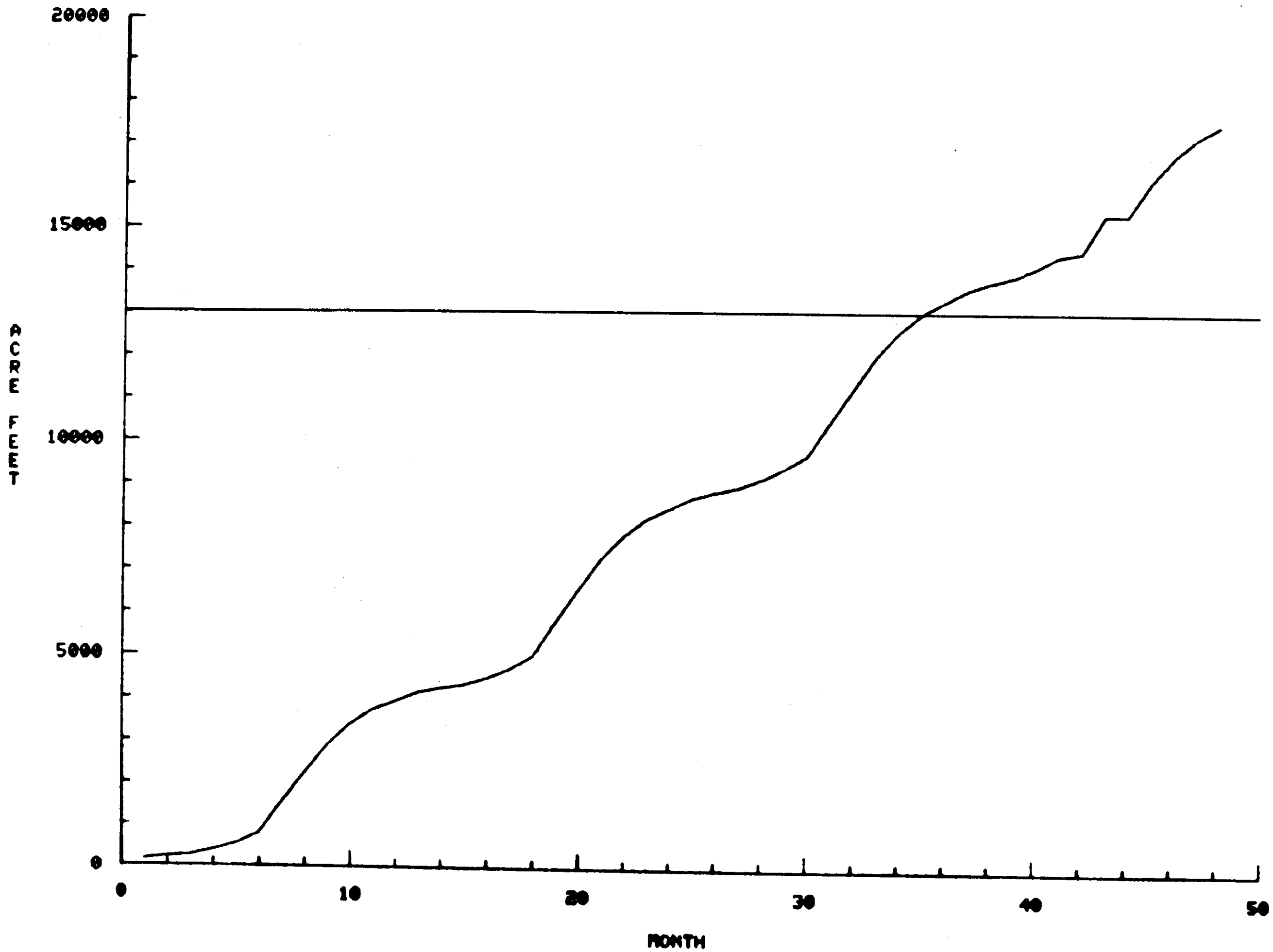


Figure S-5. Accumulated Reusable Effluent Deliverable to Rawhide Cooling Pond

The simulations are based on monthly volume data. While monthly data are good for planning purposes, they must be changed to daily volumes of water in order to be used by the river basin commissioners for their detailed daily river operations. This is easily done.

Another important objective of this research is to design a computer simulation model which can be used by individuals in water planning and management who know little or nothing about the computer and how to program it. That is, we are trying to design "conversational" programs where a user can sit at a terminal and be instructed by the computer as to what data need to be input. Figure S-6 gives an example of how the simulation model queries the user to obtain necessary data in proper sequence.

These two applications are intended to show the flexibility and usefulness of this new simulation model that has been developed for Colorado's Front Range river subbasins. The Poudre River subbasin was selected for this developmental work, but the model can be formulated equally well for any of the other subbasins. It represents a significant technological advance and provides an invaluable tool for both planning and management uses. Private sector water managers and public water policy makers ought to be able to make profitable use of this new product of research.

```
FOR RESERVOIR NO. 1;
      ENTER: UP TO 8 CHARACTER NAME? RES 1
      ENTER: NETWORK NODE NO.? 1
      ENTER: MAXIMUM CAPACITY? 5000
      ENTER: MINIMUM CAPACITY? 0
      ENTER: STARTING VOLUME ? 0
FOR RESERVOIR NO. 2;
      ENTER: UP TO 8 CHARACTER NAME? RES 2
      ENTER: NETWORK NODE NO.? 2
      ENTER: MAXIMUM CAPACITY? 8000
      ENTER: MINIMUM CAPACITY? 0
      ENTER: STARTING VOLUME ? 2000
FOR JUNCTION NO. 3;
      ENTER: UP TO 8 CHARACTER NAME? NODE 3
      ENTER: NETWORK NODE NO.? 3
FOR JUNCTION NO. 4;
      ENTER: UP TO 8 CHARACTER NAME? NODE 4
      ENTER: NETWORK NODE NO.? 4
```

Figure S-6. Example of Conversational Computer Interaction

Chapter I

INTRODUCTION

A. PROBLEM STATEMENT

Colorado water resources planners and policy makers are facing increasingly challenging problems concerning allocation of the State's water resources. Water is of critical economic, social, and environmental importance to Colorado. Unfortunately, only a finite raw water supply is made available each year from spring snowmelt in the Colorado Rockies. A portion of this annual supply is captured in a complex network of interconnected storage reservoirs, and then allocated for satisfaction of various competing demands within Colorado, as well as interstate compact agreements for flows leaving the State.

In years past, when demands placed on raw water supply were lower and the uses less diverse, this system of water collection and distribution was largely self-administering under the Colorado Appropriation Doctrine. In recent years, however, the Colorado front range has been experiencing a steadily growing pressure on available water resources. This pressure originates from both direct and indirect influences on demand. For example, expanding urban centers require more water for domestic and industrial uses, which often is obtained through transfer of irrigation water rights. Irrigated agriculture is still the leading water user in Colorado, and greater attention should focus on more efficient use of water diverted for agriculture. In-stream uses of water resources, as well as water-related recreation, are given an increasingly higher priority. Finally, the prospect of large-scale energy development in Colorado presents perhaps the greatest challenge when considering some of the projected water requirements for this use. Such energy related endeavors will not only have considerable economic importance in Colorado, but national implications as well. Rationally, one can only expect that competition for waters originating in Colorado will greatly intensify.

A complex institutional framework has evolved within which this supply/demand cycle operates. Increased demand, however, has led to over-appropriation of waters along the front range. Additional diversion of western slope waters is being scrutinized, but this source is limited. In an effort to extend the supply as far as possible, formal arrangements for the reuse or secondary use of water are being pursued, although in practice such a policy has been in existence since the first diversion of water for irrigation purposes. Of the water applied to croplands, a certain portion not consumptively used finds its way back to the stream for subsequent reuse. As the irrigation season progresses, the amount of *return flow* accruing to the river can be significant, as is the case with the Cache la Poudre River Basin in north central Colorado.

State water resources planners and managers are commissioned with the responsibility of developing water policy whereby the above circumstances, along with others, are taken into consideration in creating an atmosphere of consistency and equitability in water administration. Certain *tools* are available to the planner/manager which enable him to carry out complex analyses of alternate management strategies otherwise impossible within a reasonable time frame. Hopefully, these *tools*, such as computer models and data management systems, provide the means to test the impact of various water resources policies with reasonable accuracy before these policies are actually implemented.

Many such computer models exist for evaluating a wide range of water resources problems. A common complaint is that there is too much emphasis on proliferation of new models, and not enough on use of good models already available for actual water planning and management. Unfortunately, and for a variety of reasons, many of these models have not been employed to any large degree. Possibly because of lack of consideration of the requirements and needs of those who will use the model, many efforts at model implementation have failed. Perhaps modelers have set their sights too low in terms of the individuals they envision to be the ultimate users of their models. Through modern techniques of interactive and conversational programming, the door may be opened to a whole new class of potential users heretofore not reached; and indeed, a class of users more directly involved in water policy decisions.

B. STUDY OBJECTIVES

The primary objective of this study is to synthesize a computerized river basin planning model from currently *existing* models. The model is to be used in an interactive, conversational manner such that familiarity with computer programming is not a requirement for its use. The intended purpose of this model is to provide state and local water resources planners and managers with a comprehensible and useful tool for evaluating the impacts of alternate water management policies on water availabilities at various critical points in a basin.

The model should be capable of simulating a complex river basin system by monthly time increments over a multiyear planning horizon. Monthly increments are preferred because they usually provide sufficient accuracy for considering a planning horizon of several years, and are compatible with available data.

The model should also have the ability to consider the institutional framework within which the physical system functions. This extension beyond typical water accounting models makes it especially useful for studying systems where existing or planned priorities among various beneficial uses of water must be carefully preserved.

The *ideal* model might have the following capabilities:

1. A Conversationally-based input-output structure for ease of use by planner/managers.

2. Simulation of the water storage, transport, and distribution morphology of the system, including reservoir operation in monthly time increments. The model should have some optimizing capability with respect to reservoir operations, since searching among a myriad of possible operating rules can be extremely time consuming.

3. Consideration of non-beneficial consumptive losses such as reservoir evaporation and channel losses.

4. Inclusion of the quantifiable aspects of institutional structures governing stream diversion, water storage, and exchange.

5. Consideration of consumptive water use from municipal and agricultural sectors. This can range in detail from evapotranspiration prediction using climatic factors, to estimates of demand patterns from historical records.

6. Inclusion of possible imports to the basin from adjacent river basins.

7. Options for using rainfall-runoff watershed models to predict virgin streamflows, or simpler methods that allow estimation of virgin flows from river gage records.

8. Flexibility to consider energy consuming pumped pipeline flow as well as gravity channel flow.

9. Reasonably accurate consideration of irrigation return flows and stream-aquifer interaction. Again, there is much latitude for model detail here.

10. Well documented model calibration procedures, with careful attention to balancing model detail with available data and study goals. Automated calibration should be used wherever feasible.

A particular component not included in most available river basin models is this so-called quasi-optimizing capability for determining operating policies. The term *quasi* is used because the model is basically a simulation model, but can optimally regulate reservoir releases within a given time period, according to whatever flexibility is available.

Again, this list of model components, capabilities, and options represent the ideal model. To the authors' knowledge, no available model has as yet fulfilled this ideal. However, the components of such a model *are* available, and simply need to be properly synthesized. The purpose of this study has been to make substantial progress in this direction, and then demonstrate the capabilities of the model by attacking an actual water management problem at the river basin level which is an important contemporary issue, and work closely with those directly involved in it.

For this current model development study, all of the above model capabilities have been included, except for #5 and #7. Demand is currently estimated from historical patterns only, and there is no attempt to predict actual evapotranspiration values. Virgin flows and irrigation return flows are estimated from historical stream gage records, using known diversion data. Also, more work is needed toward achievement of goal #10. It is hoped that further continuing research will eventually fill these gaps.

Even though a model may include all of the above capabilities, the model results are only as valid as the available data. Often, such a model can be useful for helping to pinpoint data needs when inadequate data are available for its verification. However, the model results must be viewed with a high degree of skepticism. Unfortunately, this situation is the rule rather than the exception. Therefore, we must reiterate that the model is only a tool to provide guidelines and indications. Decisions must ultimately be launched from a foundation of good judgement, common sense, and clear facts.

The following report documents the structure of the model and then presents an indepth analysis of two diverse case studies which serve to demonstrate its capabilities.

One particular river basin, the upper Cache la Poudre, is used throughout this study. The first case looks at the possibility of changing the historical operating rules for certain reservoirs in the basin so as to enhance recreation potential in the high mountain reservoirs without injuring other water users. The second case is related to energy development and analyzes the problem of filling and maintaining the cooling pond for the proposed Rawhide Power Plant north of Ft. Collins, again, without damage to other water users in the basin.

Chapter II

RIVER BASIN SIMULATION MODEL

A. BACKGROUND TO MODEL SELECTION

Selection of the base or core model was contingent upon certain objective criteria including:

1. flexibility in application
2. ability to simulate a large system over a period of several years.
3. detail of model output provided
4. input data requirements
5. rapid-access computer core memory requirements
6. central processor time required for a typical run.

In addition to these qualifications, an intuitive feel of those aspects of the model which would provide a measure of trust for the user was considered. The program methodology must not be so obscure as to prohibit even a rudimentary understanding of its assumptions, approximations, capabilities, and limitations.

Several computer models were reviewed (e.g., Evans, 1971; Thaemert, 1976; U.S. Army Corps of Engineers, HEC 3, 1974; Ribbens, 1973; Jønch-Clausen, 1978; Handen, 1974; Schreiber, 1976; Maknoon, 1977; Texas Water Development Board, Systems Engineering Division, 1972). Of these models, program SIMYLD (Texas Water Development Board, Systems Engineering Division, 1972) was selected as most appropriate, based on the above criteria. A detailed review of these models can be found in Shafer and Labadie (1977). Several modifications were subsequently made to the SIMYLD model to better reflect certain features of Colorado river basins, particularly front range basins. Also, an interactive conversational data file organization computer code was written.

B. PROGRAM DESCRIPTION

The computer program SIMYLD employs the *Out-of-Kilter-Method* (OKM) (Bazaraa and Jarvis, 1977; Clasen, 1968; Durbin and Kroenke, 1967; Ford and Fulkerson, 1962; Fulkerson, 1961) to minimize the total *cost* of flows in a network of interconnected reservoirs, river reaches, pump canals, and gravity flow canals. SIMYLD is capable of indirectly preserving water diversion and storage priorities established by water rights in the basin. This capability is achieved through a ranking procedure which is translated into *pseudo-costs* of water transfer. Using this ranking procedure, SIMYLD apportions available water for storage in various reservoirs and diversion of flow from the river according to their priority. If pump canals are included, the actual energy costs can be used. Otherwise, the costs used in the model are for ranking priorities for water use only. Other more informal institutional structures, such as water exchange agreements (i.e., the diversion of water out of priority as long as downstream senior direct flow rights are satisfied through reservoir releases) can be included.

C. PROGRAM METHODOLOGY

The underlying principle of the operation of SIMYLD is that most physical water resources systems can be represented as capacitated flow networks. The *real* components of the system are represented in the network as nodes (storage and non-storage points) and links (canals, pipelines, river reaches). Reservoirs, demand points, canal diversions, and river confluences are represented as nodes, while river reaches, canals, and closed conduits are node to node linkages. In order to consider demands, inflows, and desired reservoir operating rules, several artificial nodes and linkages must be created. These additional nodes and linkages also insure the circulating nature of the network, which is a necessary condition if the Out-of-Kilter Algorithm is to be employed. Figure 1 presents a simplified diagram of key components (real and artificial) of SIMYLD.

Basic assumptions associated with the model include:

1. All storage nodes and linkages must be bounded from above and below (i.e., minimum and maximum storages and flows must be given).

2. Each linkage must be unidirectional with respect to flow.

3. All inflows, (including irrigation return flows), demands and losses (except channel losses) must occur at nodes.

4. Several import nodes can be designated for water entering the system from across system boundaries.

5. Each reservoir can be designated as a spill node for losses from the system proper.

6. Spills from the system are the most expensive type of water transfer, in the sense that the model seeks to minimize unnecessary spill.

7. Irrigation return flows must be estimated during model calibration and then correlated with average, wet and dry years for use in management runs.

8. Channel losses (bed seepage) are computed as a percentage of total flow in any particular reach on a monthly basis.

Reservoir operating policies are provided by the user as desired in-storage volume for each reservoir at the end of each month throughout the simulation period. Two differing modes of entry are available. The first mode on entry involves simply programming the desired ending storage as a percentage of reservoir capacity for each month of the simulation period. The second method is one of establishing three separate operating rules corresponding to three different hydrologic

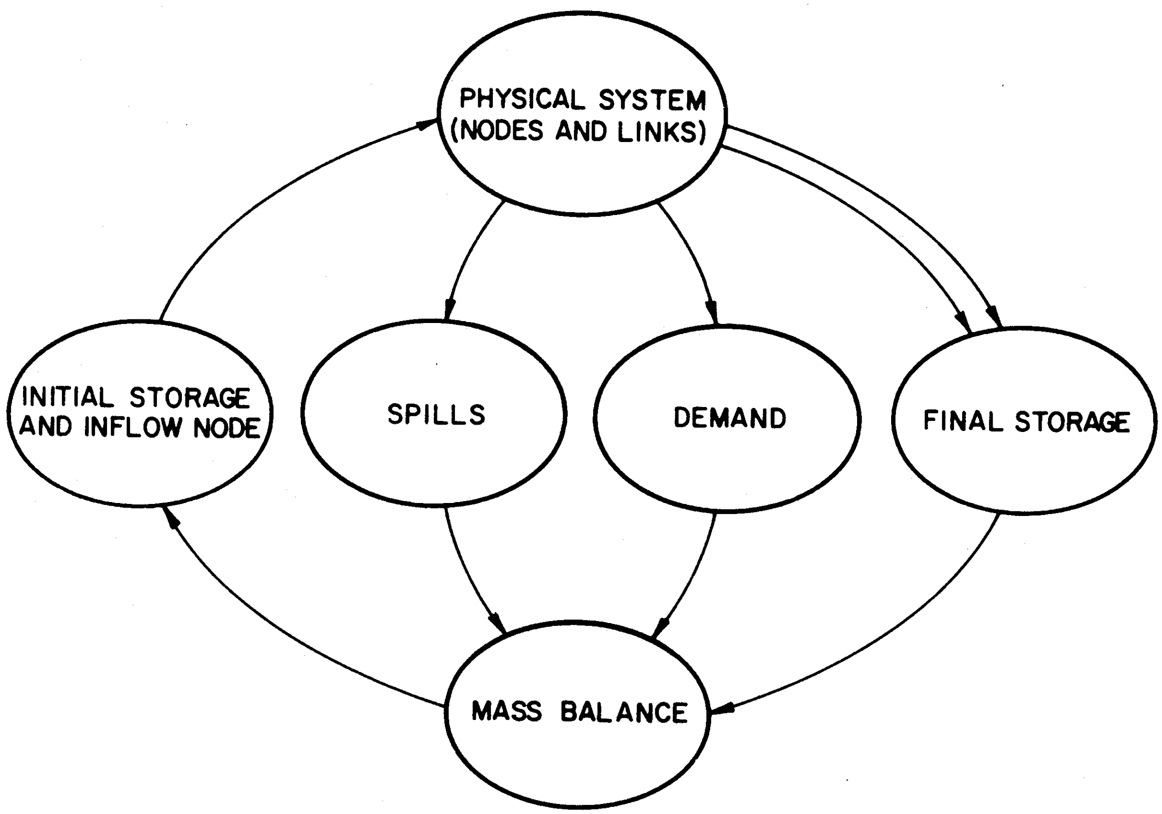


Figure 1. Link Configuration - Program SIMYLD

states calculated monthly by the model. These states are based on parameters input by the user. Associated with each of these states (Average, Dry, Wet) is a corresponding set of operating rules with ranking priorities. These hydrologic states are computed by selecting all or some of the reservoirs within the system and performing an analysis based on inflows and current volume of water in storage.

Within the confines of mass balance throughout the network, SIMYLD sequentially solves the following linear optimization problem via the Out-of-Kilter Method.

$$\text{minimize} \sum_{i=1}^{N} \sum_{j=1}^{N} w_{ij} q_{ij} \tag{1}$$

subject to:

$$\sum_{i=1}^{N} q_{ij} - \sum_{i=1}^{N} q_{ji} = 0 \; ; \qquad j = 1,\ldots,N \tag{2}$$

$$\ell_{ij} \leq q_{ij} \leq u_{ij} \; ; \qquad \text{for} \quad i,j = 1,\ldots,N \tag{3}$$

$$\ell_{ij} \geq 0$$

where:

q_{ij} = integer valued flow from node i to node j

w_{ij} = weighting or priority factor per unit of flow from node i to node j

ℓ_{ij} = lower bound on flow in the linkage connecting node i to node j

u_{ij} = upper bound on flow in the linkage connecting node i to node j

Equation 2 insures that the flow into any one node is equal to the flow out of that node. The OKM is an extremely efficient primal-dual simplex algorithm that takes advantage of the special structure of a network-type problem.

The reasoning behind labeling SIMYLD as a *quasi-optimization* model stems from the fact that the global optimum is not actively sought. The network flow problem is solved successively time period by time period.

D. MODIFICATIONS TO SIMLYD: PROGRAM MODSIM

Expanded Capability: The modified code MODSIM has expanded capabilities over the original code. The new code can consider up to 40 nodes (storage and non-storage) and 50 links. Also, the new code will perform monthly analyses for a planning period as long as 20 years.

Output Options: The original code output results in three reports: (1) echo print of input data, (2) monthly summaries of results for each year of analysis, and (3) a summary report (quite lengthy, for long planning periods) by node and year. The user now has the option of suppressing any or all of these reports according to his computational objectives.

Area-Capacity Points: Eighteen data points relating reservoir capacity to reservoir surface area were originally required. This meant that zero filled entries must be made if, for instance, data were such that only 12 pairs of points were available. This leads to computing inefficiency and increased input-output time to read the remaining pairs of zeros. The revised code will accept a variable number of area-capacity data points.

Import Nodes: SIMYLD, as originally constructed, would consider only one import node (i.e., flow originating outside of the network). MODSIM includes a variable number of possible import nodes.

Target Storage Levels: SIMYLD originally computed a hydrologic state on a monthly basis by considering current reservoir storage levels and inflows. As mentioned earlier, three possible states exist: Wet, Average and Dry. Based on the calculated state, a corresponding operating policy for the month is selected. In this way, for a long period of analysis only, three target storage levels can be used for any one reservoir. However, the option has been included in the model whereby the user can input separate target storage levels for each reservoir and for each month throughout the entire analysis.

Varying Priorities: In the original code, only three differing priorities for any node (storage and/or demand) can be included. Again, these priorities correspond to Wet, Average, or Dry conditions calculated by the model. An additional option has been included which enables the user to input a separate priority for any node for each year of the analysis. This expanded capability means that instead of a maximum of three priorities associated with a Wet, Average, or Dry state, a varying priority can be input for each year of analysis.

Channel Losses: A significant addition to SIMYLD is the capability of including channel losses directly. A loss coefficient for each reach must be included in data input. This coefficient represents the fraction of the total flow in the link that would be lost. For example, some of the earthlined irrigation ditches in the Cache la Poudre basin have estimated loss coefficients from 20 percent to 33 percent of the flow in the ditch. Subroutine CHANLS was added to the code to calculate the expected channel losses for each month. The procedure is as follows: first, network flows are solved via the

Out-of-Kilter Algorithm with no losses. Initially, all flows are set to zero, or the lower bound if greater than zero. The losses in each link are computed by multiplying the loss coefficient by the calculated flows. This loss is established as a demand at the downstream node for each link. The Out-of-Kilter Algorithm is solved again with the increased demand. However, the initial feasible solution is now set equal to the previous optimum solution. New link losses are then computed and the procedure is repeated until acceptable convergence has occurred.

Local File Creation: In order to facilitate additional analyses, all link flows (every link, every month) are read onto local files which can be saved as a permanent file and read by subsequent user developed programs for further analyses.

E. DATA REQUIREMENTS

The model inputs include the following:

1. physical description of system to be modeled
2. operational criteria for the reservoirs
3. unregulated inflows to the river basin (i.e., virgin flows)
4. imported water
5. demands for municipal, industrial, and agricultural water
6. evaporation rates from the reservoirs
7. channel loss coefficients for each reach.

As was previously mentioned, a conversational interactive data management program has been developed which eliminates many programming problems such as tedious sessions of data formatting and computer card punching. Also, the interactive nature of data entry greatly facilitates rapid analysis of alternate management schemes. To reduce central core requirements, inflows, demands, and evaporation rates must be input via externally (to MODSIM) created binary files. An example of the conversational input format is shown in Figure 2 for a simple system as shown in Figure 3.

F. OUTPUT OF RESULTS

The user has the option of obtaining one or more of three possible output reports. These include:

1. an echo of the input data pertaining to the system configuration
2. a detailed *monthly* report providing entire nodal and linkage conditions such as:

   a. storage node:

      initial storage
      unregulated inflows
      upstream spills
      demand
      surface area
      evaporation loss
      downstream spills
      shortages
      system loss
      water pumped into a node
      water pumped from a node
      end-of-month storage (actual)
      end-of-month storage (desired)

   b. non-storage node:

      demand
      shortage
      unregulated inflow

   c. linkage:

      total monthly flow as volume
      loss as volume
      yearly mean flow

3. node by node annual summaries for the entire simulation period plus maximum linkage flows and simulation period average flows in each linkage.

```
************************ P R O G R A M   O R G A N I Z E ************************

 ** BEGIN FILE O **

 IS THIS A CALIBRATION RUN  (YES OR NO) ? NO
 ARE CHANNEL LOSSES TO BE COMPUTED  (YES OR NO) ? YES
 ECHO PRINT OF INPUT DATA  (YES OR NO)? YES
 SUMMARY OUTPUT  (YES OR NO)? NO
 AVG., WET, DRY STATES TO BE COMPUTED  (YES OR NO)? YES
 ENTER: UP TO 80 CHARACTER TITLE
? TEST NETWORK - TEST#3


 ** BEGIN FILE A **

 ENTER: NO. OF NETWORK NODES? 4
 ENTER: TOTAL NO. OF NETWORK LINKS? 3
 ENTER: NO. OF RESERVOIRS ? 2
 ENTER: NO. OF RIVER REACHES? 3
 ENTER: NO. OF DEMAND NODES ? 1
 ENTER: NO. OF SPILL NODES? 2
 ENTER: NO. OF IMPORT NODES ? 1
 ENTER: NO. OF YEARS TO BE SIMULATED? 1
 ENTER: CALENDAR YEAR BEGINNING SIMULATION? 1978
 ENTER: FROM-TO YEARS OF DETAILED OUTPUT DESIRED? 1,1
 IS FIRM YIELD TO BE CALCULATED  (YES OR NO)? NO


 ** BEGIN FILE B **

 FOR RESERVOIR NO. 1;
       ENTER: UP TO 8 CHARACTER NAME? RES. #1
       ENTER: NETWORK NODE NO.? 1
       ENTER: MAXIMUM CAPACITY? 5000
       ENTER: MINIMUM CAPACITY? 0
       ENTER: STARTING VOLUME ? 0
 FOR RESERVOIR NO. 2;
       ENTER: UP TO 8 CHARACTER NAME? RES. #2
       ENTER: NETWORK NODE NO.? 2
       ENTER: MAXIMUM CAPACITY? 8000
       ENTER: MINIMUM CAPACITY? 0
       ENTER: STARTING VOLUME ? 2000
 FOR JUNCTION NO. 3;
       ENTER: UP TO 8 CHARACTER NAME? NODE #3
       ENTER: NETWORK NODE NO.? 3
 FOR JUNCTION NO. 4;
       ENTER: UP TO 8 CHARACTER NAME? NODE #4
       ENTER: NETWORK NODE NO.? 4


 ** BEGIN FILE C **

 ENTER: 2 SPILL NODE(S) IN ORDER OF PREFERENCE? 1,2


 ** BEGIN FILE D **

 ENTER: NO. OF AREA-CAPACITY POINTS PER RES.? 3
 FOR RESERVOIR NO. 1;
       ENTER: POINT 1 [AREA-CAPACITY] ? 0,0
       ENTER: POINT 2 [AREA-CAPACITY] ? 10,2500
       ENTER: POINT 3 [AREA-CAPACITY] ? 18,5000
 FOR RESERVOIR NO. 2;
       ENTER: POINT 1 [AREA-CAPACITY] ? 0,0
       ENTER: POINT 2 [AREA-CAPACITY] ? 25,4000
       ENTER: POINT 3 [AREA-CAPACITY] ? 35,8000
```

Figure 2. Example of Conversational Model Input Format

```
** BEGIN FILE E **

AVG., WET, AND DRY HYDROLOGIC STATES WILL BE COMPUTED
FOR DEMAND NODE NO. 1;
      ENTER: NETWORK NODE NO.? 4
      ENTER: PRIORITY FOR AVG. HYDROLOGIC STATE? 26
      ENTER: PRIORITY FOR DRY  HYDROLOGIC STATE? 12
      ENTER: PRIORITY FOR WET  HYDROLOGIC STATE? 85
      IS MONTHLY DEMAND TO BE INPUT VIA DATA FILE  (YES OR NO) ? YES


** BEGIN FILE F **

FOR IMPORT NODE NO. 1;
      ENTER: NETWORK NODE NO.? 2
      ENTER: TOTAL ANNUAL IMPORT ? 2400
      ENTER: MONTHLY DISTRIBUTION? 0 0 0 0 0 0 .1 .2 .3 .2 .2 0


** BEGIN FILE G **

ENTER: NO. OF RESERVOIRS IN SUBSYSTEM? 2
ENTER: NETWORK NODE NO. OF RESERVOIRS IN SUBSYSTEM ? 1,2
ENTER: FRACTION FOR AVERAGE LOW AND AVERAGE HIGH ? .35 .70


** BEGIN FILE H **

ARE CONVERSION FACTORS NECESSARY  (YES OR NO)? NO


** BEGIN FILE I **

FOR RESERVOIR NO. 1;
      ENTER: PRIORITY FOR AVG. HYDROLOGIC STATE? 55
      ENTER: DESIRED MONTHLY DISTRIBUTION? 1 1 1 1 1 1 1 1 1 1 1 1
      ENTER: PRIORITY FOR DRY HYDROLOGIC STATE ? 17
      ENTER: DESIRED MONTHLY DISTRIBUTION? .5 .5 .5 .5 .5 .5 .5 .5 .5 .5 .5 .5
      ENTER: PRIORITY FOR WET HYDROLOGIC STATE ? 80
      ENTER: DESIRED MONTHLY DISTRIBUTION? 0 0 0 0 0 0 0 0 0 0 0 0
FOR RESERVOIR NO. 2;
      ENTER: PRIORITY FOR AVG. HYDROLOGIC STATE? 21
      ENTER: DESIRED MONTHLY DISTRIBUTION? .2 .3 .4 .5 .5 .5 .6 .7 .8 .9 .8 .4
      ENTER: PRIORITY FOR DRY HYDROLOGIC STATE ? 8
      ENTER: DESIRED MONTHLY DISTRIBUTION? 1 1 1 1 1 1 1 1 1 1 1 1
      ENTER: PRIORITY FOR WET HYDROLOGIC STATE ? 67
      ENTER: DESIRED MONTHLY DISTRIBUTION? 0 0 0 0 0 0 0 0 0 0 0 0


** BEGIN FILE J **

FOR NETWORK LINK NO. 1;
      ENTER: MAXIMUM CAPACITY? 10000
      ENTER: MINIMUM CAPACITY? 0
      ENTER: ORIGIN NODE NO. ? 1
      ENTER: TERMINATION NODE NO.? 3
      ENTER: LOSS COEFFICIENT? .10
FOR NETWORK LINK NO. 2;
      ENTER: MAXIMUM CAPACITY? 9500
      ENTER: MINIMUM CAPACITY? 0
      ENTER: ORIGIN NODE NO. ? 2
      ENTER: TERMINATION NODE NO.? 3
      ENTER: LOSS COEFFICIENT? .20
FOR NETWORK LINK NO. 3;
      ENTER: MAXIMUM CAPACITY? 15000
      ENTER: MINIMUM CAPACITY? 0
      ENTER: ORIGIN NODE NO. ? 3
      ENTER: TERMINATION NODE NO.? 4
      ENTER: LOSS COEFFICIENT? .15
```

Figure 2. (Cont'd)

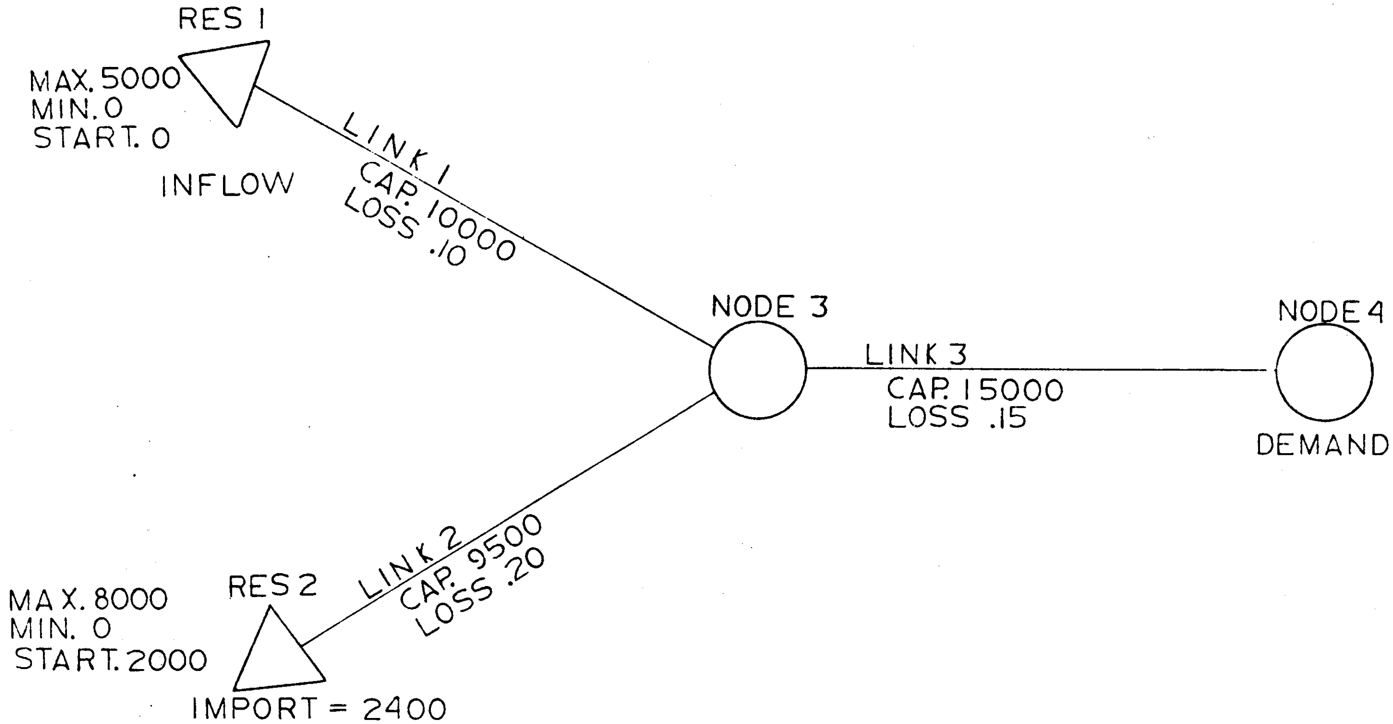


Figure 3. Example Node-Link Configuration

Chapter III

PRESENTATION OF CASE STUDIES

A. INTRODUCTION

Two case studies were undertaken to fully demonstrate the capability and utility of MODSIM for aiding in the analysis of changes in water resources policy within a river basin. In addition, it is hoped that these case studies will provide the potential user with insight into the formulation of his problem in such a manner that can be readily analyzed by MODSIM. Considerable thought was devoted to the selection of appropriate case studies that were relevant, timely, and provided potential for the actual use of the results. Therefore, several water resources planning and/or management problems currently concerning area (Colorado Front Range) decision-makers and water managers were evaluated. These perceived problems were judged according to such factors as complexity, information requirements, potential cost (time and money), and urgency as related to other water allocation problems. The case studies were also selected in such a way as to demonstrate the wide range of problems that can be attacked by MODSIM.

The two case studies prosented in this report differ completely in objectives; however, they are both located in the same river basin (the Cache la Poudre River Basin) in north-central Colorado (Figure 4). Even though two entirely different problem formulations are necessary, much of the information requirements remain the same (evaporation rates, gaged inflow records, area-capacity relationships, demands, etc.).

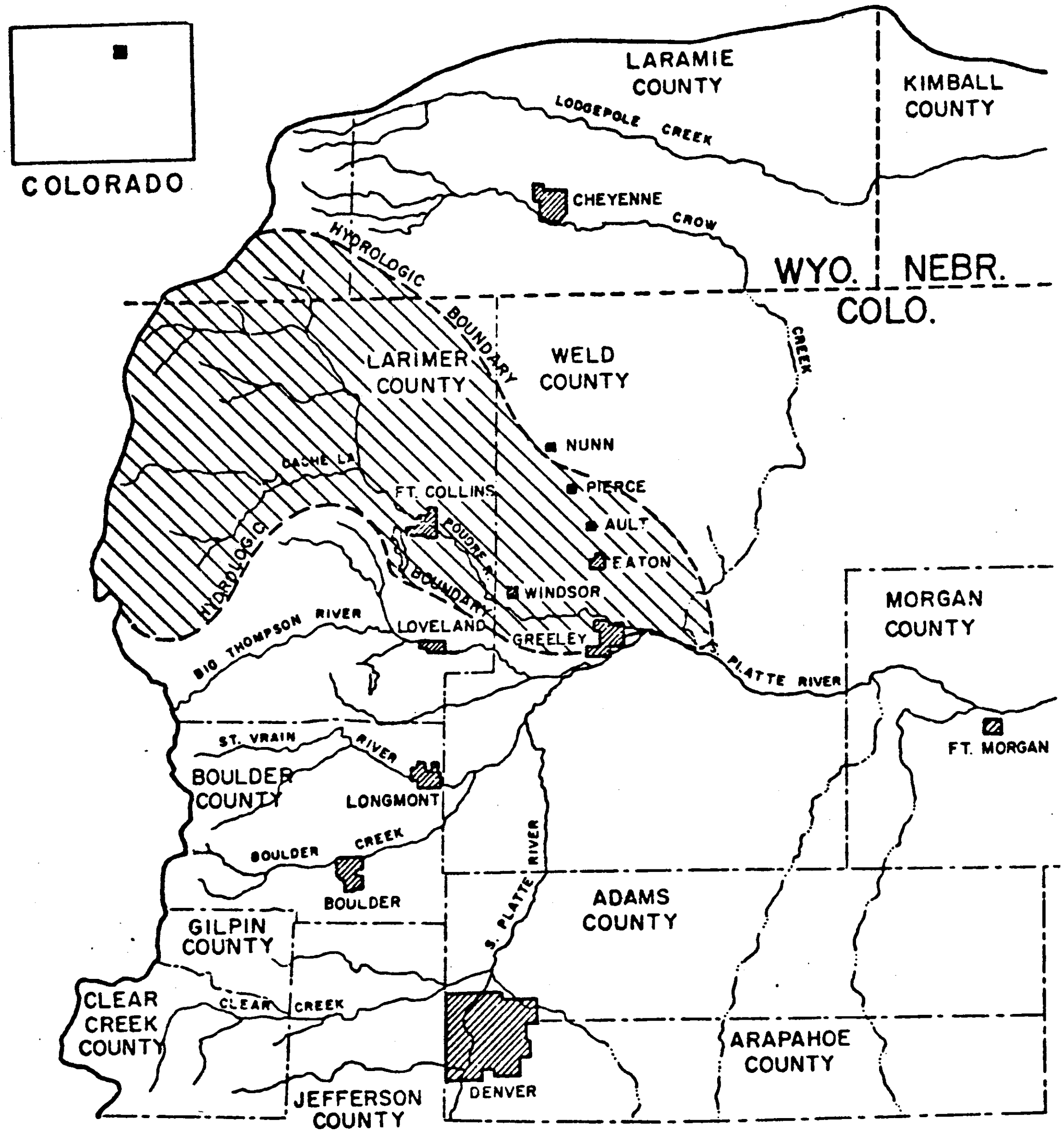


Figure 4. Location of the Study Area

In other words, within the same hydrology and institutional framework, many varying problems coexist.

As part of Water Division 1, District 3, the Cache la Poudre River Basin has as complex a system of interrelated water storage and distribution structures and regulations as anywhere along the Front Range. District 3 is also one of the most productive agricultural areas in Colorado. Consequently, irrigated agriculture has dominated the water use in the area. The Cache la Poudre River Basin is also favorable as a study area since there has been much previous modeling work done, although not related to the case studies presented here. However, much information can and has been extracted from these previously completed studies. Also, since the Cache la Poudre River is highly over-appropriated, it affords the challenge of modeling a system in great need of comprehensive planning studies.

B. BACKGROUND INFORMATION

B.1 Physical description of the study area

The extremes in elevation in the basin differ by about 7550 vertical feet. The agricultural portion of the valley represents almost 50 percent of the entire basin area and ranges in elevation from roughly 4650 feet above MSL to 5800 feet. The western boundary of the Cache la Poudre River Basin is the Continental Divide, with a maximum elevation of 12,200 feet above MSL (Evans, 1971).

The natural surface water supply is composed of spring snowmelt and direct precipitation. Additional supply is realized from various transbasin diversions. The Colorado-Big Thompson (CBT) Project is the most significant of these diversion projects and adds substantial flow to lower reaches of the Cache la Poudre River during irrigation seasons. Table 1 lists sources of water supply to the basin and their corresponding percentage.

Table 1. Sources of Water Supply for the Cache la Poudre River Basin (Evans, 1971)

SOURCE	Percentage (%)
Natural Inflows (Snowmelt, Precipitation)	44
Pumped Groundwater	33
CBT	17
Other Imported Waters (Transbasin Diversions)	6
	100

Within the Cache la Poudre system there are more than 30 major storage reservoirs located on the plains, plus an additional nine high country reservoirs with significant storage. These reservoirs are owned for the most part by established irrigation companies throughout the basin. For example, the North Poudre Irrigation Company has an elaborate system of canals and interconnected reservoirs and plays an important role in the local economy due to an extensive involvement in an exchange system which has developed in the basin. Figures 5 and 6 display the major features of the Cache la Poudre River Basin.

As mentioned previously, the natural flow in the Cache la Poudre River has long been over-appropriated. Therefore, to augment this natural supply, a series of transbasin diversions have been established. This importation of western slope water is limited, however, by a number of legally binding obligations. These obligations include the

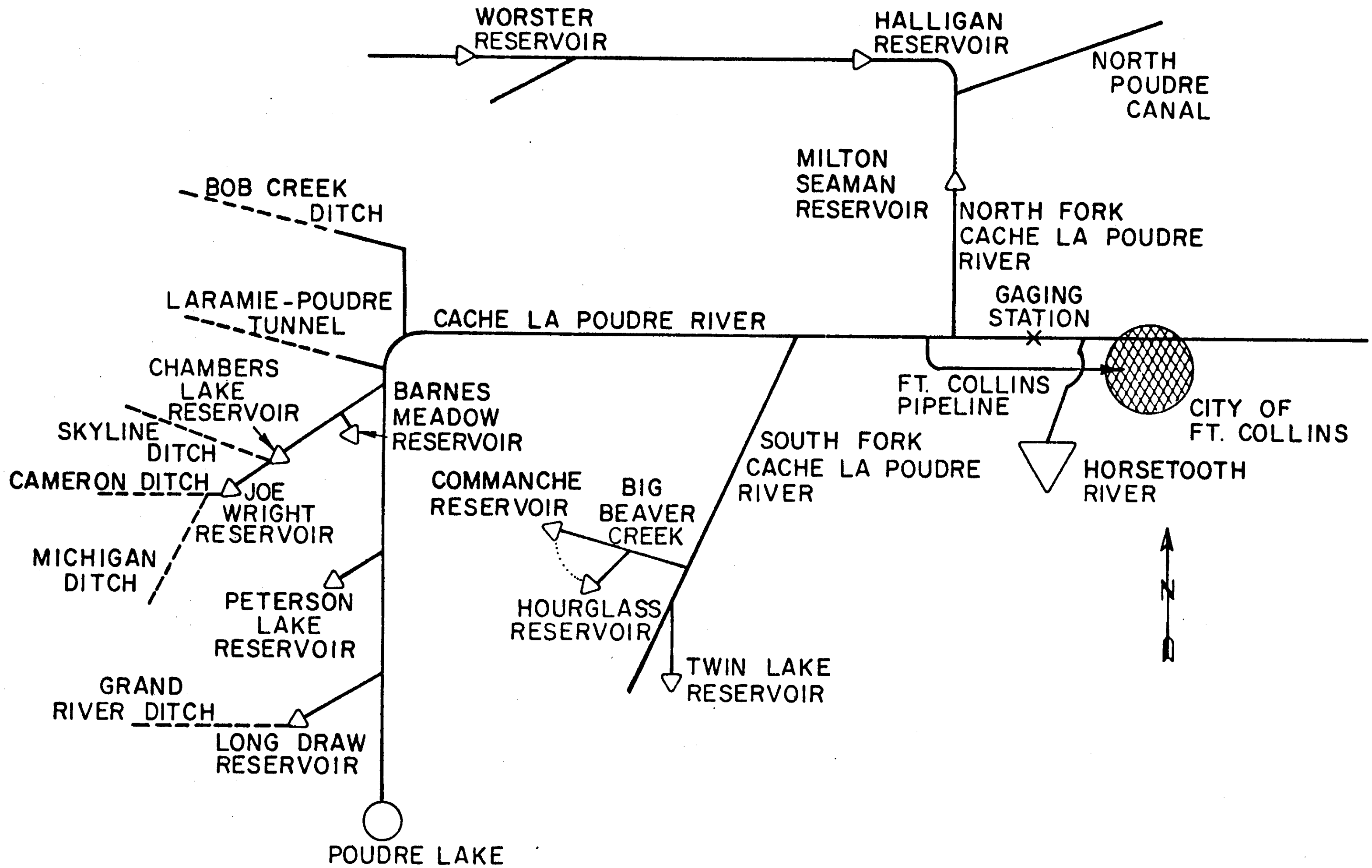


Figure 5. Schematic of the Poudre River Basin System

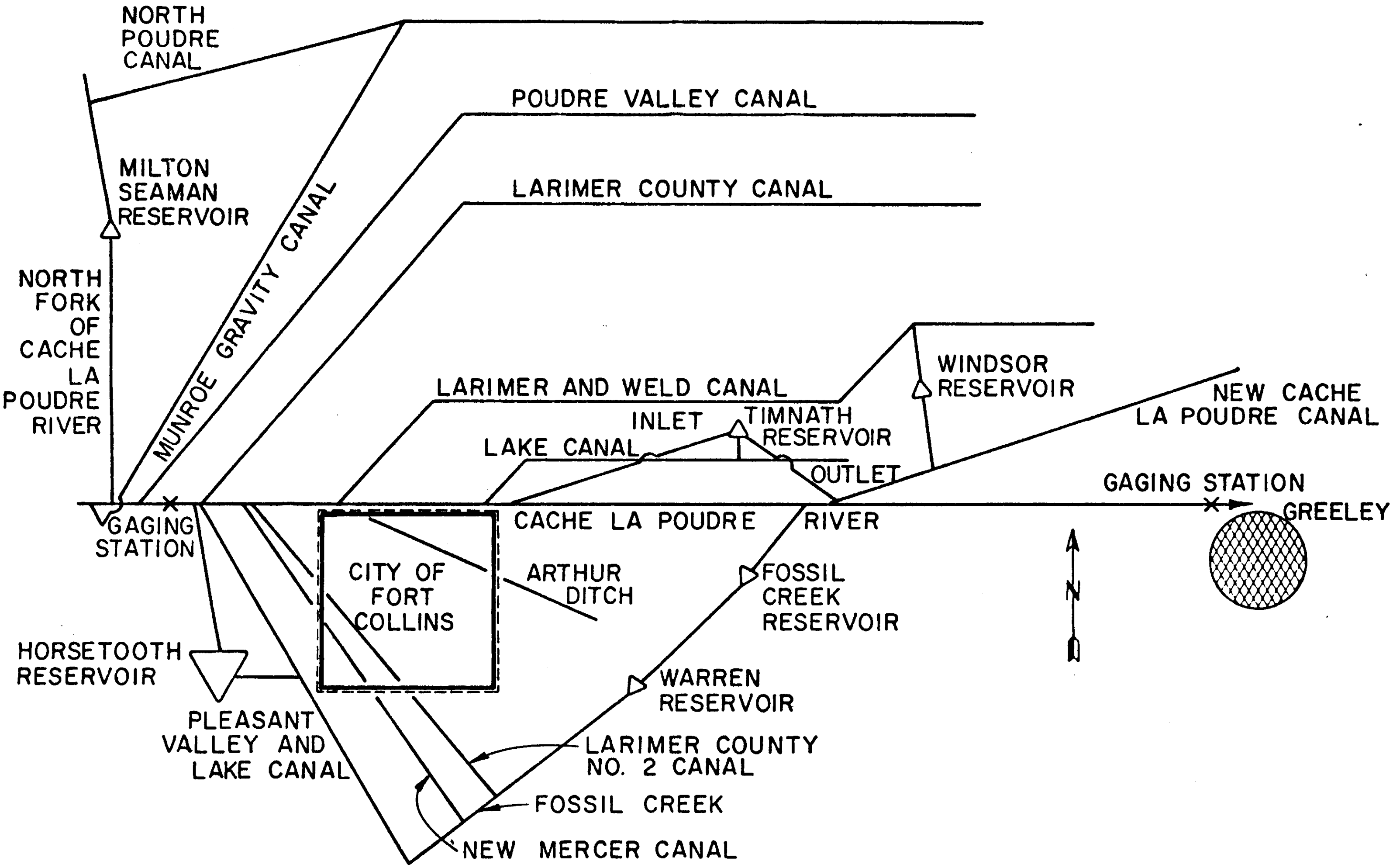


Figure 6. Detailed Schematic of Diversion Canals in the Upper Basin

Laramie River Decree, the Colorado River Compact and the North Platte River Decree. The largest transmountain diversion of water is the CBT Project. Originally, CBT water was intended solely for supplemental irrigation water. Municipalities (including Fort Collins) have subsequently acquired more than 23 percent of CBT water. Historically, high mountain transbasin diversions other than CBT have contributed, on the average, 45,000 acre-feet of water annually to the basin (Evans, 1971).

B.2 Exchange system

Early in the evolution of the current irrigation scheme in the Poudre Valley, it was realized by the administrators of water in the basin that greater efficiency in water use could be achieved by creating an exchange system. Though Colorado constitutionally supports the appropriation doctrine and senior water right holders must receive their direct flow appropriation first, an exchange system has been developed which allows junior water right holders to receive water through development of additional storage. The important point is that this storage need not be available upstream of their point of diversion.

A maximum mean monthly natural flow of 1769 cfs in the Cache la Poudre River occurs in June. Unfortunately, it can be shown from a review of direct flow rights on the river that most major canals could not operate in June (highest flow month) without the use of some kind of exchange system. Most canals have undergone several expansions, each time filing for an additional decree with a priority date based on the time of the new construction. Through such action, the river has become over-appropriated to the point where as of 1970, for example, only two years in 35 could the Greeley No. 2 Canal exercise its entire right (priorities 37, 44, 72, 83). The river has approximately 200 formal rights filed for its water. It is unlikely that Larimer and Weld Canal or North Poudre Canal would ever receive any water.

Exchanges of stored and direct flow water between ditch companies occur in conjunction with the reservoirs throughout the basin. Few reservoirs are located such that they can directly service the acreage of the owner. Subsequently, through the exchange system, it is of little significance whether or not a reservoir is located above or below the ditch system of its owner. With the addition of CBT water, which is capable of delivery via the river at any point below the Poudre Valley Canal, the exchange of water throughout the basin becomes even more attractive from an efficiency viewpoint. This system of exchanges has an important bearing on the management strategies which are to be analyzed as part of this case study (for additional information, see Evans, 1971, pp. 115-118).

B.3 Fort Collins Water System

Fort Collins raw water supply is derived from four sources: (1) CBT water, (2) shares in Water Supply and Storage Company, (3) shares in North Poudre Irrigation Company, and (4) direct flow rights. Table 2 lists the annual amounts of these supply sources.

Table 2. Fort Collins Water Supply (Wengert, 1975)

Source	Mean Annual Supply (acre-feet)
CBT	7,203
Water Supply & Storage Co.	833
North Poudre Irrigation Co.	4,190
Direct Flow	10,000
	22,226

The City has two water treatment plants with a combined capacity of approximately 44 mgd. Treatment Plant 1 is located 11 miles northwest of Fort Collins on the Cache la Poudre River and has a capacity of 20 mgd. The second plant is situated at the base of Horsetooth Reservoir Soldier Canyon Dam and has a capacity of 24 mgd. The capacity of Plant 2 is scheduled for a 10 mgd expansion by 1980 (Wengert, 1975).

West Fort Collins Water District serves an area to the northwest of Fort Collins. The District purchases treated water from the City and exchanges one acre-foot of CBT water for every unit of treated water the City supplies the District. It is assumed that two percent (2%) of the total gross water supply to the City is diverted to West Fort Collins Water District. Furthermore, no return of this diversion is realized at the City's waste treatment facilities. In other words, Fort Collins does not recover any of the water it supplies West Fort Collins.

M.W. Bittinger and Associates, Inc. (1975) conducted a study in which a detailed analysis of the consumptive use of treated water within the City of Fort Collins was undertaken. Consumptively used water and percentage of adjusted (minus West Fort Collins Water District) total inflow are provided on a monthly basis for 1974. Table 3 lists the results. The Bittinger report states:

> As long as the uses of City water remain in the approximate proportions that existed in 1974, the percentages...should be acceptable for determining the amount of City effluent available for a succession of uses without harming other water rights on the river.

Due to varying microclimatic conditions and changes in land use, these percentages (Table 3) may fluctuate somewhat.

Table 3. Consumptive Water Use Fort Collins - 1974 (Bittinger, 1975)

Month	Adjusted Inflow (acre-feet)	Total Consumptive Use (acre-feet)	Percent
JAN	626.7	6.8	1.1
FEB	577.6	6.8	1.2
MAR	679.5	10.9	1.7
APR	881.8	378.9	42.9
MAY	2029.3	1231.5	60.7
JUN	2251.8	1239.0	55.0
JUL	2855.9	1163.0	45.5
AUG	2353.1	1094.6	46.5
SEP	1541.6	541.7	35.1
OCT	1166.6	254.0	21.8
NOV	844.9	13.6	1.6
DEC	798.0	10.9	1.4

At the wastewater treatment end of the City's system there are two options for treated effluent release. The effluent can either be returned to the river or diverted to Fossil Creek Reservoir.

C. CASE STUDY 1: HIGH MOUNTAIN RESERVOIR RECREATION STUDY

C.1 Problem statement

As stated previously, several high mountain reservoirs are located within the basin boundaries. In the past, these reservoirs have been operated exclusively for the provision of a late season irrigation water supply. Such a policy has often resulted in the complete emptying of these reservoirs toward the end of the irrigation season. Attention has been focused on the inclusion of recreation in a multipurpose framework for some of these reservoirs.

The City of Greeley, Colorado, owns and operates six high mountain reservoirs in the Cache la Poudre River Basin. Of these six reservoirs, water stored in five is sold on a seasonal basis to the North Poudre Irrigation Company and water stored in the sixth (Milton Seaman) is used for exchange purposes and municipal supply. The five high mountain Greeley-owned reservoirs are Peterson, Barnes Meadow, Commanche, Twin Lake, and Big Beaver. These reservoirs, along with the North Poudre Irrigation Company reservoir and canal system, form an autonomous unit in that all water originating in the Greeley reservoirs is delivered to the North Poudre system.

The five high mountain reservoirs were evaluated according to their perceived recreation potential by outdoor recreation specialists assuming that stable pool elevations could be maintained at or near maximum levels. The analysis included such considerations as fisheries potential, scenic beauty, private versus public ownership of riparian lands, ease of access, etc. The results showed that Barnes Meadow and Twin Lake reservoirs have the highest recreation potential of the five. Commanche Reservoir and Peterson Reservoir were believed to have limited recreation potential while Big Beaver Reservoir was declared to have no recreation potential whatsoever due to private ownership of riparian lands (Aukerman, et al, 1977). The problem in this case study is one of determining if it would be possible, from a hydrologic and legal standpoint, to maintain a stable pool elevation, at or near maximum, in one or more of these reservoirs according to the preferences outlined above. This problem is not as straight forward as it may first appear in that such a change in the operating policy of these reservoirs would, to some extent, alter the traditional hydrology of the basin. This alteration must occur in such a manner that the North Poudre Irrigation Company demands for Greeley reservoir water are satisfied, no injury to downstream water rights holders is incurred, and that appreciable changes in the flow regime of the river do not result.

C.2 Study Objective

The objective of this case study is to investigate opportunities to operate the high mountain reservoirs in such a manner that would allow the maintenance of storages at or near capacity while meeting the North Poudre Irrigation Company demands from other reservoirs owned and operated by the company. The North Poudre Irrigation Company owns and operates many plains reservoirs with storage capacities significantly greater than those of the high mountain reservoirs under consideration. Halligan, Park Creek, and North Poudre No. 15 plains reservoirs have traditionally held large carry-over storages from season to season. These reservoirs have less recreation potential. Therefore if in the management of the Greeley-North Poudre system as a whole, the severe late season drawdown in the selected high mountain reservoirs could be curtailed while allowing storage levels in the plains reservoirs to more widely fluctuate, enhanced mountain reservoir recreation may be provided.

The approach taken in investigating this problem is to isolate the Greeley high mountain reservoir subsystem and the North Poudre Irrigation Company subsystem. In this manner only water released from the high mountain reservoirs along with other reservoir water controlled by North Poudre needs to be considered. This allows analyses of changes in the operating policies of the reservoirs without considering direct flow rights along the river or other reservoir water not directly involved with the study.

C.3 System Configuration and Decomposition

Due to the interdependence of system components, management of the high mountain reservoirs cannot be analyzed without proper consideration of the demand points for their stored water. However, once the reservoirs to be studied are identified, along with the various distribution and use subsystems to which they contribute water, a spatial decomposition isolates this subsystem of water supply, distribution, and use for further analysis. As long as all sources and sinks of *reservoir* water in the subsystem are considered, a meaningful study of the decomposed system can be conducted even though the entire system is no longer under investigation. This approach allows the problem to remain tractable without great sacrifice in accuracy and detail. Figure 7 shows the decomposed Greeley-North Poudre subsystem for this case study.

Only the demand for intrabasin high mountain reservoir water is of interest for this problem. Accordingly, imported water is ignored along with direct flow of river water to satisfy irrigation requirements. Since the origin of the reservoir water contributing to demand satisfaction is the only concern, its final destination can be considered a single demand center without introducing any error into the analysis. All of the individual North Poudre Irrigation Company plains reservoirs (N.P. No. 1 and those to the east) provide water to turnouts for application to fields. Of interest to this study is the *total* monthly volume of mountain reservoir water supplied to these plains reservoirs.

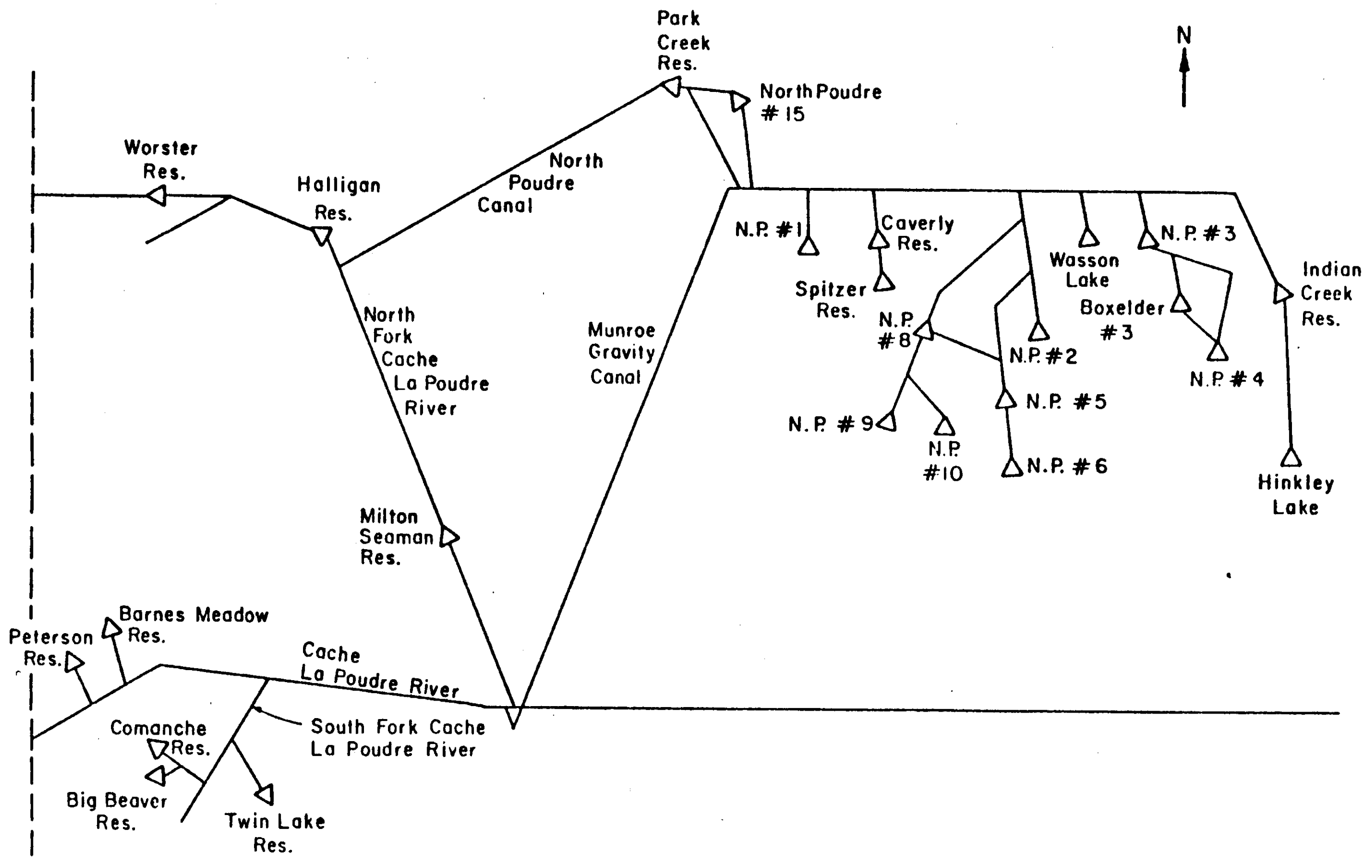


Figure 7. Schematic of the Greeley-North Poudre System

Therefore, the North Poudre plains reservoirs are aggregated into one large plains reservoir whose surface area and storage volume are equal to the sums of the surface acreages and volumes of the individual plains reservoirs. This maneuver allows the total monthly demand for water from the high mountain reservoirs to be lumped together at one demand center (Figure 8).

Once the physical system has been isolated, and all important components identified, it must be translated into a corresponding graphical network of nodal points and linkages. Care must be exercised during this translation to insure that the essence of the physical system is captured in its entirety. All nodes and links are then labeled numerically. Reservoirs must be labeled first, followed by non-storage nodes. Figure 9 displays the network configuration for this case study.

D. CASE STUDY 2: RAWHIDE PROJECT

D.1 Problem Statement

The problem selected for the second case study addresses itself to the availability of water for cooling purposes and other in-plant uses for the proposed *Rawhide Project*. The Rawhide Project is a coal-fired electric generation plant to be located approximately 20 miles north of Fort Collins, Colorado. The project is designed to augment projected power demands of the municipalities of Estes Park, Fort Collins, Longmont, and Loveland, Colorado. The first 230 megawatt unit should be operational by 1985. Such facilities require adequate supplies of water. The Platte River Power Authority (PRPA) is negotiating with various potential water suppliers, including the City of Fort Collins.

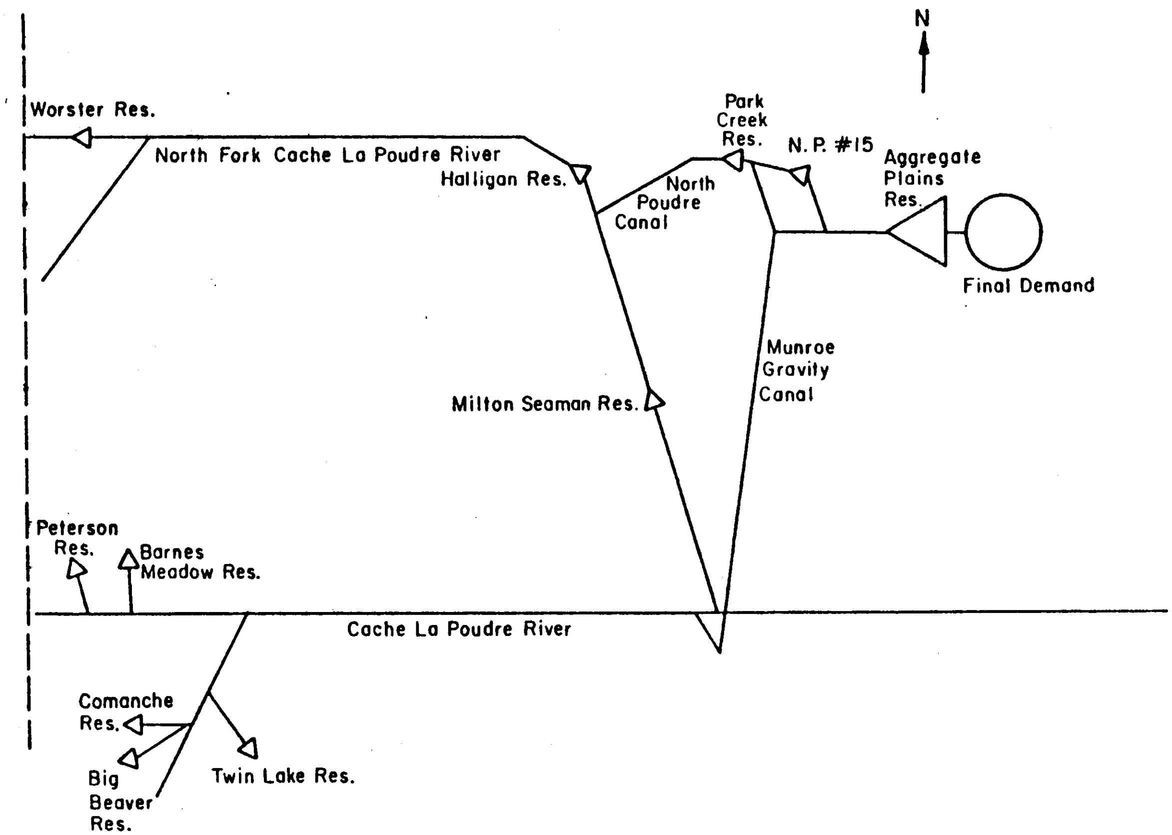


Figure 8. Greeley-North Poudre System with Aggregated Plains Reservoirs

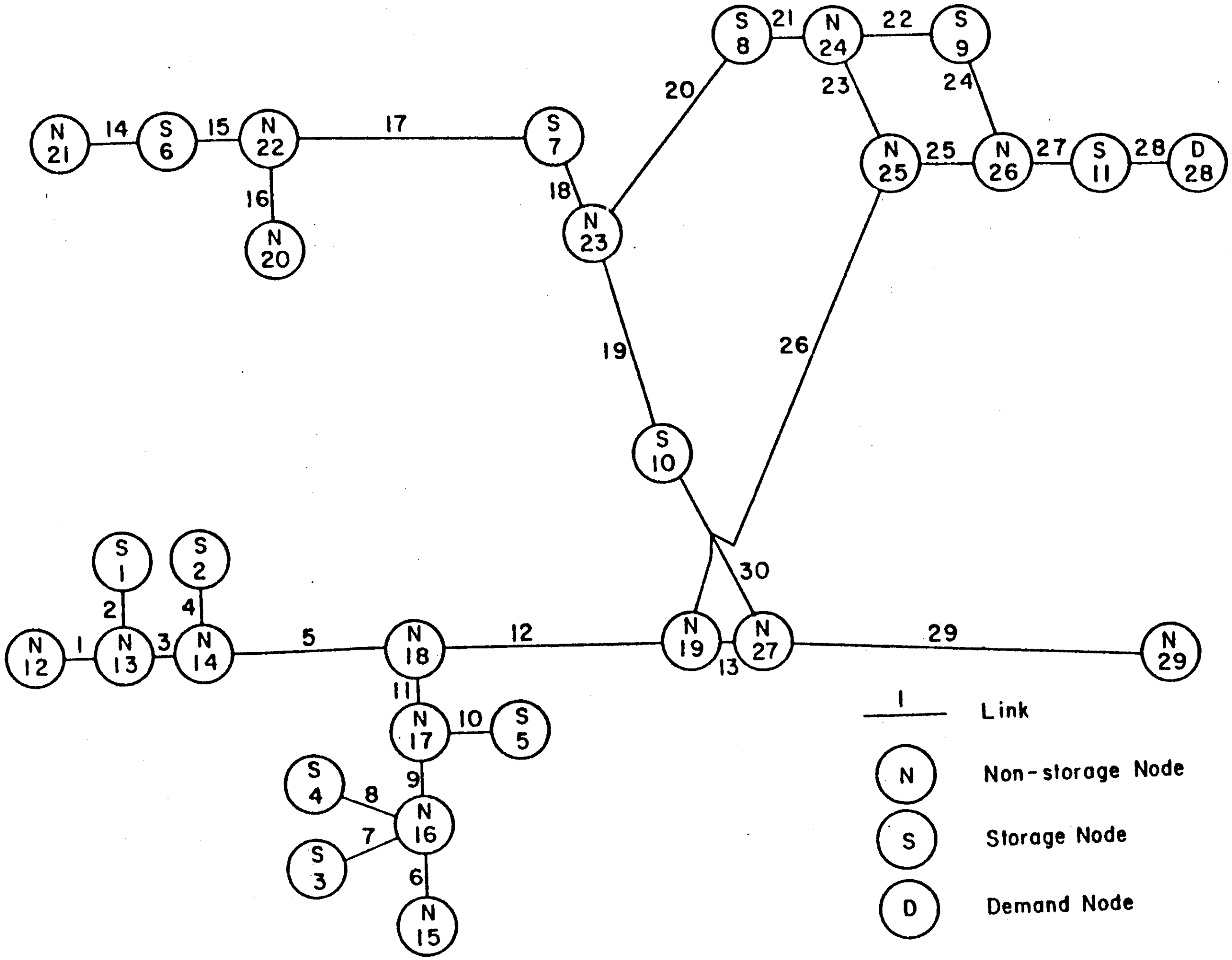


Figure 9. Link-Node Configuration for Greeley-North Poudre System

A preliminary contract has been made between Fort Collins, PRPA, and the Water Supply and Storage Irrigation Company outlining a scheme whereby the water requirements of the Rawhide Project could possibly be met. However, before any of the parties enter into a formal agreement, the potential effect of such a scheme on those parties directly and indirectly involved or impacted must be ascertained.

The project calls for the construction of a 13,000 acre-foot reservoir from which waters can be circulated through the power plant for cooling and additional purposes. The Rawhide Project is scheduled for commencement of operation in 1985. However, the Rawhide Reservoir must be full prior to the beginning of power generation. To accomplish this requirement, the agreement between the parties concerned states that filling must begin in 1981. Upon filling the reservoir, the Rawhide Project will require no less than 4200 acre-feet of firm water annually and a stable reservoir elevation within two or three feet.

To accomplish the above tasks, Fort Collins is to provide the Rawhide Project with the opportunity to utilize sewer effluent attributable to newly developed or imported water first used by the City. Imported or foreign water is water which originates outside of the Cache la Poudre River Basin and is diverted from some basin other than the Poudre Basin. The significance of *newly developed* refers to the fact that changing the diversion of sewer water attributable to *old* foreign water would result in possible *injury* to those users who have historically come to rely on its availability. In contrast, *new* foreign water is water which only recently or in the future is imported into the Cache la Poudre River Basin in excess of waters which constitute old foreign water.

New foreign waters for Fort Collins originate in the adjacent North Platte River drainage and are diverted across the basin divide via the Michigan Ditch. These waters are then placed in Joe Wright Creek, tributary to the Poudre River. At this point, the water can be used directly or stored in the expanded capacity of Joe Wright Reservoir.

Joe Wright Reservoir is owned and operated by Fort Collins and is being enlarged by the City from 800 acre-feet of water to approximately 8,000 acre-feet. Historic diversions through the Michigan Ditch have been estimated by the parties involved as 1,000 acre-feet per year. Accordingly, the reuse of the first 1,000 acre-feet annually diverted through the Michigan Ditch is, in effect, prohibited. This is not to say that the Rawhide Project cannot divert the effluent from the City's first use of the initial 1,000 acre-feet. However, if such an action takes place, the City must release from other sources the amount of water that would have existed if the 1,000 acre-feet were used by the City and the corresponding return flow was not diverted to the power plant.

New foreign water diverted into the basin via the Grand River Ditch is also available for reuse by the Rawhide Project after first use by Fort Collins. This water can be stored, upon importation, in Long Draw Reservoir which is owned by the Water Supply and Storage Company. However, only 6,000 acre-feet of storage space in this reservoir is to be made available to Fort Collins for storage of Grand River Ditch imports.*

*Maximum capacity of Long Draw Reservoir is approximately 10,500 acre-feet.

D.2 Study Objective

The objective of this case study is to determine, first, if the cooling pond could be filled prior to the beginning of power generation in 1985, and, second, if a minimum of 4,200 acre-feet of reusable water can be provided at a uniform rate thereafter. For this case study all water that becomes available in the basin must be considered. This includes direct flow river water, Colorado-Big Thompson Project water, intrabasin reservoir water, and, of course, the transbasin diversions via Michigan and Grand River ditches. This objective has many ramifications. Injury to water users downstream from the pipeline intake must not occur or must be compensated. A *borrowing* arrangement must be made in order to maintain uniformity in delivery of reused water to the pipeline. A stable pool elevation in the cooling pond must be maintained. The preference of the City's direct flow right over other sources of water must be preserved. Finally, spills from Joe Wright Reservoir and Long Draw Reservoir must be considered. However, as in Case Study #1, the total river basin system can be decomposed into a subsystem of the specific components necessary to analyze this problem.

D.3 System Configuration and Decomposition

As previously discussed, the Poudre River system is extremely complex in both composition and operation. Fortunately, the system has two control points situated in advantageous positions. The State of Colorado has two gaging states located on the Poudre River. The upstream gage is situated near the mount of Poudre Canyon before most of the ditch diversions occur, while the downstream gage is located on the Poudre at the confluence of the South Platte River.

Due to the size of the system (number of interrelated components) it would be all but impossible to model the entire system. Therefore, the complete system is decomposed to a point where the key components of the case study are individually considered, but the remainder of the system is aggregated in various ways. In this manner, the integrity of the system as a whole is preserved while only certain components are *directly* modeled.

The components of the decomposed system pertaining to the Rawhide Project are listed in Table 4. The system can be defined in this manner as a result of the placement of the aforementioned gaging stations. Flow adjustments are made between gages, as well as from the upstream gage to the headwaters of the Poudre River. The effect of varying diversion schemes on the aggregated systems components can be determined *a posteriori*. Figure 10 is a schematic diagram depicting the major components of the decomposed system.

Table 4. Rawhide Project Subsystem Components

Reservoirs	Irrigation Ditches	Other Conveyances
Long Draw	Munroe Gravity Canal	Ft. Collins Pipeline
Joe Wright	Larimer & Weld Canal	Charles Hansen Canal
Chambers Lake	Lake Canal	Timnath Reservoir Inlet
Horsetooth	New Cache la Poudre Canal	Rawhide Pipeline
North Poudre No. 6		
Windsor	Imports	
Timnath	Michigan Ditch	
Fossil Creek	Grand River Ditch	
Rawhide Cooling Pond		

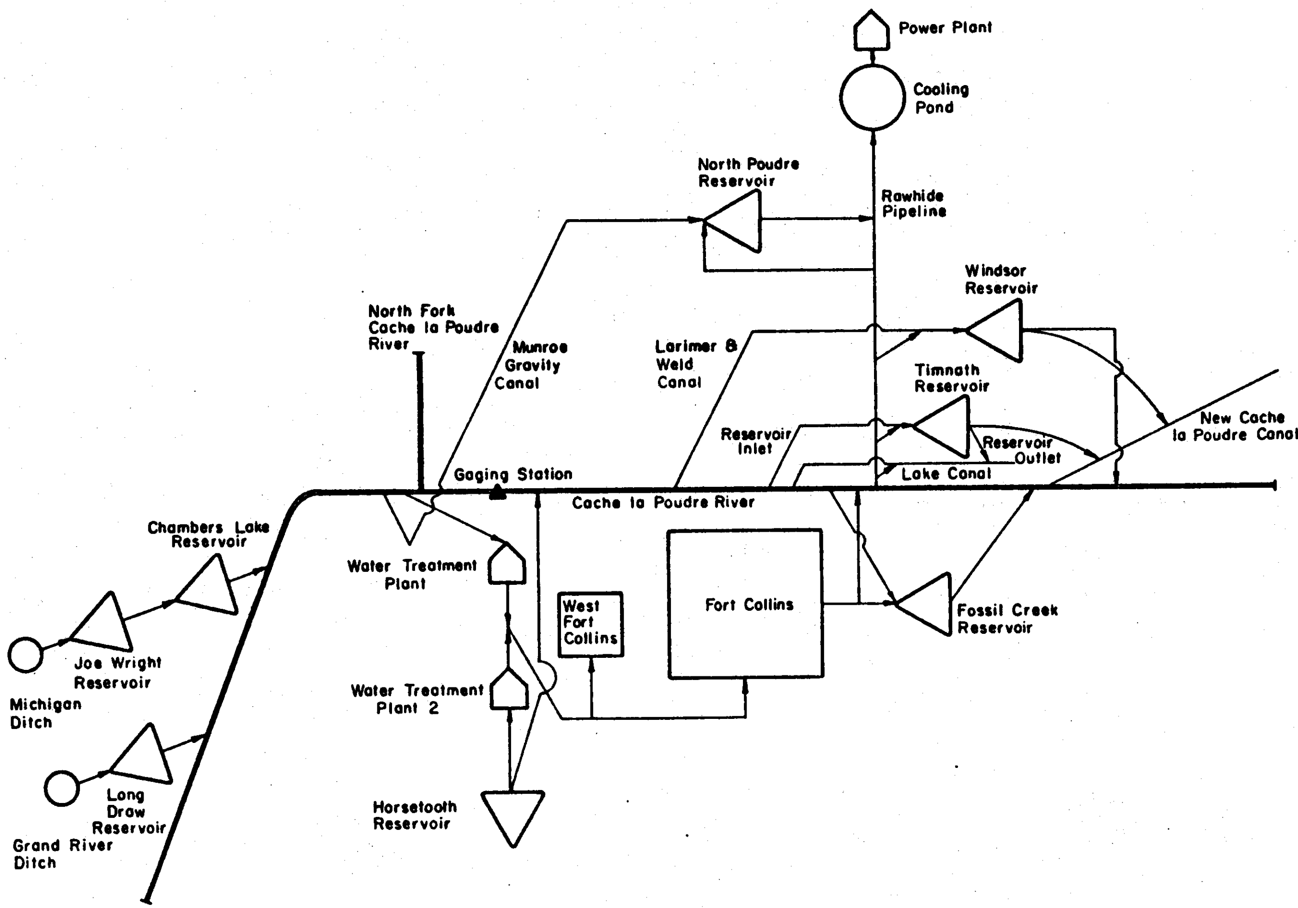


Figure 10. Components of the Rawhide Case Study

Once the physical system to be modeled has been delineated, it must be translated into a node-link network configuration. Particular attention must again be afforded this phase of any study to insure that the essence of the system remains intact. Figure 11 shows the network system for which the model is calibrated. Table 5 lists the names of the nodes and the flow capacity of each link. Notice that the Fort Collins water treatment plants have been represented as links instead of nodes. The upper bound on each link corresponds to the respective monthly treatment capacity of each plant. To effectively model the decomposed system, 35 nodes and 47 links are required to represent the physical system, plus additional artificial nodes and arcs.

E. DATA ORGANIZATION

Since both case studies involve the same river basin, commonalities in data requirements exist. The same hydrologic, climatic, structural, and institutional characteristics are encountered in each case study. This section identifies the agencies and individuals who have made available the information needed to conduct the case studies. Also, this section contains the method of calculation of the evaporation rates used throughout the analysis. Channel characteristics and reservoir characteristics are also presented, along with other necessary data common to both studies. Information which is specific to one case study is introduced later in the appropriate section of this report. All data must be compatible, therefore, units are selected as follows: (1) flows--acre-feet/month, (2) storage--acre-feet, (3) surface area--acres, (4) net evaporation rate--feet, and (5) demands--acre-feet.

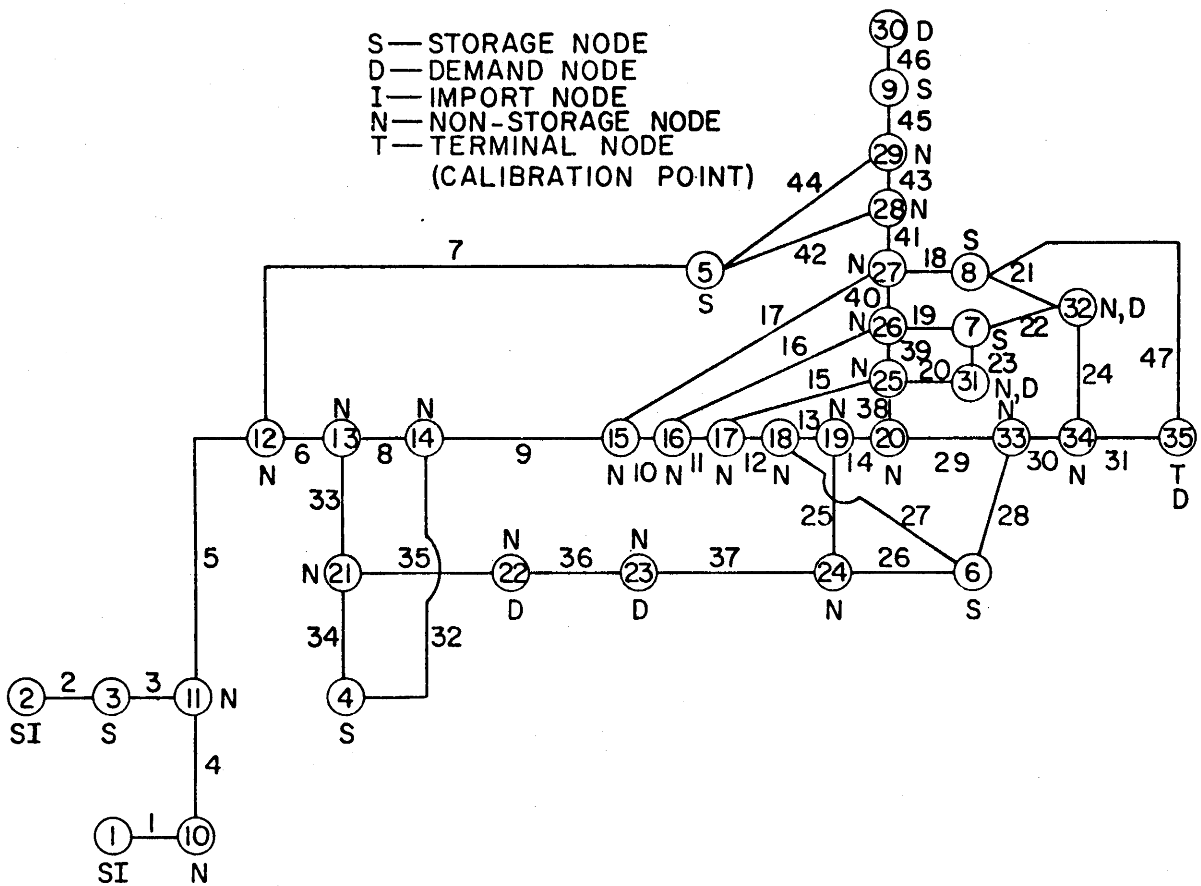


Figure 11. Link-Node Configuration for the Rawhide Case Study

Table 5. Rawhide Project Network Components Description

Node #	Name	Node #	Name
1	Long Draw Reservoir	19	Ft. Collins Return Flow
2	Joe Wright Reservoir	20	Rawhide Pipeline Diversion
3	Chambers Lake Reservoir	21	Ft. Collins Inflow
4	Horsetooth Reservoir	22	West Ft. Collins
5	North Poudre No. 6 Reservoir	23	Consumptive Loss
6	Fossil Creek Reservoir	24	Dummy
7	Timnath Reservoir	25	Rawhide Pipeline
8	Windsor Reservoir	26	"
9	Rawhide Cooling Pond	27	"
10	Upper Stem Poudre River	28	"
11	"	29	"
12	Munroe Canal Diversion	30	Rawhide Power Plant
13	Ft. Collins Pipeline Diversion	31	Lake Canal
14	Confluence N. Fork Poudre River	32	New Cache la Poudre Canal
15	Larimer & Weld Canal Diversion	33	Release from Fossil Creek
16	Timnath Reservoir Inlet	34	New Cache la Poudre Canal Diversion
17	Lake Canal Diversion	35	Terminal
18	Fossil Creek Reservoir Inlet		

Link #	Maximum Flow (ac-ft/mo)	Link #	Maximum Flow (ac-ft/mo)
1	15000	25	4026
2	15000	26	4026
3	15000	27	11100
4	300000	28	11100
5	300000	29	300000
6	300000	30	300000
7	15000	31	300000
8	300000	32	91000
9	300000	33	1779
10	300000	34	2247
11	300000	35	4026
12	300000	36	4026
13	300000	37	4026
14	300000	38	0
15	158	39	0
16	10070	40	0
17	60667	41	0
18	60667	42	0
91	10070	43	0
20	158	44	0
21	17689	45	0
22	10070	46	0
23	10070	47	17689
24	35490		

E.1 Sources of Information

Data requirements for performance of the case studies were met from the following sources.

1. The Water Commissioner, District 3, provided data concerning both reservoir and channel characteristics. Also, the Commissioner provided valuable assistance in interpreting the water rights structure of the Cache la Poudre River.
2. Information concerning the allocation of Horsetooth Reservoir water via the Colorado-Big Thompson Project was made available by the Northern Colorado Water Conservancy District offices located in Loveland, Colorado.
3. Detailed daily diversion data for all structures in Water District 3 were obtained from the Colorado Water Data Bank through the Division of Water Resources, State Engineer's Office.
4. The United States Bureau of Reclamation, Denver Office, provided information concerning evaporation rates from reservoir surfaces. These data were refined by accounting for precipitation taken from records compiled by the State Climatologist.

E.2 Evaporation Rates

Representative estimates of the expected evaporation rates were difficult to obtain because of a lack of information specific to the area of interest. The rates obtained from the Bureau of Reclamation (USBR) were not oriented toward this particular geographic region. However, the monthly distribution of the annual total was considered acceptable for irrigation years 1973-1975 (Shafer and Labadie, 1977). Two gross evaporation rates were necessary to differentiate between the plains reservoirs (5000 to 6000 feet above MSL) and the high mountain reservoirs (8000 to 9000+ feet above MSL). An adjustment of the monthly distribution of the total annual value for the mountain reservoirs was made to reflect periods of ice and snow cover on the surface during winter months and differences in vapor pressure and wind velocities during summer. Figure 12 shows these monthly percentages of the total annual evaporation. Annual summaries of climatological data obtained from the Office of the State Climatologist were used to calculate the net evaporation rates for each month during the three-year period. Mean annual corrected pan evaporation at Grand Lake (elevation 8288 ft) and Fort Collins (elevation 5001 ft) were divided into corresponding monthly values according to the distribution in Figure 12. The observed monthly precipitation for stations at Red Feather Lakes (elevation 8237 ft) and Fort Collins were subtracted from these gross monthly rates to derive a representative net monthly evaporation rate for the plains reservoirs and high country reservoirs (Figure 13).

E.3 Channel Characteristics

Since each physical arc must be bounded from above (lower bound equals zero) actual channel capacities were obtained from the CWDB and personal interviews with John W. Neutze, Commissioner, District 3. Typical capacities, along with loss coefficients where appropriate, are provided in Table 6.

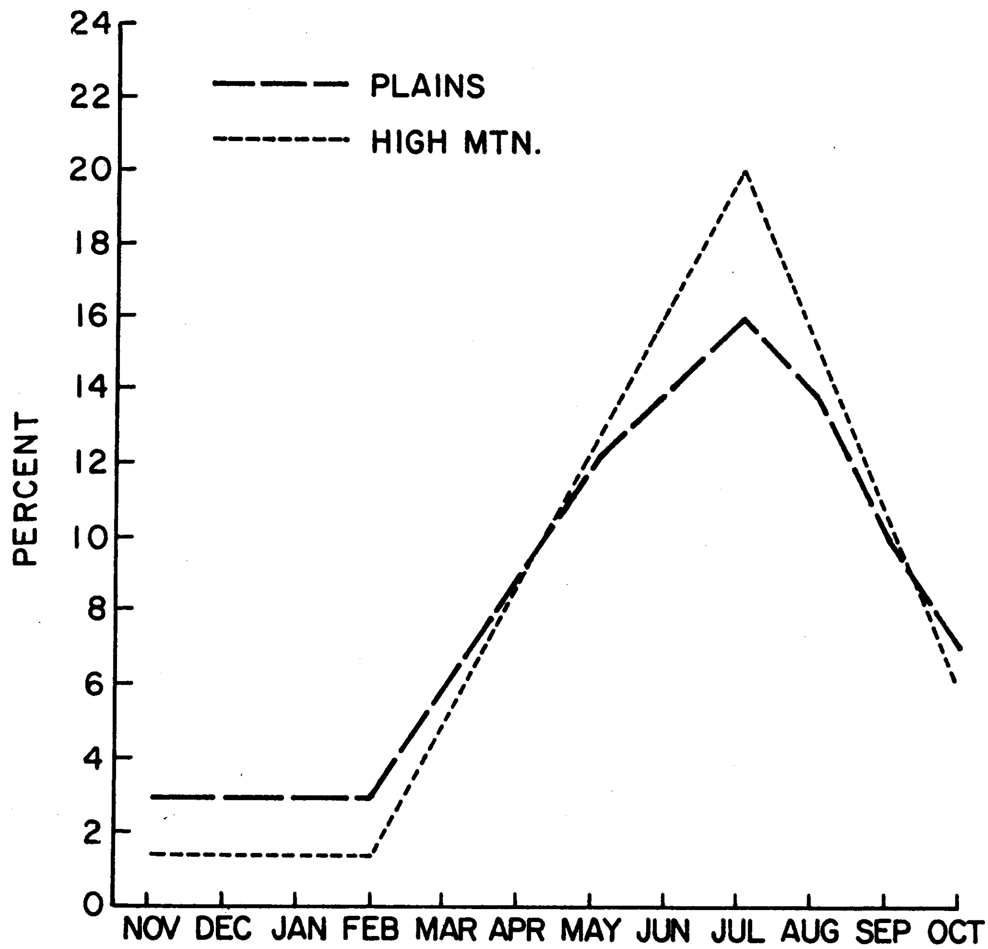


Figure 12. Monthly Distribution of Evaporation as Percent of Gross Annual Rate

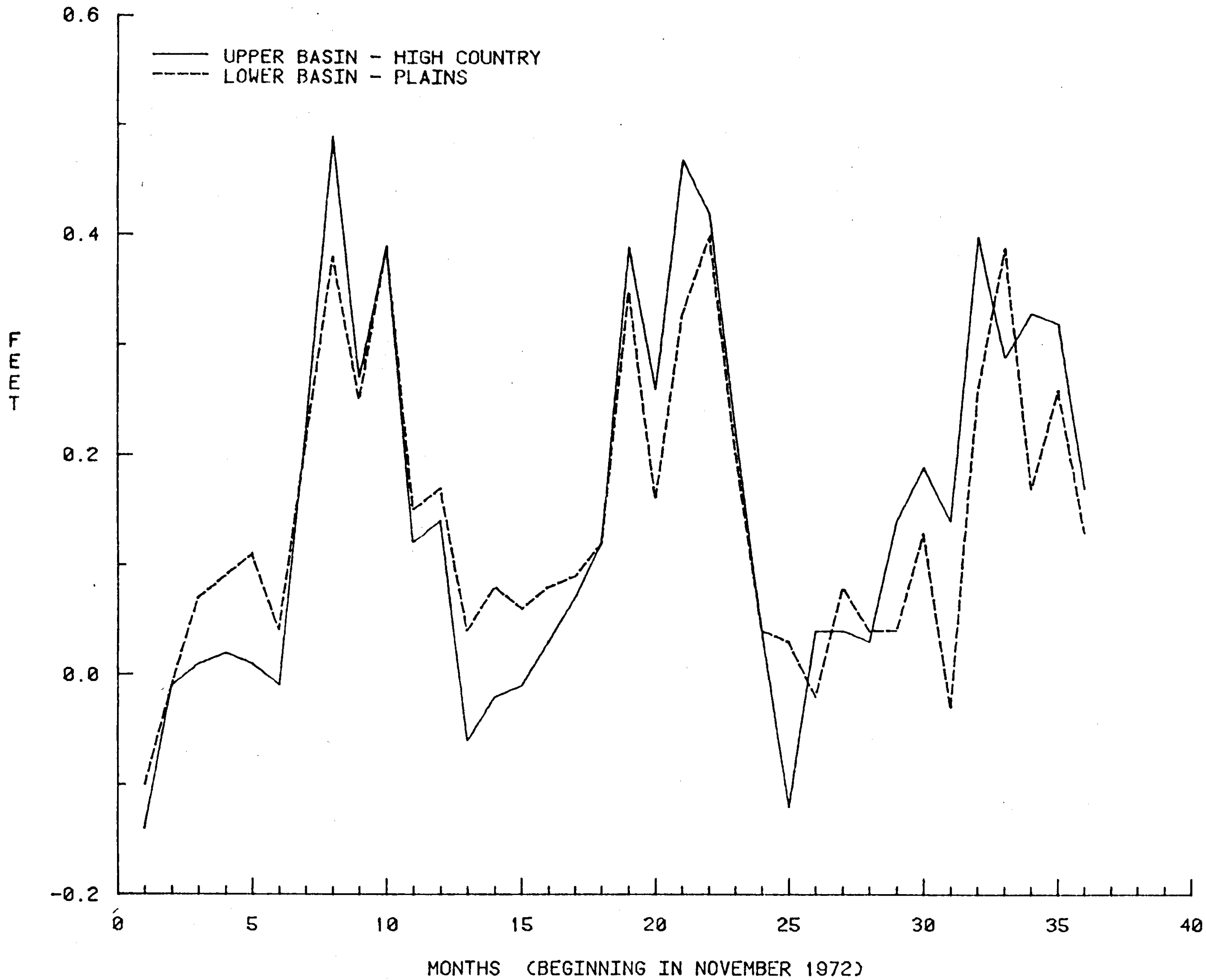


Figure 13. Net Monthly Evaporation

Table 6. Typical Channel Capacities and Loss Coefficients

Capacities	Capacity (acre-feet/month)	Loss (Percentage of Flow)
Mainstream Cache la Poudre	300,000	5.0
Munroe Gravity Canal	15,000	20.0-33.0
Hansen Supply Canal	91,000	---
Larimer and Weld Canal	60,667	20.0-33.0
Timnath Inlet	10,070	20.0-33.0
Lake Canal	9,100	20.0-33.0
New Cache la Poudre Canal	35,297	20.0-33.0

E.4 Reservoir Characteristics

MODSIM uses a linear interpolation procedure to determine surface area from tables of volume versus surface area points for each reservoir. From an estimate of average surface area during any particular month, the amount of evaporation (net of precipitation) occurring from the water surface can be calculated. The model will accept up to 18 pairs of volume-surface area points for each reservoir. These points were calculated by solving a series of exponential equations relating volume and surface area to gage height (Thaemert, 1976). An interactive conversational computer program was written to calculate these tables, allowing zero or one discontinuity in each curve. Table 7 contains an example calculation of area-capacity points. Horsetooth Reservoir is not included for reasons which are discussed in the following chapter.

Table 7. Example Area-Capacity Relationships

Point	Timnath Reservoir			Fossil Creek Reservoir			Long Draw Reservoir		
	Gage Ht (ft)	Area (ac)	Vol. (ac/ft)	Gage Ht (ft)	Area (ac)	Vol. (ac/ft)	Gage Ht (ft)	Area (ac)	Vol. (ac/ft)
1	0.	0	0	0.	0	0	0.	0	0
2	3.778	70	196	4.000	8	40	8.889	69	772
3	5.667	89	345	6.000	28	241	13.33	91	1335
4	6.556	106	517	8.000	54	170	17.78	112	1969
5	9.444	131	776	10.00	80	318	22.22	131	2661
6	11.33	163	1110	12.44	112	530	26.67	149	3403
7	13.22	196	1522	14.00	147	817	31.11	166	4191
8	15.11	230	1988	16.00	188	1188	35.56	182	5019
9	17.00	265	2517	18.00	232	1652	40.00	198	5884
10	18.89	301	3107	20.00	281	2219	44.44	213	6783
11	20.78	337	3760	22.00	333	2897	48.89	228	7715
12	22.67	374	4475	24.00	390	3697	53.33	242	8676
13	24.56	412	5251	26.00	450	4626	57.78	256	9667
14	26.44	451	6090	28.00	515	5692	62.22	270	10519
15	28.33	490	6992	30.00	583	6906			
16	30.22	529	7955	32.00	655	8273			
17	32.11	569	8981	34.00	730	9804			
18	34.00	609	10070	36.00	810	11100			

F. COMPARISON OF CASE STUDIES

There are marked differences in these case studies which help to demonstrate the utility of MODSIM for water policy analysis. The high mountain reservoir recreation study is a straight-forward analysis of the ability to alter the operating policies of several reservoirs to achieve the same end result as far as demand satisfaction is concerned, while enhancing recreation opportunities on certain reservoirs. Only the water normally contributed to the irrigation system by these reservoirs is important. Once the model has been satisfactorily calibrated, the study becomes a matter of adjusting reservoir priorities in such a manner that allows one to determine the effect of differing operating rules on the decomposed system. No further interpretation of the results produced by MODSIM is necessary, and the outcome of many varying operating policies can be determined quickly. The institutional framework within which the system operates is only marginally involved (by design) in this analysis. As long as the final demand for reservoir water is met, no injury to the North Poudre Irrigation Company and all other downstream users will occur.

In comparison, the second case study (Rawhide Project) is a much more sophisticated problem. Here, the hydrology is important, but of equal importance is the legal system. For instance, Fort Collins must first exercise its monthly direct flow right before drawing any reservoir water. Since all water in the basin is being considered, as opposed to only reservoir water in the first case study, model calibration must not only include reservoir storages, but also river flows.

There is much more flexibility in system operation due to the added complexity of the second case study. This flexibility must be taken into consideration when adjusting priorities throughout the network.

The primary goal of the high mountain reservoir study is one of determining to what degree the operating policy of the plains reservoirs can be traded with that of the high mountain reservoirs. Demands are given the highest priority and the model does the best it can to achieve target storage levels once the demand has been satisfied. The Rawhide Project, however, not only has certain demands which must be met, but qualifications on how they are met. These qualifications or constraints vary widely from month to month and are dependent upon both the hydrologic and institutional conditions present in any one month. Where the output of results by MODSIM for the first case study is adequate enough to draw particular conclusions about the problem, certain parts of the results provided by MODSIM for the Rawhide Project must be further analyzed to arrive at a conclusion.

Chapter IV

MANAGEMENT STUDIES

This chapter presents the results of the management studies associated with each of the case studies outlined in Chapter III. The results produced by MODSIM are reported and then the implications of these results are discussed. Since both case studies represent *real world* problems confronting Colorado decision makers, the conclusions drawn from these studies and the associated impacts of these conclusions on the Cache la Poudre River system are important, and are explained in detail. It should again be emphasized that we are focusing on the Poudre system as a demonstration of the capabilities of MODSIM as a general simulation tool for the Colorado Front Range.

A. CASE STUDY

A.1 Methodology

The management strategy developed for this case study centers around the possibility of enhancing recreational potential in certain high country reservoirs; in particular, Barnes Meadow and Big Beaver reservoirs. As previously mentioned, these two reservoirs are considered to have the highest recreation potential of the five Greeley high mountain reservoirs. The management of these reservoirs with recreation included in a multipurpose framework is in marked contrast to the traditional operating policy demonstrated during the calibration phase.

The same simulation period used for model calibration is also used to perform the management study. Irrigation years 1973-75 are deemed acceptable for the analysis since they do represent a wet to dry cycle in the basin and complete information concerning the decomposed system is available. Also, during these years the high mountain reservoirs were emptied at the end of each year, which is in conflict with stated management objectives.

The goal of this management study is to determine *what if*, for the three years in question, the high mountain reservoirs were operated in such a fashion that would provide for suitable water related recreation. The desired monthly storage levels for all five reservoirs are set at the maximum capacity of each reservoir. Desired storage levels for the remaining reservoirs less attractive for recreation are set at zero, thereby allowing these storage levels to freely fluctuate, based on the operation of the five high mountain reservoirs. The priorities assigned to each reservoir reflect the ordered preference of meeting the new management operating rules. Table 8 lists all the reservoirs and their corresponding priorities. Determination of these priority factors requires successive approximation. A set of initial priorities are selected. MODSIM computes storage levels based on these values. These storage levels are then compared to the desired levels for recreation enhancement, and the priority factors adjusted appropriately. It must also be remembered that throughout this analysis, the priority established on demands is significantly higher than any reservoir storage priority to insure satisfaction of the demands for reservoir water.

It can be seen from these priorities that Barnes Meadow and Twin Lake reservoirs are given equally the highest consideration for storage maintenance, followed in order by Peterson, Commanche, and Big Beaver reservoirs. Priorities for the remaining non-recreational reservoirs reflect a desire to maintain water as high as possible in the system for added flexibility.

Table 8. Storage Priorities for High Mountain Reservoir Management Analysis

Reservoir	Priority Factors*		
	1972-1973	1973-1974	1974-1975
Peterson	50	50	50
Barnes Meadow	40	40	40
Big Beaver	80	80	80
Comanche	60	60	60
Twin Lake	40	40	40
Worster	75	75	75
Halligan	85	85	85
Park Creek	90	90	90
North Poudre #15	115	115	115
Milton Seaman	200	200	200
Aggregate	150	150	150

*A lower value is interpreted as a higher priority.

A.2. Results of Analysis

Figures 14 through 21 graphically display the results of this management analysis. Both the historical and the calculated monthly ending storage values are plotted over the 36 month simulation period. Keeping in mind that the same demand for reservoir water is met in each instance, and based on admittedly conservative evaporation rates, the alternative management strategy is clearly *hydrologically* viable. Upon initial filling, Barnes Meadow and Twin Lake reservoirs maintain near capacity storage levels throughout the simulation period, as expected. Also, Peterson Reservoir, which has the next greatest recreation potential (reflected by its priority in relation to Barnes Meadow and Twin Lake reservoirs) remains filled near capacity. Commanche and Big Beaver reservoirs are drawn empty in late 1975, which is acceptable. The remainder of the reservoirs fluctuate between zero storage and their maximum capacity as dictated by the demand pattern.

Carry-over storage at the end of the three-year period should be reasonably consistent with that calculated during calibration. A value of 6053 acre-feet of total carry-over storage was obtained from MODSIM calibration. This compares to a value of 4709 acre-feet of total carry-over storage for the new management scheme. A difference is expected due to changes in the distribution of the carry-over storage and variations in channel losses between calibration and management study results. Consequently, a difference of 1344 acre-feet is not considered significant when the entire storage capacity of the subsystem is an order of magnitude greater.

A.3. Discussion of Results

It is clear from Figures 14 through 21 that the proposed management strategy simply specifies a shifting of stored water from reservoirs not

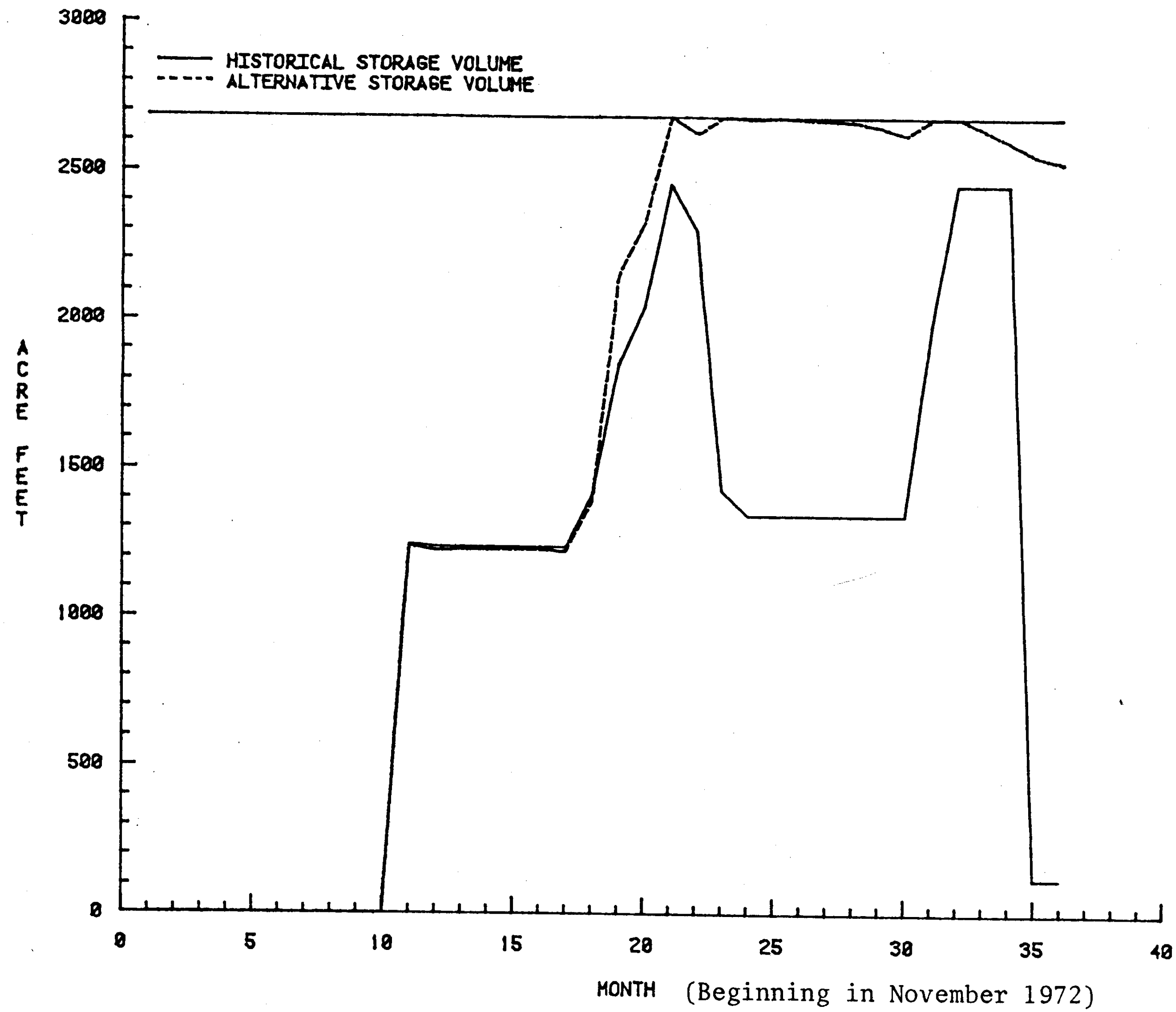


Figure 14. Barnes Meadow Reservoir

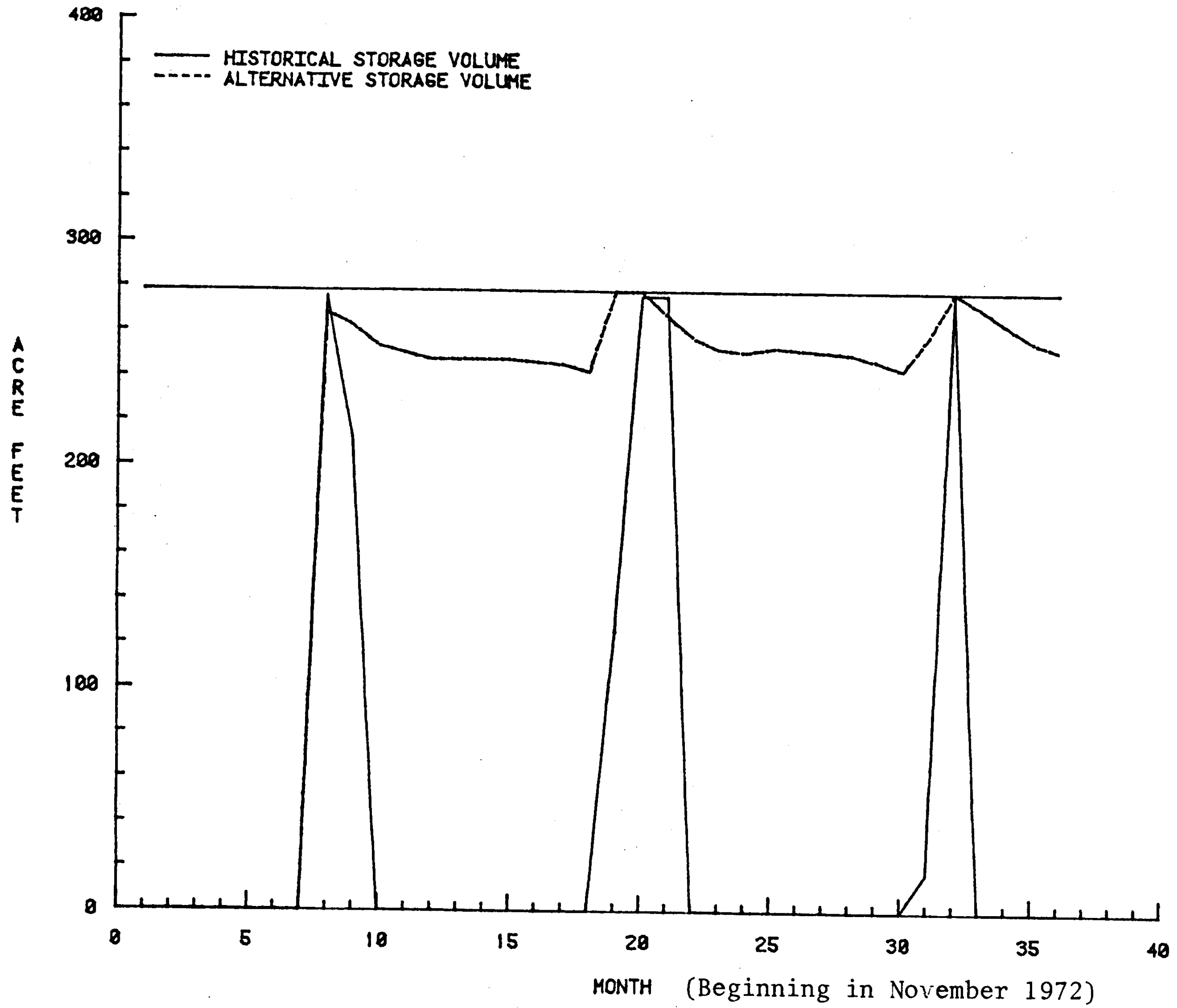


Figure 15. Twin Lake Reservoir

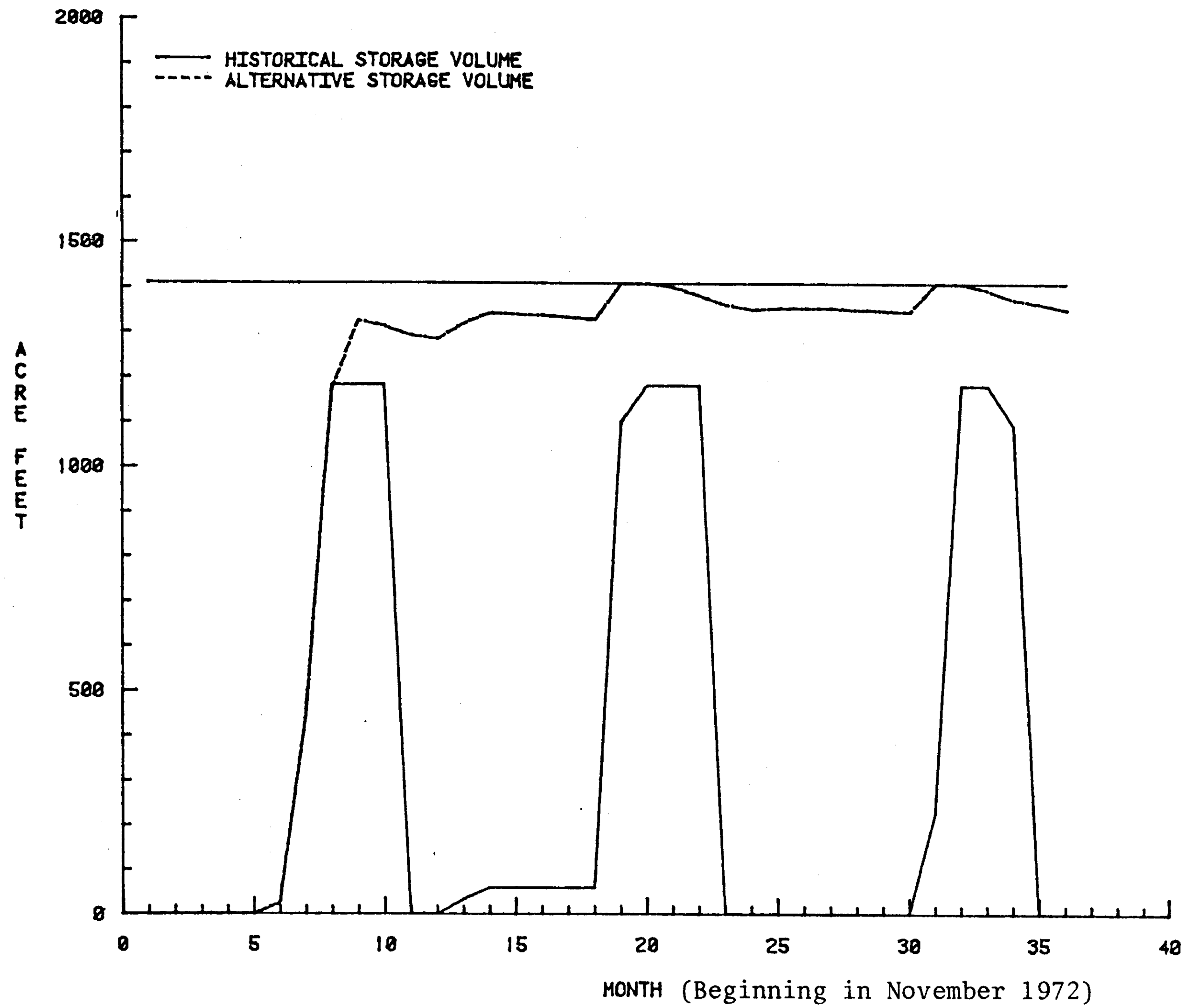


Figure 16. Peterson Reservoir

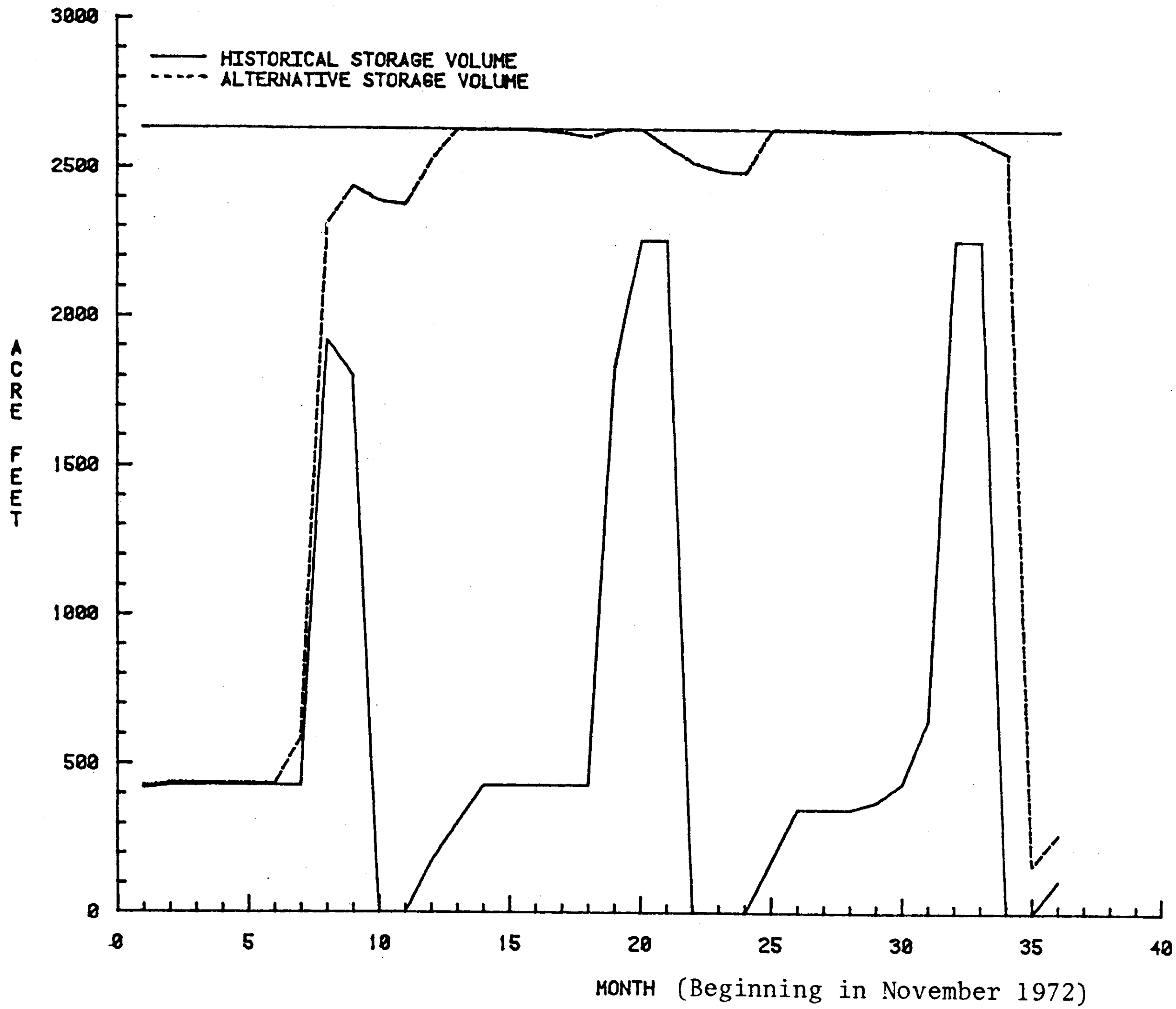


Figure 17. Commanche Reservoir

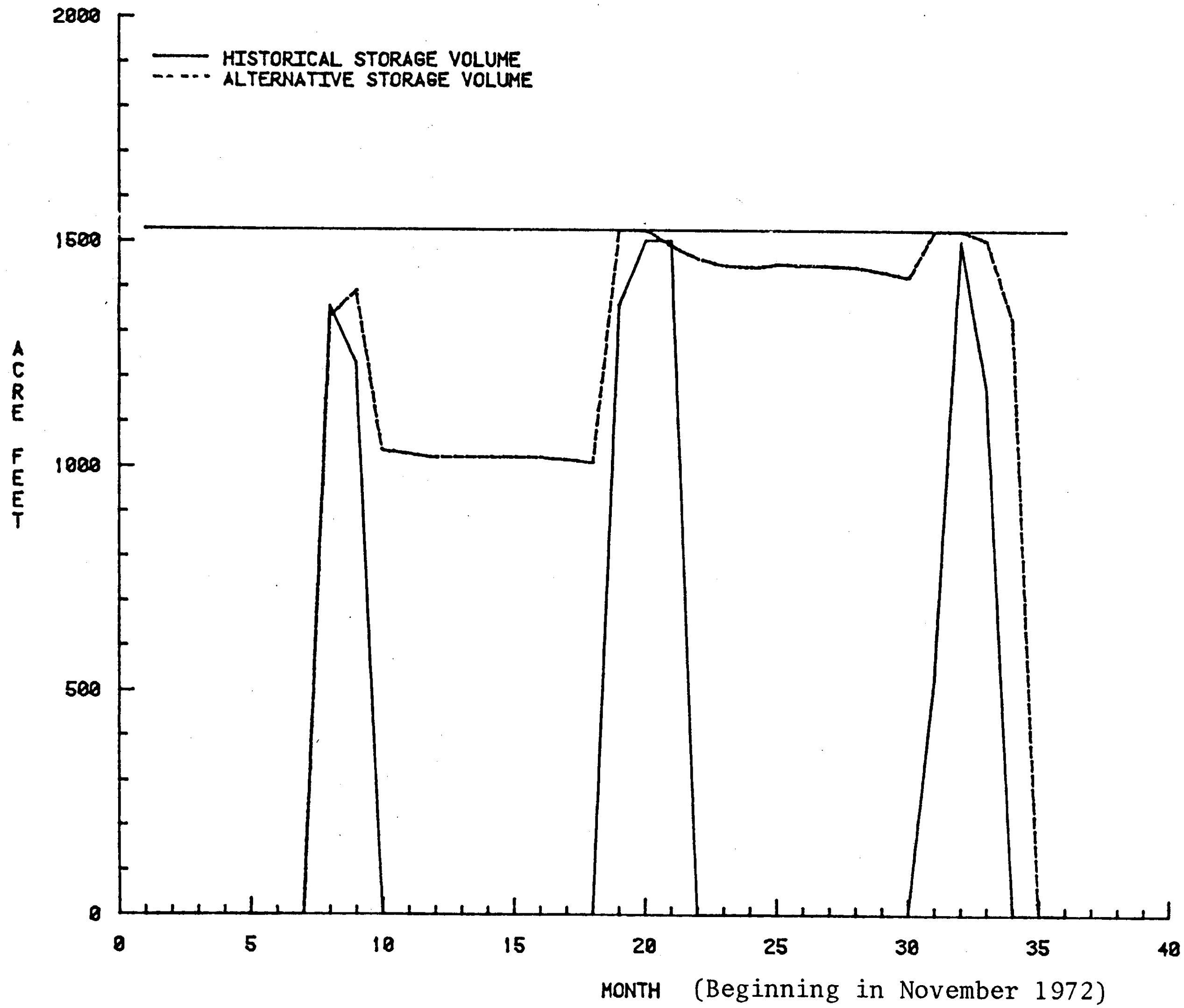


Figure 18. Big Beaver Reservoir

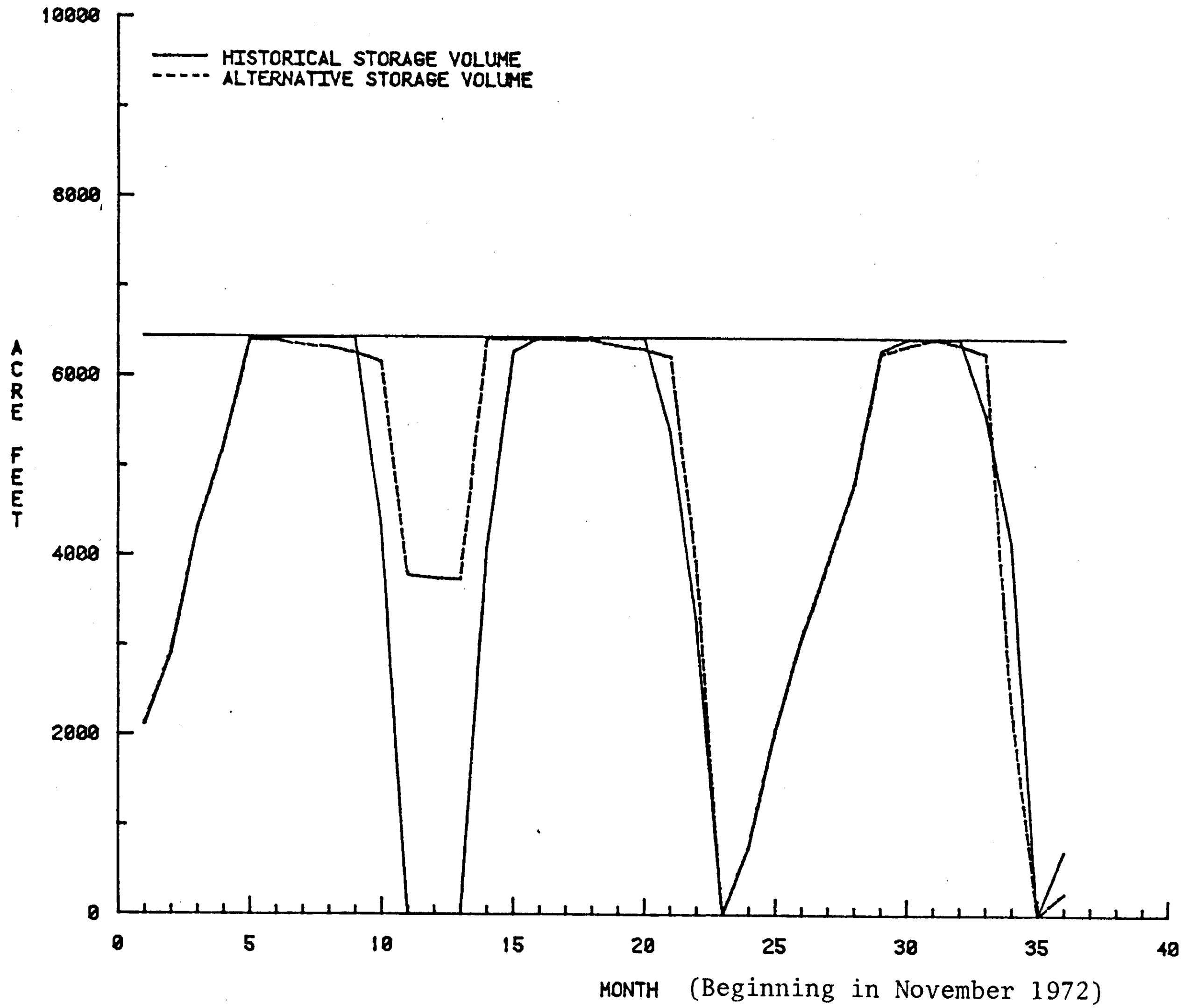


Figure 19. Halligan Reservoir

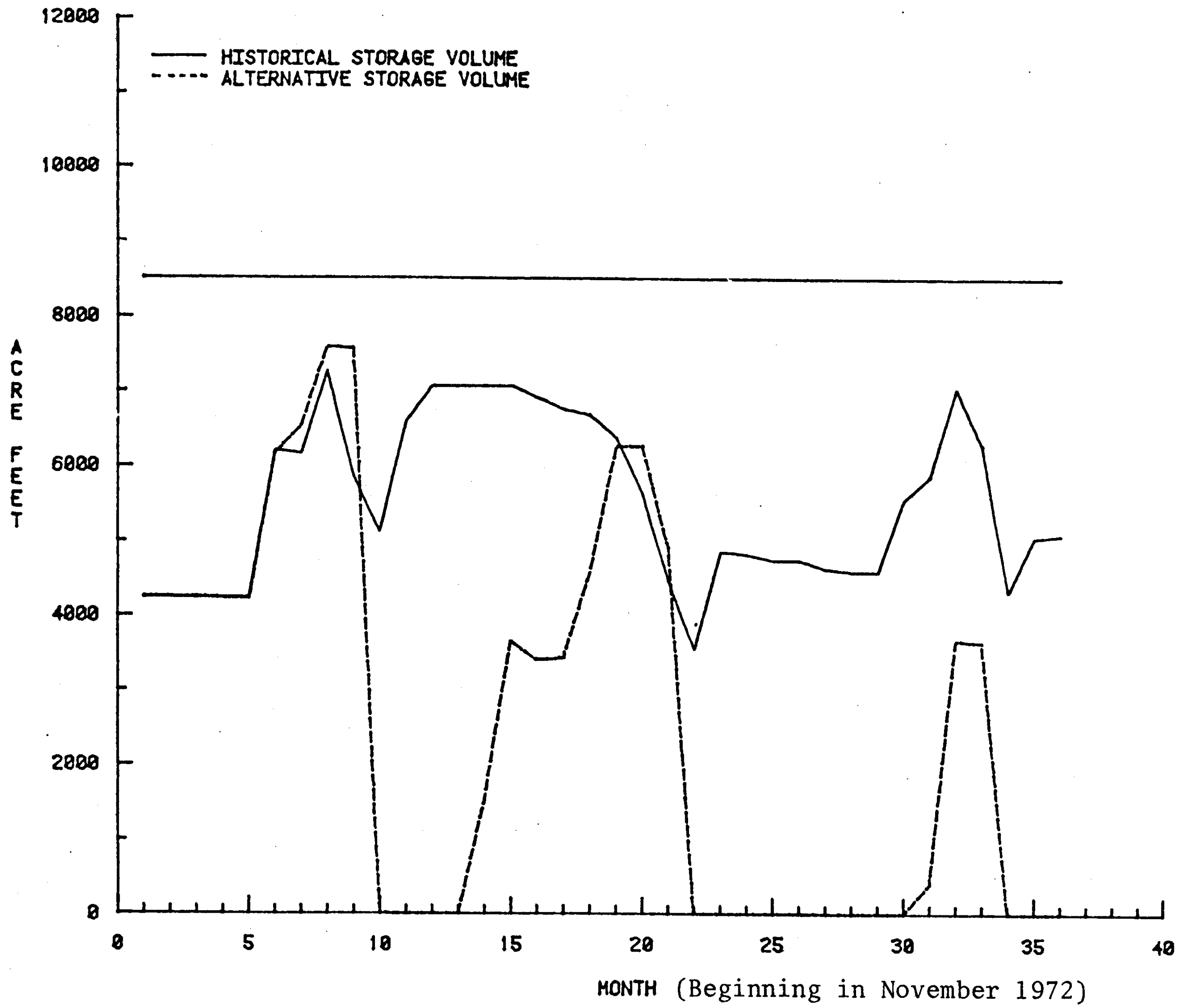


Figure 20. Park Creek Reservoir

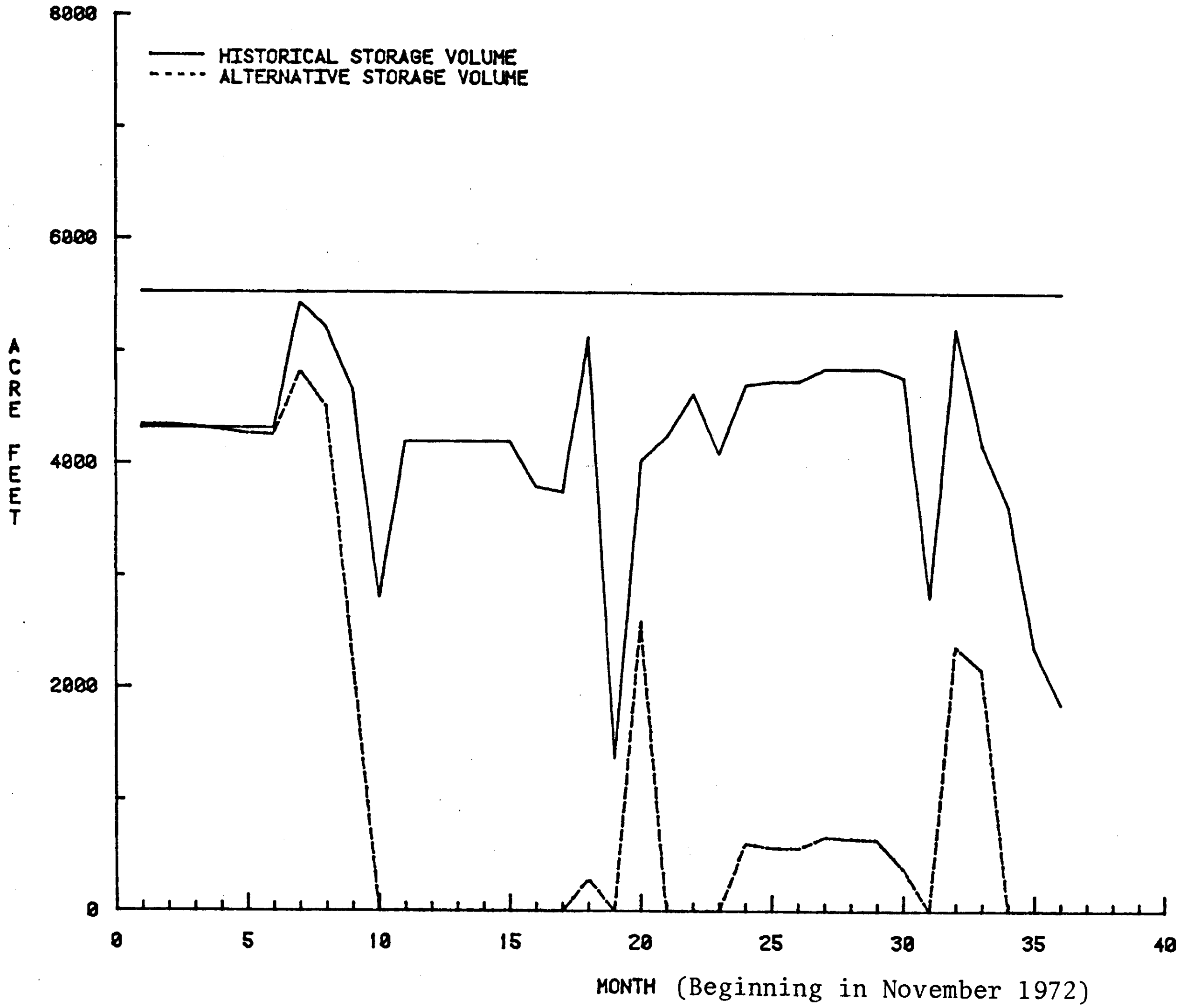


Figure 21. North Poudre No. 15 Reservoir

conducive to recreation to those high country reservoirs with greater recreation potential. Large conservation pool levels are able to be maintained in three out of the five high country reservoirs. Commanche Reservoir, however, must be emptied along with Big Beaver Reservoir, which appears to have little recreation potential. For the three-year period considered in this study, it is evident that enough water is available in the subsystem to maintain storage levels in certain selected high country reservoirs, while still meeting the historical demand for water from all the reservoirs under investigation. This is partly due to the large difference in storage volume between the plains reservoirs and the high mountain reservoirs. The total combined storage volume for Twin Lake, Commanche, Peterson, and Barnes Meadow reservoirs is approximately 7000 acre-feet, while the combined storage of the plains reservoirs is over 25,000 acre-feet, not including Milton Seaman Reservoir or the aggregated reservoirs.

The simulated operation of Halligan Reservoir is very near that which took place historically, except MODSIM produced slightly less drawdown at the end of 1973. For 1974 and 1975, the historical and simulated operation of the reservoir is identical. Significant operational changes in plains reservoirs occur in Park Creek Reservoir and North Poudre Reservoir No. 15. From the figures, it is readily evident that a highly fluctuating, intraseasonal storage and release policy has been replaced by a more regular filling and emptying policy not unlike the operating policy historically observed for the high country reservoirs. Also, it should be noted that the ending storage in Worster Reservoir is the same for the new management scheme as the ending storage historically recorded, insuring that no additional water was obtained from this source. It is included in the analysis because Halligan Reservoir is on-line downstream from it, so that releases from Worster Reservoir contribute to the total inflow to Halligan Reservoir. To insure that no double accounting takes place, the initial storage in the aggregate reservoir is set equal to zero, thereby not allowing additional water from this source to be allocated toward the satisfaction of its own demand. The ending storage in the aggregate reservoir is also zero, which means that no water was taken from the other reservoirs unnecessarily.

There are many *legal* issues which also must be dealt with before attempting to actually implement this type of management practice. Such a strategy involves the storing of water out of legal priority. However, stored water is merely being transferred to other portions of the system, and overall demands should continue to be satisfactorily met. The exchange program is specificially designed for such an action.

The release or storage of water in the Greeley high mountain reservoirs would have no impact downstream of the turnout to the Munroe Canal. Fortunately, since the Munroe Canal is the highest (most upstream) diversion for irrigation water in the system, changing the operating policy of the high mountain reservoirs would have zero impact (positive or negative) on the remaining water use structure within the basin. It is true, however, that flow levels in the Poudre River upstream of the Munroe Canal will be affected by changes in the operating policies of the high mountain reservoirs. Historically, releases from these reservoirs during late summer help to augment the natural flow in the river, which is low during this time. In recognition of this fact, the effect of the new management strategy on river flow levels is determined. Traditionally, the split between high mountain reservoir water delivered to the Munroe and North Poudre canal system and other reservoir water delivered to the system is approximately 35 percent and 65 percent respectively. The new management scheme results in a split in delivery of roughly 2 percent and 98 percent between high country and plains reservoirs. This change in percentage of the prospective sources of reservoir water is most critical in the first year when the mountain reservoirs are filling and release no water. Subsequent to filling, only that portion of the annual inflow necessary to maintain the storage pool is held while the remainder is released downstream. Calculated river flows vary from historical values only during the months of May through September (the typical operating period for high country reservoirs). Table 9 shows the percentage decrease in total river flow above the Munroe Canal and the resultant adjusted flow for 1973, the most critical year, for the new management scheme.

The minimum monthly flow occurs in February and is 1301 acre-feet. This flow is unaffected by the change in operating policy of the high mountain reservoirs. A decrease in flow volume begins in May and increases, as expected, to a maximum of approximately 87 percent of the historical flow in September. However, the adjusted flow in September (7,534 acre-feet) is still above the minimum flow in six out of the twelve months. Based on this analysis, it is concluded that the new management strategy will not seriously alter volumetric flow levels in the river.

In case of severe drought conditions, water could still be taken from the high country reservoirs to meet pressing downstream agricultural, industrial, and municipal water needs. Such emergency releases could be conducted in ways which would distribute the drawdown proportionally to the capacity of each reservoir in order to minimize the destruction of the fishery of any one particular reservoir. Since, by definition,

Table 9. Change in River Flow above Munroe Canal - 1973

Month	% Decrease in Total River Flow Above Munroe Canal	Calculated Adjusted River Flow Above Munroe Canal - Acre-feet
NOV	0	2,497
DEC	0	1,590
JAN	0	1,460
FEB	0	1,301
MAR	0	2,000
APR	0	3,470
MAY	0.18	89,310
JUN	0.33	132,976
JUL	0.68	76,035
AUG	9.56	25,541
SEP	12.95	7,534
OCT	0	5,210

the high mountain reservoirs are at higher elevations, there is much greater flexibility in meeting downstream water demands as a result of the new management approach. A small release from several of these reservoirs would serve the same purpose as a large release from a single reservoir.

B. CASE STUDY #2

B.1 Methodology

The goal of this case study is to determine if, using that portion of effluent from Fort Collins attributable to new foreign water, the Rawhide Project cooling pond could be filled by 1985 and if, from the same source, a minimum of 4200 acre-feet can be supplied to the power plant annually. To pursue this goal using MODSIM, the network for which the model was calibrated must be revised to better account for the proportions of new foreign water delivered to the City and new foreign water spilled downstream (Figure 22). Also, the interaction between the river and the Rawhide Pipeline is eliminated so that no direct flow may enter the pipeline. However, the network is adjusted in such a manner that still allows the City to divert effluent directly to the river as well as to the pipeline and Fossil Creek Reservoir. Long Draw Reservoir is decomposed into two reservoirs (dashed line) to reflect the fact that only 6000 acre-feet are available for storage of imported water. All imports to Long Draw Reservoir occur at node 10 with a storage capacity of 6000 acre-feet, while intrabasin inflows to Long Draw Reservoir are restricted to node 1 with a storage capacity of 4400 acre-feet. The combined capacity of the reservoir is then 10,400 acre-feet. Linkages directly connecting Joe Wright Reservoir and Long Draw Reservoir with Fort Collins (links 2 and 4, respectively) were included in order to differentiate between these sources and the exercise of the direct flow

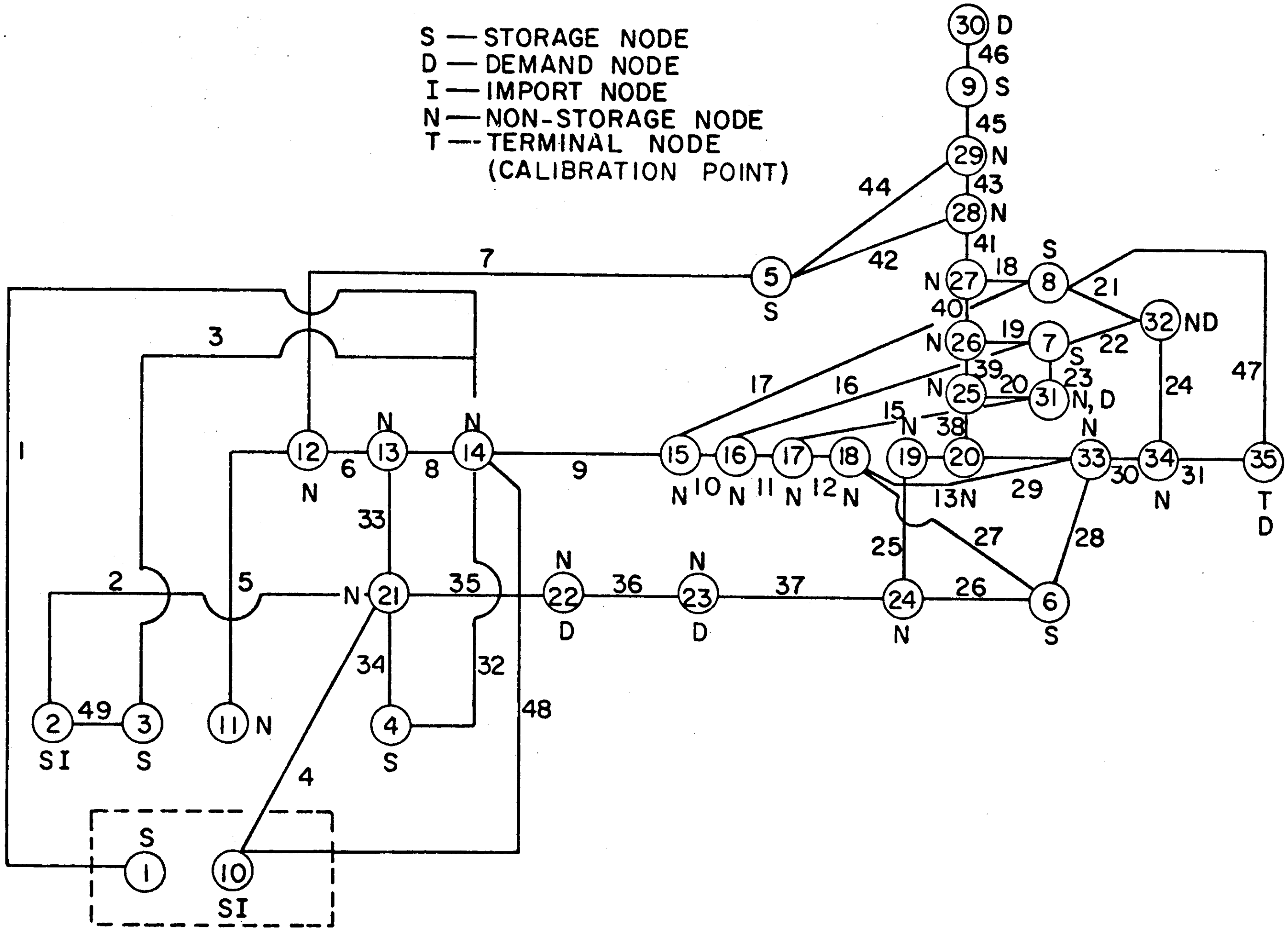


Figure 22. Revised Node-Link Configuration for Rawhide Case Study

rights of the City. These reservoirs also remain linked (directly or indirectly) to the river. Such a change allows the model to account for spills of water downstream that are not diverted to the City. Appropriate channel losses are considered in both branches for each reservoir.

Although the model was calibrated for the three-year historical period 1973 to 1975, the required management study planning horizon is 19 years, from 1981 to 1999. This period is chosen in accordance with contract specifications which state that the filling of the cooling pond is to be initiated in 1981; the operation of the first generating unit is to begin in 1985; and the Windy Gap Project is to assume responsibility for meeting Rawhide Project demands in the year 2000. This extended 19-year period is consistent with the calibration phase since the river is over-appropriated which means that the water rights structure should not change appreciably. It is also assumed that the direct flow rights the City holds for Cache la Poudre River water will remain constant over this period. Table 10 lists the total monthly direct flow right exercised by Fort Collins. Each month throughout the analysis the appropriate direct flow must be totally diverted by the City before any reservoir water, including Horsetooth Reservoir water, can be delivered to the City. This constraint on the operation of the system is satisfied by setting the upper bound for the link connecting the City with the river at the City's direct flow right for each month and giving the link a very low cost as compared to all other links. In this manner, the most attractive transfer (from an optimization viewpoint) of water in the network is via this link (#33), and when feasible, flow should be at the upper bound.

The total annual demand for water by Fort Collins had to be estimated for the period 1981 to 1999. This was accomplished by fitting an

Table 10. Fort Collins Monthly Total Direct Flow Right

Month	Acre-Feet
NOV	864
DEC	893
JAN	893
FEB	807
MAR	893
APR	1054
MAY	1186
JUN	1148
JUL	1186
AUG	1186
SEP	1148
OCT	1035
TOTAL	12293

Table 11. Projected Annual Fort Collins Demand

Year	Acre-Feet	Year	Acre-Feet
1981	19451	1991	26074
1982	20334	1992	26773
1983	21097	1993	27494
1984	21661	1994	28229
1985	22244	1995	28987
1986	22839	1996	29769
1987	23454	1997	30565
1988	24082	1998	31385
1989	24729	1999	32227
1990	25245		

Table 12. Modified Consumptive Loss Percentages for the City of Fort Collins (Resource Consultants, Inc., 1978)

Month	Consumptive Loss (%)
NOV	1.5
DEC	1.5
JAN	1.5
FEB	1.5
MAR	1.5
APR	25.8
MAY	27.5
JUN	51.4
JUL	60.1
AUG	57.6
SEP	47.3
OCT	29.4

exponential curve to the values forecast for years 1980, 1990, and 2000 by the Water Utilities Department, City of Fort Collins (1977). The projected annual Fort Collins demand over the period of analysis is presented in Table 11. The same monthly distribution of the annual demand is employed for the management study as for the calibration phase. However, the monthly consumptive loss percentages for the City were modified slightly to better conform to normal conditions. These modified values are listed in Table 12. These values are used to determine what portion of the total monthly diversion of water by the City is available as effluent. It must be remembered, however, that under the contract, only the effluent attributable to new foreign water can be diverted to the pipeline. Again, the sequential preference of source of supply for Fort Collins is: (1) direct flow river water, (2) new foreign water (Joe Wright and Long Draw reservoirs), and (3) Horsetooth Reservoir water. If in any given month the City has fully exercised its direct flow right, it can start to use the transmountain water (if available), and the resulting effluent can be diverted to the pipeline.

It was necessary to generate monthly data for both sources of foreign water (Michigan Ditch and Grand River Ditch) over the period of analysis. Resource Consultants, Inc. (1978) generated these data by determining the similarity of runoff potential of the watersheds which provide water for the Michigan Ditch and Grand River Ditch systems. Four years (1974 through 1977) of monthly data pertaining to the potential reusable water from the Michigan Ditch was correlated with the historical yield of the North Fork of the Michigan River to obtain 19 years of generated diversions via the Michigan Ditch. Table 13 contains these estimates of Michigan Ditch diversions. These data are input to MODSIM as annual values with appropriate monthly distributions.

Table 13. Generated Monthly Estimates of Michigan Ditch Diversions to Joe Wright Reservoir (acre feet)

Year	May	June	July	Aug.	Sept.	Total
1981	152	1848	1123	334	30	3487
1982	237	2651	1262	315	39	4504
1983	199	2280	1061	266	33	3839
1984	151	1841	1120	333	30	3475
1985	211	2424	1125	281	35	4076
1986	204	2346	1089	272	34	3945
1987	241	2694	1288	322	40	4585
1988	144	744	341	52	0	1311
1989	147	1787	1092	325	29	3380
1990	209	2412	1118	279	35	4053
1991	190	1165	832	143	48	2378
1992	199	2287	1064	266	32	3848
1993	208	2386	1105	276	34	4009
1994	199	2281	1062	265	33	3840
1995	212	2434	1131	283	35	4095
1996	219	2497	1170	292	37	4215
1997	151	1847	1123	333	30	3484
1998	214	2430	1130	283	35	4092
1999	209	2407	1115	278	34	4043

Estimates of Grand River Ditch diversions were generated in much the same manner and are reported in Table 14.

In Figure 23, the generated total imports of water from the Michigan Ditch and Grand River Ditch are plotted for each year. These values are then separated into three distinct groups; with the limitation that for any one year both imports must be in the same category. These groups are then interpreted as wet (1973), intermediate (1974), and dry (1975) according to the results of the calibration phase. Therefore, for each year a complete and representative hydrology is obtained for input to the model. For example, for 1985 the generated transmountain diversions are coupled with the 1985 projected Fort Collins demand. Historical adjusted inflows and demands, along with the estimated return flows for 1974, are then combined with the 1985 projections to form a complete and consistent hydrological sequence for 1985. This approach is justifiable because the river is vastly over-appropriated. It is likely that no additional water will be allocated to the various demand centers without significant changes in the character of the basin, which are not expected over the planning period. Also, dry years in relation to unregulated inflows originating within the basin, and the amount of demand satisfaction realized in any year is directly proportional to the water available from snowmelt. This is the reason that, for this example, 1974 demands and return flows remain coupled with 1974 inflows. Likewise, it is doubtful that, for this limited area, great differences (relative to the size of the basin) in snowpack would occur. Finally, it can be shown from the historical record that very rarely are there more than two dry years in succession, or for that matter two wet years. This observation influenced the placement of the imports into their respective categories.

Table 14. Generated Monthly Estimates of Grand River Ditch Diversions to Long Draw Reservoir (acre feet)

Year	May	June	July	Aug.	Sept.	Total
1981	308	1679	644	168	0	2799
1982	305	3763	4475	1322	305	10170
1983	555	3202	1786	493	123	6160
1984	219	1263	704	194	49	2429
1985	366	1993	764	199	0	3322
1986	406	2683	3740	1138	163	8130
1987	223	2753	3274	967	223	7440
1988	97	642	894	272	39	1944
1989	112	740	1032	314	45	2243
1990	916	4997	1916	500	0	8329
1991	85	557	777	236	34	1689
1992	779	4501	2510	693	173	8656
1993	282	1633	911	251	63	3140
1994	261	1504	840	232	58	2895
1995	1032	5632	2159	563	0	9386
1996	937	5109	1958	511	0	8515
1997	227	1312	732	202	50	2523
1998	599	3462	1931	533	133	6658
1999	158	1043	1454	443	63	3161

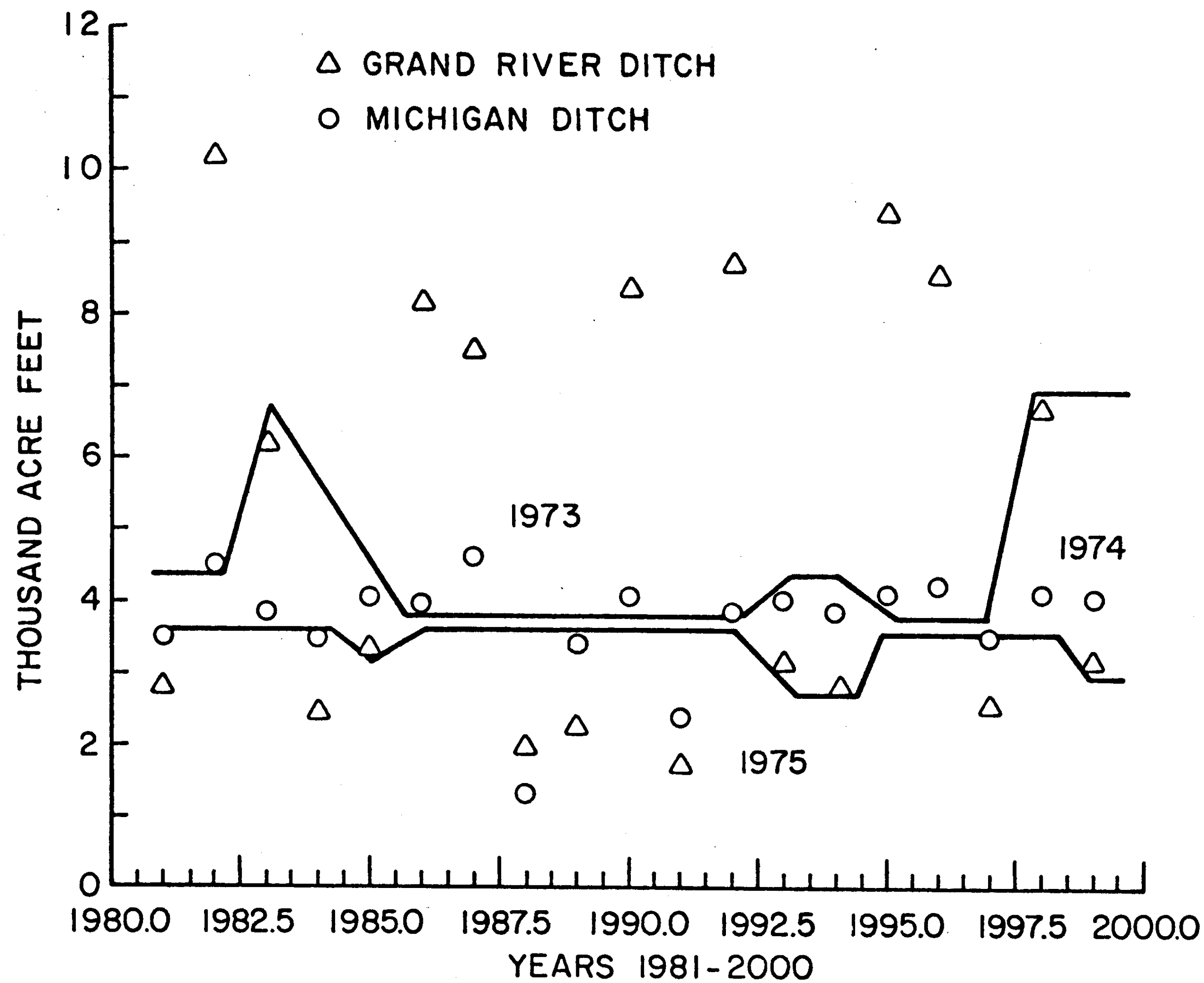


Figure 23. Generated Projections of Future Imported Water Amounts

The hydrologic situation for each year of the analysis is constructed in the above fashion.

The 19 years of data were programmed and an initial set of priorities were chosen. MODSIM computed the transfers of water throughout the network based on these priorities. The results were analyzed by a supplemental computer program which takes the linkage flows calculated by MODSIM and tabulates the reusable effluent attributable to Joe Wright and Long Draw reservoir releases delivered to Fort Collins. The priorities (of storage versus release in the reservoirs) were then adjusted in such a manner as to converge on a value of 4200 acre-feet or more annual reusable water from these two reservoirs. A discussion of the method of adjustment of these priorities is included in the final section of this chapter. Fifteen successive adjustments of these priorities were necessary before a reasonable conclusion was obtained.

B.2. Results of Analysis

First, the projected demand for water by Fort Collins is satisfied, without exception, in every year throughout the simulation period. Also, Fort Collins direct flow right is fully exercised in every month of the analysis, as required. Figure 24 shows the proportions of the supply (direct flow, Horsetooth Reservoir, Long Draw Reservoir, and Joe Wright Reservoir) contributing to the yearly projected demand. It is interesting to note that the amount of Horsetooth Reservoir water required, according to the final scheme, steadily increases while the amount of Joe Wright and Long Draw reservoir water remains fairly constant.

In Figure 25 the amount of reusable effluent resulting from Joe Wright Reservoir and Long Draw Reservoir releases to the City is displayed. Only in the first year (1981) is the return flow less than the 4200

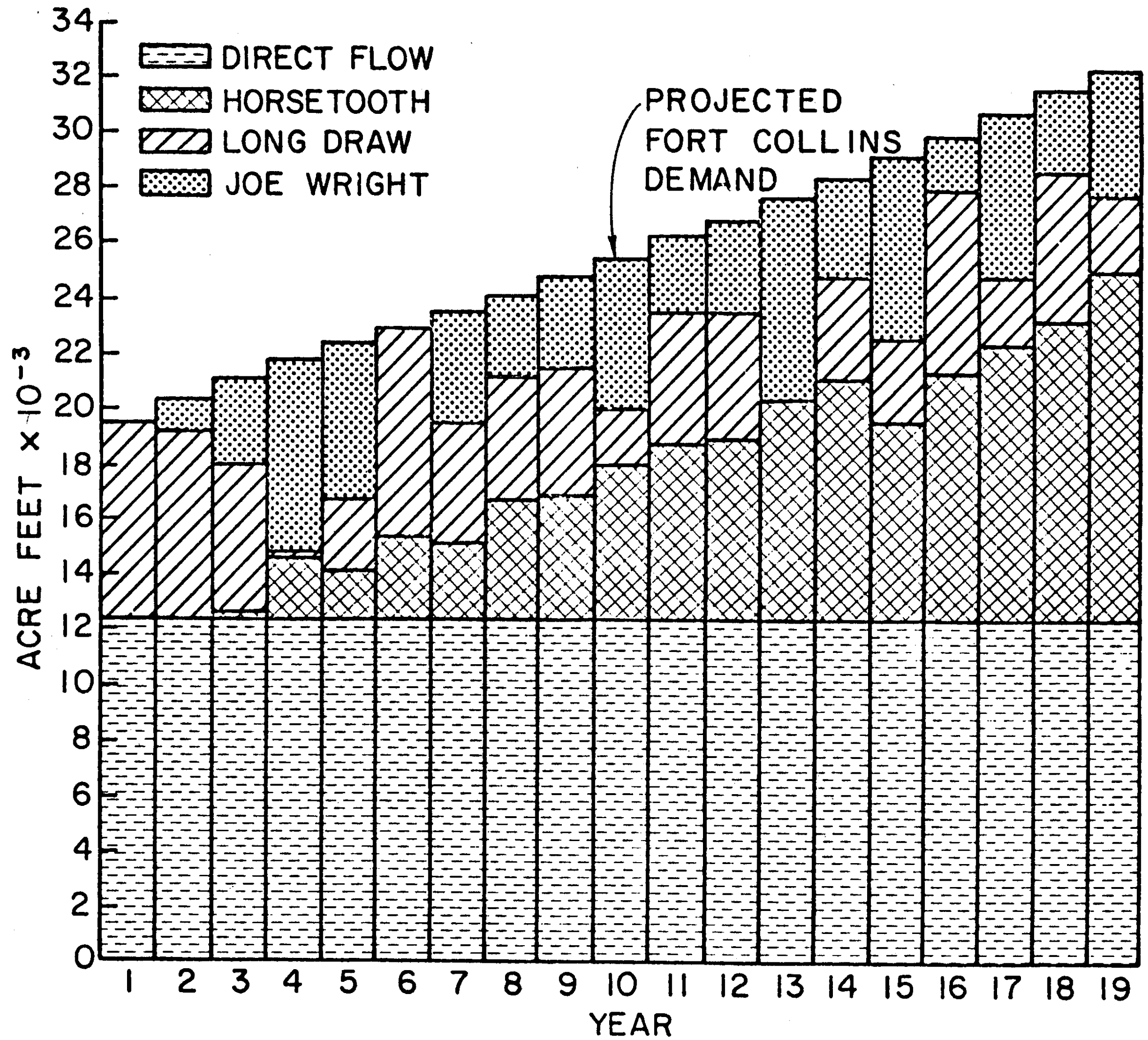


Figure 24. Projected Sources of Supply to Fort Collins Calculated by MODSIM

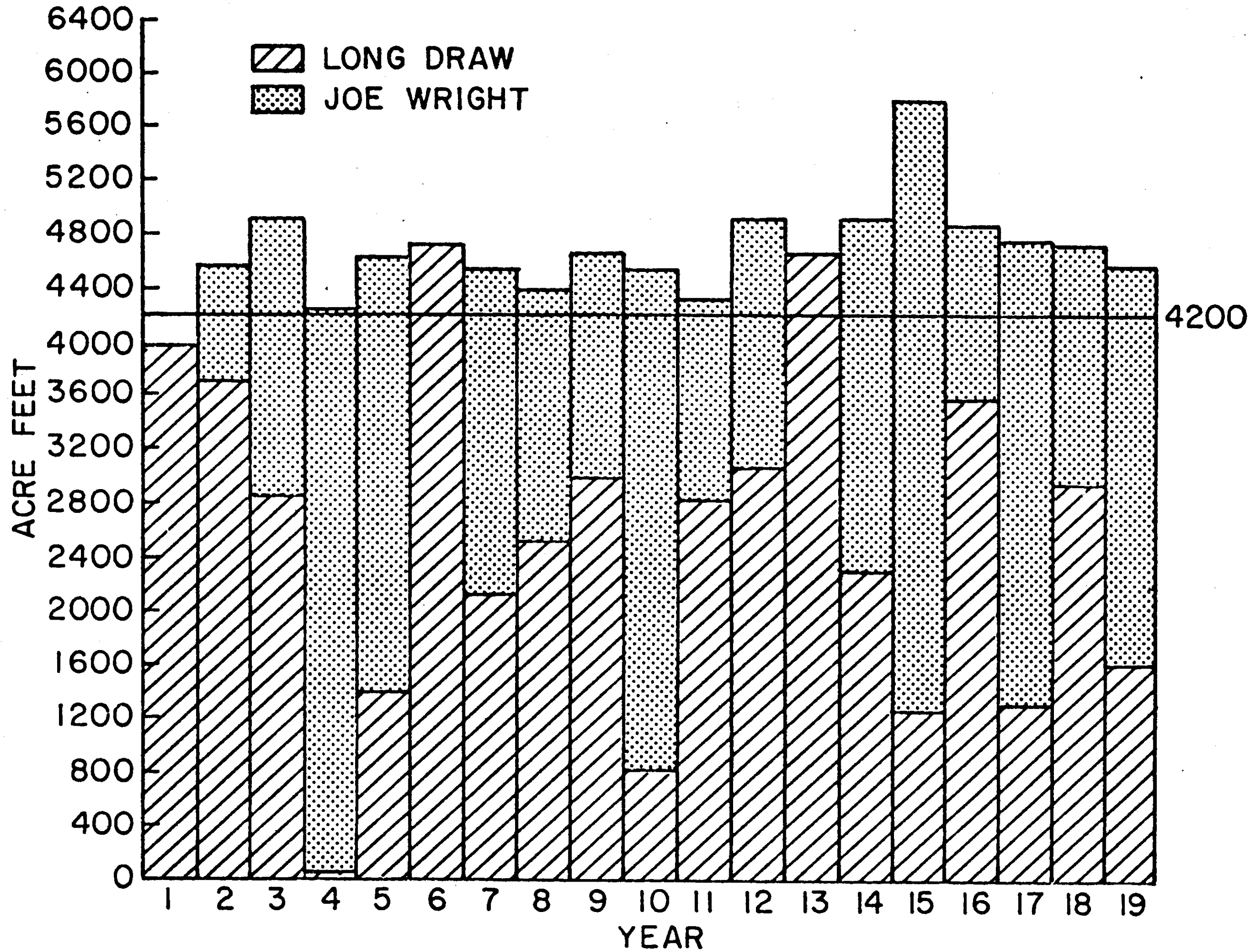


Figure 25. Projected Annual Amount of Reusable Effluent from Fort Collins

acre-foot target. This is because the projected Fort Collins demand for 1981 is too small to allow enough water from the reservoirs to be used to obtain 4200 acre-feet of reusable effluent. However, in all the remaining years this target is exceeded. Excluding the first year, the mean annual deliverable effluent to Rawhide Pipeline is 4662 acre-feet, and for the entire 19-year period a surplus of 8776 acre-feet above the annual 4200 acre-feet required is calculated. Also, during several high flow years (i.e., when importation of relatively large amounts of foreign water occurs) spills from these two reservoirs occur. The total amount of spills calculated by the model equals 4075 acre-feet; 336 acre-feet from Joe Wright Reservoir and 3739 acre-feet from Long Draw Reservoir.

As noted earlier, the first four years of the analysis are designated as a filling period for the cooling pond. From the results obtained from MODSIM, there are 17,651 acre-feet of reusable water available for filling the pond during this period. A uniform rate of delivery is not essential to the filling; therefore, no borrowing or exchange program needs to be invoked. For the first four years, water is delivered to the pond as available. The capacity of the pond is estimated at 13,000 acre-feet, which means that about 4650 acre-feet of excess water is available for evaporative losses during filling. MODSIM calculates an evaporation loss during filling of 2239 acre-feet. This leaves an additional 2411 acre-feet for contingencies. The implications of these results are discussed in the next section.

B.3. Discussion of Results

The amount of carry-over storage provided in both Joe Wright and Long Draw Reservoirs from year to year is of critical importance to the ability of these reservoirs to meet the demand for reusable effluent.

Figure 26 shows the combined and individual carryover storage for these reservoirs throughout the period. However, to avoid spills as much as possible the reservoirs must be evacuated early in the year to allow storage space for the incoming transmountain diversions. This is particularly true during high flow years. The most realistic case is tested for this management study, in that the initial storage in Long Draw Reservoir is 6000 acre-feet while Joe Wright Reservoir starts empty. Ending storages are also 6000 acre-feet and zero, respectively.

From the manipulation of the storage priorities for Long Draw REservoir and Joe Wright Reservoir, certain insights into operational guidelines can be gained. The priorities selected for a particular simulation are based on the results obtained from the previous run. This means that past the initial run, a certain degree of foreknowledge or forecasting is employed by the user in determining the adjustments of the priorities to better conform with his mental notion of how the system should function. It is not unrealistic to assume that the actual real-time operation of these reservoirs will be performed with such knowledge available. A better understanding of system response will be acquired with experience. Estimates of snowpack conditions will provide information concerning the hydrology for the upcoming season, which in turn will allow for preliminary formulation of operational guidelines. There is also added realism since the model does the best it possibly can, given flexibility in the system, to apportion water to the various demand and storage centers on a month-to-month basis. Anticipated future inflows are not assumed to be explicitly forecasted and included in the optimization. However, it does select the optimum operating policy for the current month. The *user* must adjust the priorities placed on the

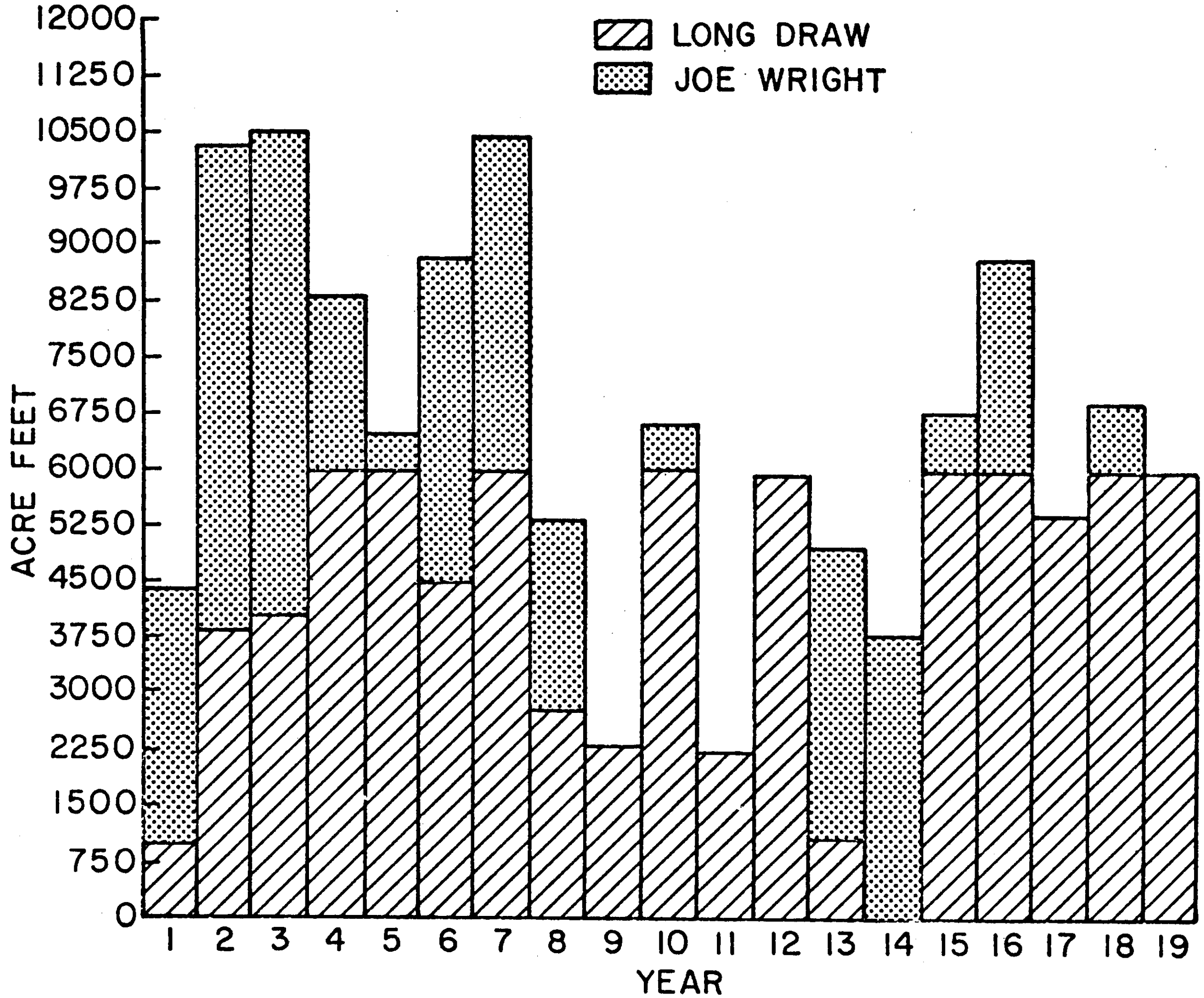
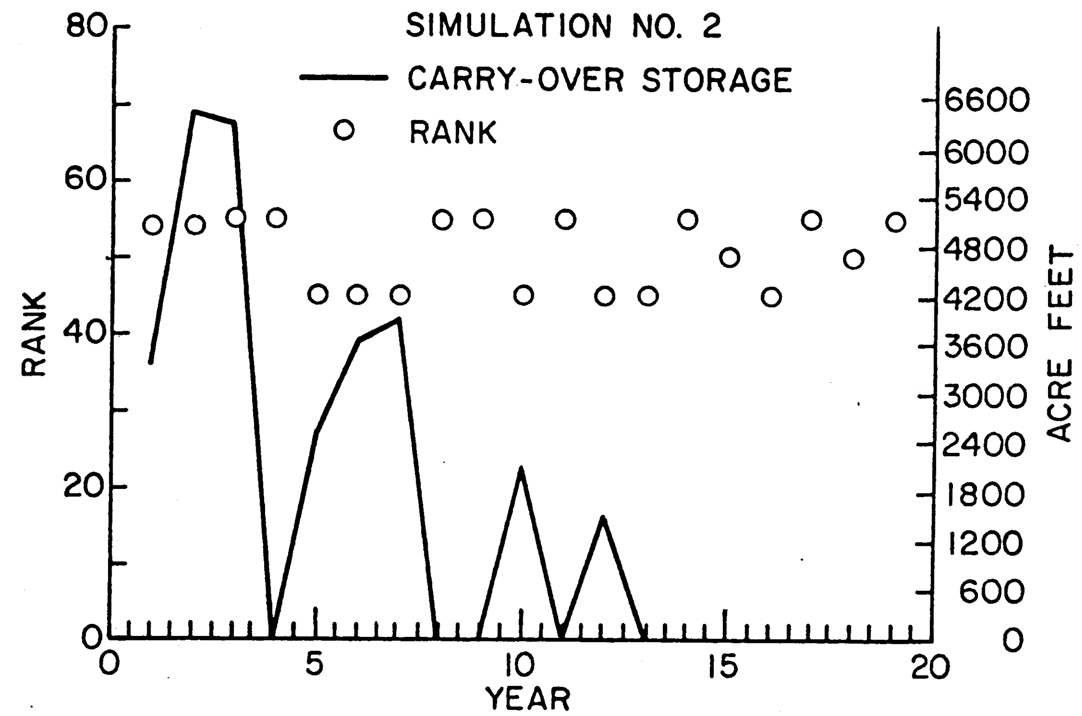


Figure 26. Projected Annual Carryover Storage in Long Draw and Joe Wright Reservoirs

transfer of water throughout the network to consider previous conditions and anticipate future developments.

An example of the above discussion is shown in Figures 27 and 28, which display the sensitivity of storage priorities for Joe Wright and Long Draw reservoirs in determining carryover storage. In both cases, for simulation #2, carryover storage was minimal beyond 10 years, resulting in severe deficiencies in reaching the 4200 acre-foot target in many of these years. However, through successive adjustment of the priorities adequate carryover storage was achieved (simulation #15). *Adequate* refers to the fact that through the provision of carryover storage, 4200 acre-feet, or more, of reusable effluent could be realized from these reservoirs even during dry years. The relationship between storage priority and carryover storage is not linear, however. Physical feasibilities are also active in determining carryover storage as well as the demand structure and variability of monthly consumptive loss rates. From Figures 27 and 28 it is evident that in the first five years or so of the analysis, the change in the priorities between the two simulation runs for both reservoirs has very little impact on carryover storage. Therefore, there is no basic scheme in changing priorities other than gaining experience with the model. However, after a few model runs, the effect of changing the relative and absolute values of the priorities can be anticipated with greater and greater confidence.

Along with the determination of the priorities to be placed on water transfers throughout the system, target storage levels must also be determined. Initially, the desired monthly ending storage levels for Long Draw and Joe Wright reservoirs were established at maximum capacity.



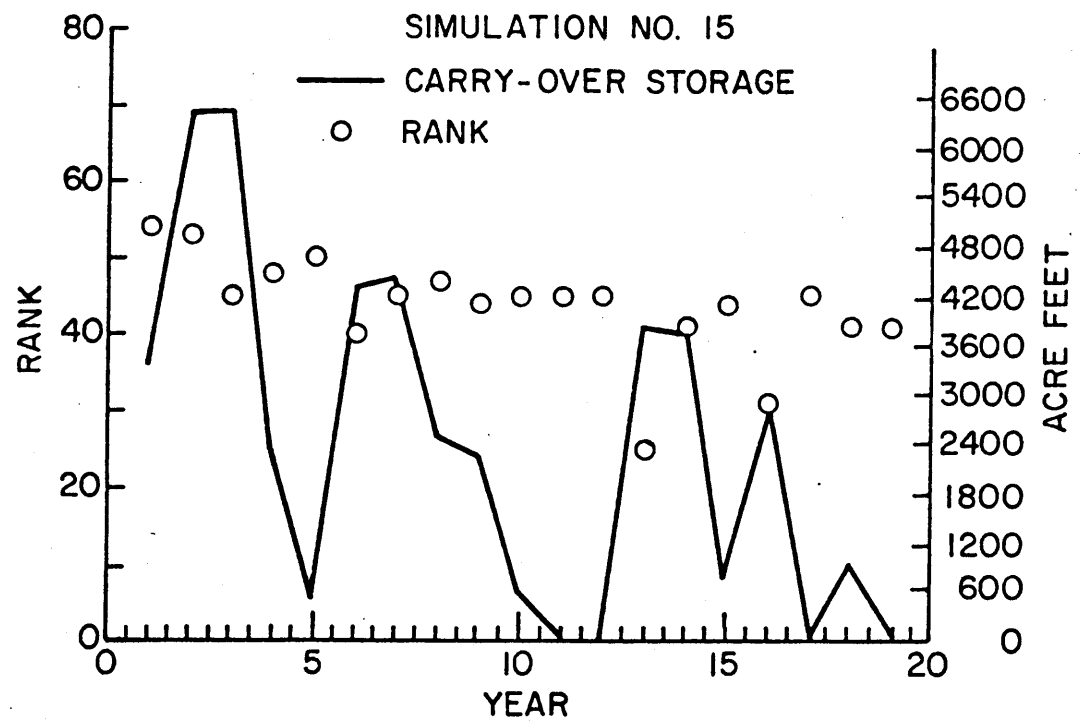


Figure 27. Sensitivity of Carryover Storage to Rank Priorities for Joe Wright Reservoir

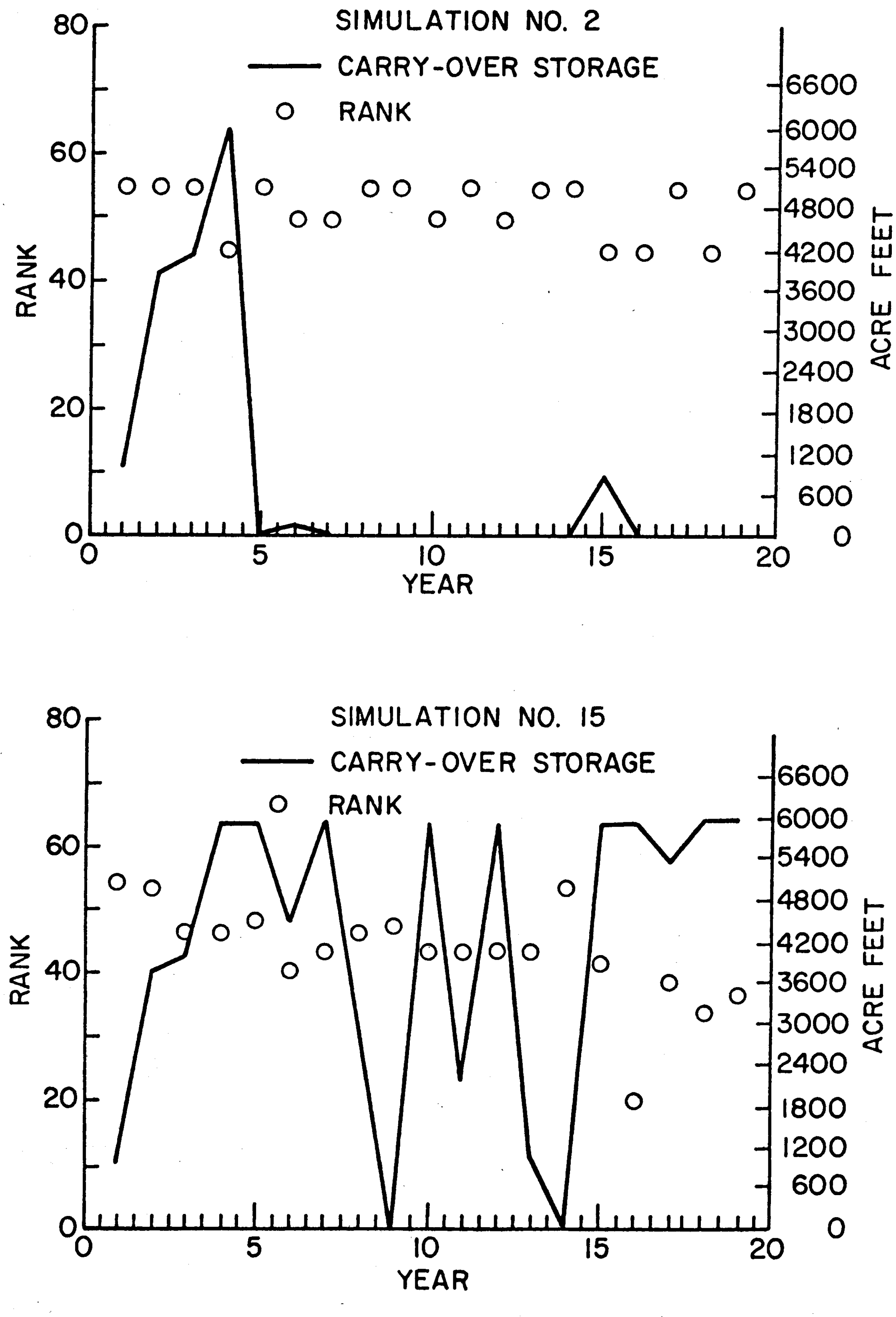


Figure 28. Sensitivity of Carryover Storage to Rank Priorities for Long Draw Reservoir

Subsequently, it was discovered that such a policy leads to a greater amount of spills (water lost from first use opportunity by the City) than necessary. For this reason, in the first years of the analysis target storage levels were set below maximum capacities in order to evacuate part of the reservoirs to allow for the storage of anticipated large inflows later in the season. Figures 29 and 30 display the target monthly ending storage and the calculated monthly ending storage throughout the 19-year period for each reservoir. During the later part of the period, storage levels in Joe Wright Reservoir approach the maximum capacity but do not reach it, while Long Draw Reservoir storage levels remain at or near capacity during the final months. This scheme does not totally eliminate spills but it does reduce them considerably. Also, foreknowledge of the magnitude of transbasin diversions coupled with the variable consumptive loss rates characteristic of the return flow of the City, can be used to minimize spills. During high flow years, it is advantageous to transfer a large amount of foreign water to the City during the high consumptive loss months; while conversely, it is of benefit to transfer more foreign water to the City in low flow years during the low consumptive loss months.

Demand shortages throughout the remainder of the system are aggregated at the terminal node, and are reasonably consistent with the demand shortages occurring during the calibration phase of this study. An underestimate of the availability of Horsetooth Reservoir water to meet this demand is possibly part of the cause for the shortage. As Fort Collins draws increasing amounts of Horsetooth Reservoir water to meet projected demands, an increasing portion of this water becomes

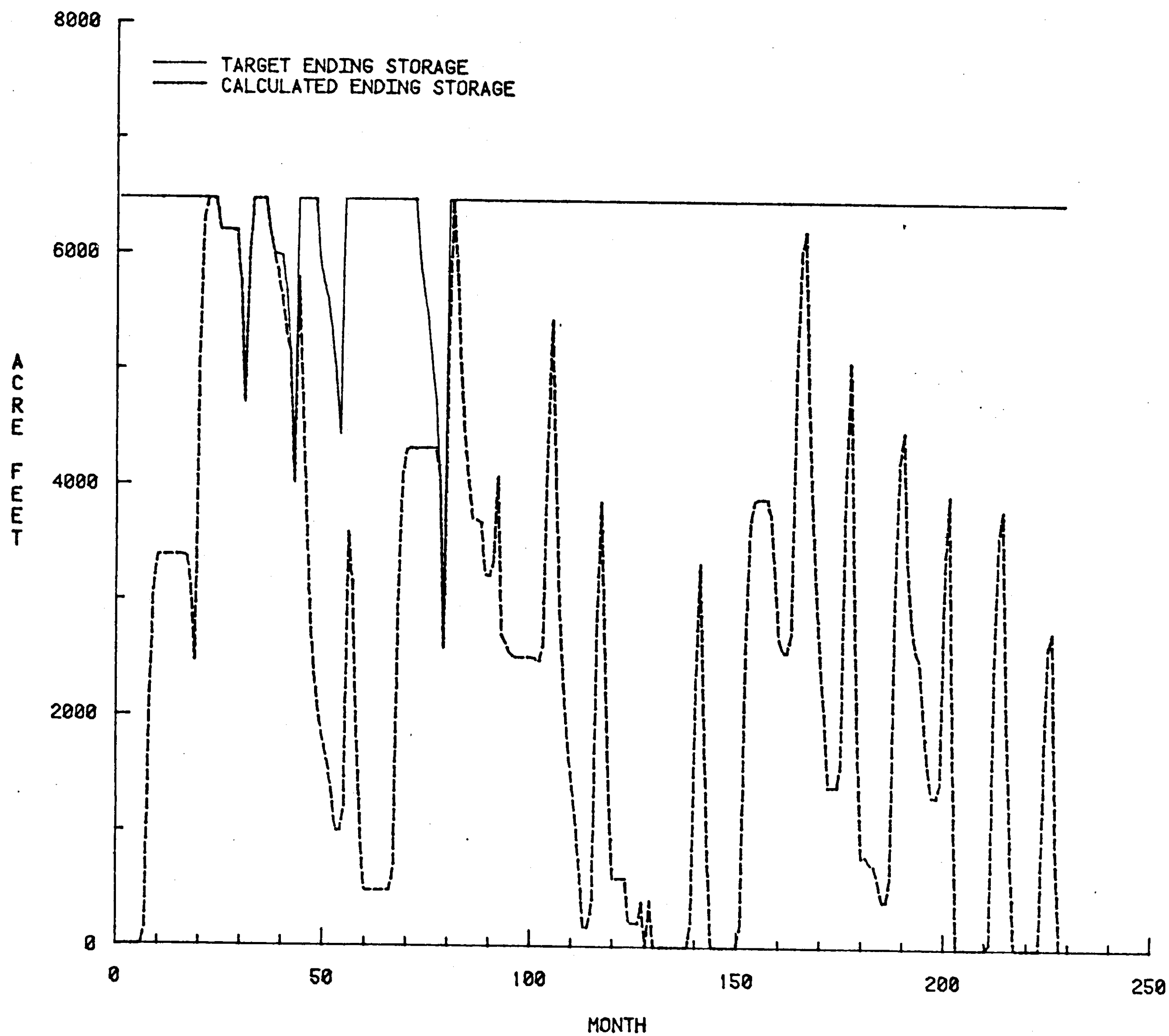


Figure 29. Target vs. Calculated Storage Levels for Joe Wright Reservoir

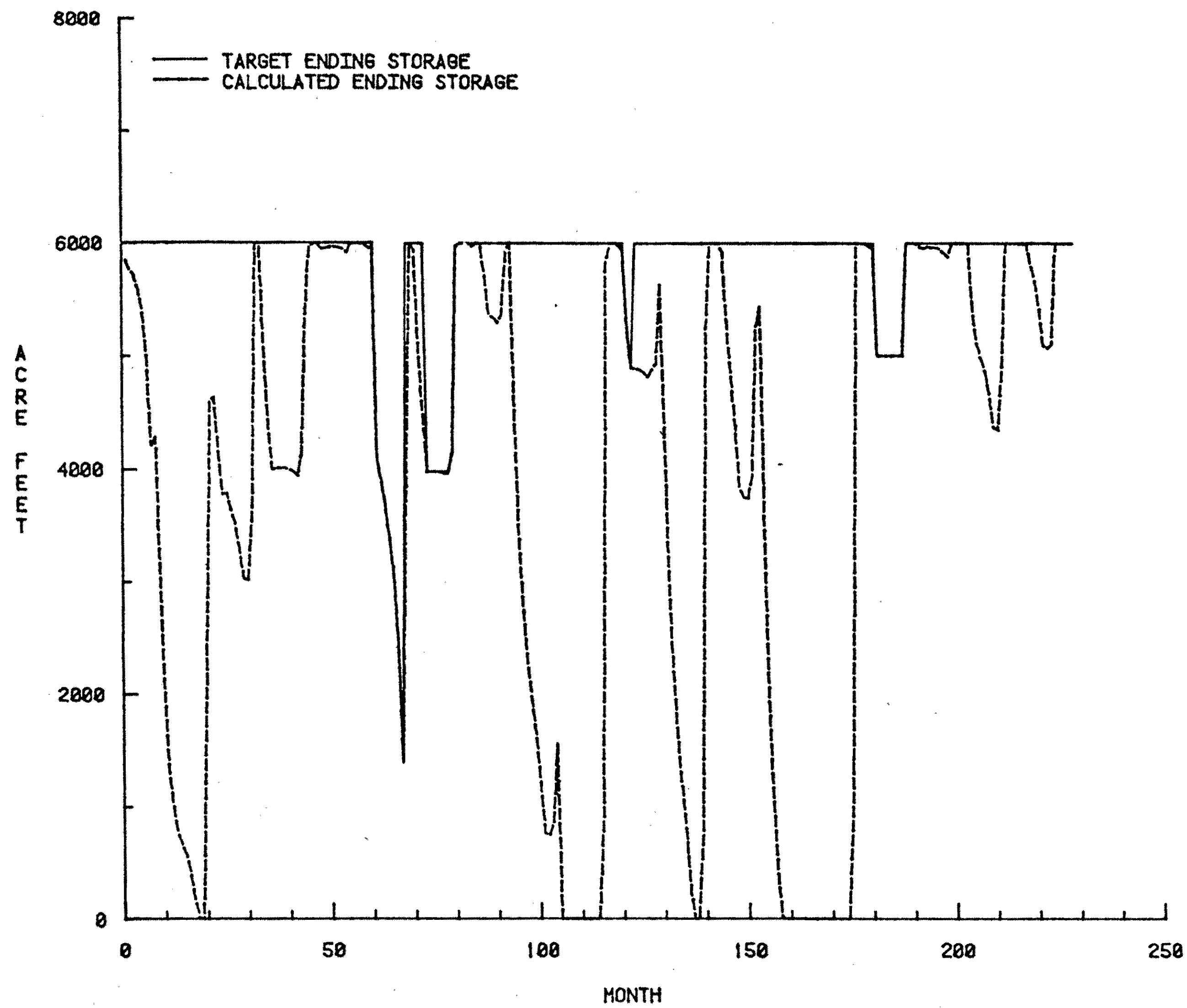


Figure 30. Target vs. Calculated Storage Levels for Long Draw Reservoir

unavailable for downstream demand satisfaction. However, the shortages remain uniformly low (Figure 31), and most likely will be satisfied from additional Colorado-Big Thompson water imported to the basin. The simulated operating policy of the other reservoirs in the system is closely aligned with historical storage and release patterns in that they fill and empty on a seasonal basis during the period of analysis.

Finally, a *borrowing* agreement must be made between North Poudre Irrigation Company (owner of Fossil Creek Reservoir) and Fort Collins in order to provide a more desirable uniform rate of delivery of reusable effluent to the power plant. Such an arrangement would commence in 1985 and would consist of the borrowing, by Rawhide, of water intended for Fossil Creek Reservoir, so as to compensate for the difference between the reusable effluent and the desired pipeline diversion during months when the reusable effluent is less than the desired diversion. Otherwise, Rawhide Project will repay Fossil Creek Reservoir when the amount of reusable effluent exceeds the desired pipeline flow during any one month. Such an agreement is advantageous to both parties since the Rawhide Project will benefit from a uniform pumping rate and Fossil Creek Reservoir will receive additional water (i.e., since the reusable effluent will likely exceed 4200 acre-feet each year) to its storage decree, and usually during low flow months. Also, the borrowing arrangement should have no impact on the direct flow rights structure along the river, since the pipeline would be borrowing only on the reservoir storage rights. Table 15 contains two examples of how this arrangement would function; the first year (1985) of power generation and 1991, the year the lowest level of reusable effluent is expected. Even for the worst year, the repayment is over 100 acre-feet greater than the amount borrowed.

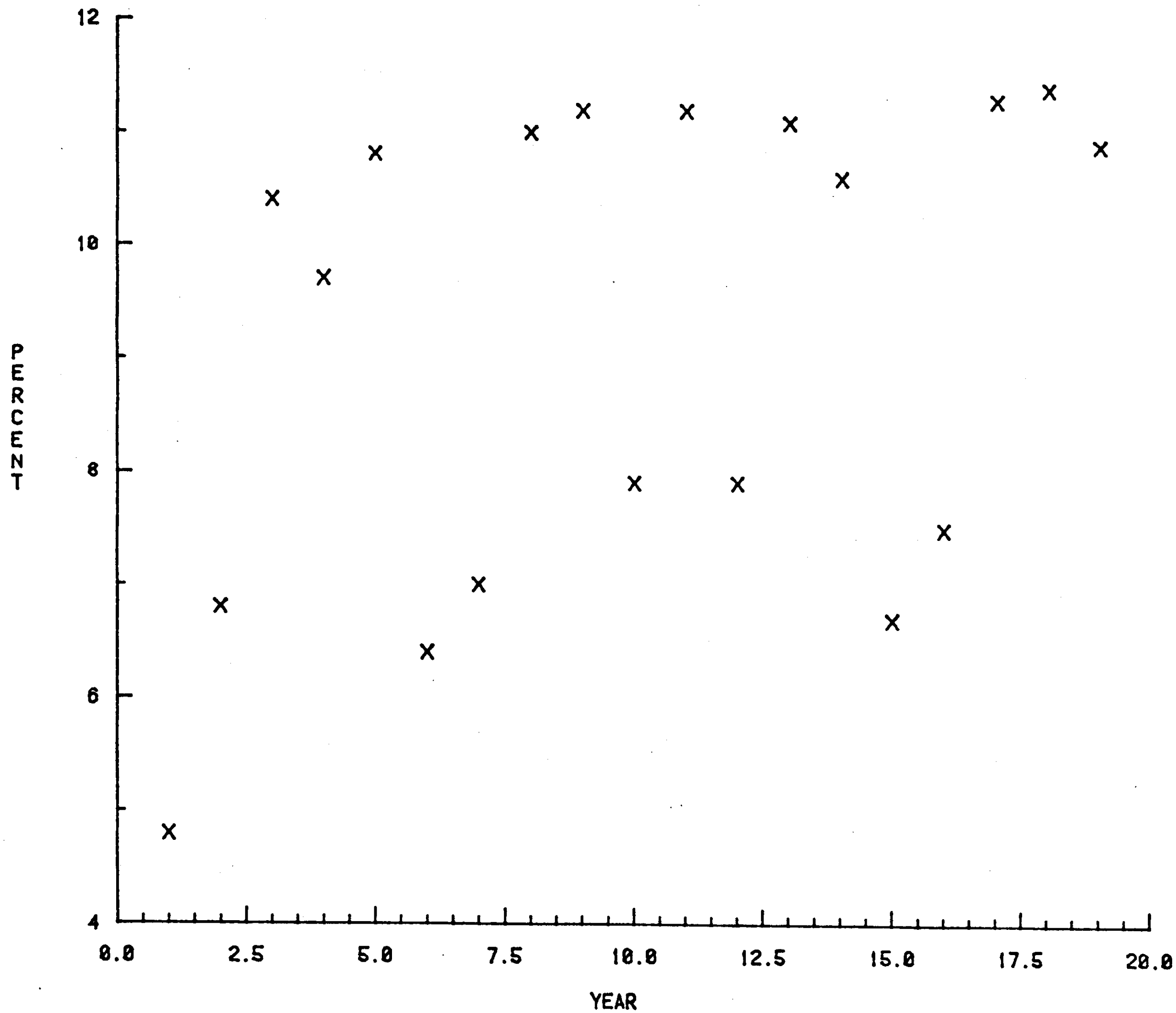


Figure 31. Percent Shortages at the Terminal Node

Table 15. Example Borrowing Arrangement Between Pipeline and Fossil Creek Reservoir

Year	Month	Exchange with Fossil Creek Reservoir		Pipeline-Reservoir Exchange	
		Reusable Effluent	Desired Pipeline Diversion	Borrow From Fossil Creek	Repay Fossil Creek
1985	NOV	312	345	33	
	DEC	197	357	160	
	JAN	171	357	186	
	FEB	256	322	66	
	MAR	303	357	54	
	APR	0	345	345	
	MAY	145	356	211	
	JUN	882	345		537
	JUL	833	357		476
	AUG	639	356		283
	SEP	485	345		140
	OCT	339	357	18	
		4562	4200	1073	1436
1991	NOV	512	345		167
	DEC	337	357	20	
	JAN	0	357	357	
	FEB	362	322		40
	MAR	0	357	357	
	APR	0	345	345	
	MAY	0	356	356	
	JUN	913	345		568
	JUL	160	357	197	
	AUG	835	356		479
	SEP	674	345		329
	OCT	522	357		165
		4315	4200	1632	1748

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