SYNTHESIS AND CALIBRATION OF A RIVER BASIN WATER MANAGEMENT MODEL

by

John M. Shafer
John W. Labadie

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by

John M. Shafer
Graduate Research Assistant

and

John W. Labadie
Associate Professor

Department of Civil Engineering
Colorado State University

submitted to

Office of Water Research and Technology

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COLORADO WATER RESOURCES RESEARCH INSTITUTE

Colorado State University
Fort Collins, Colorado
Norman A. Evans, Director

ABSTRACT

A computer model is presented for quantifying the impacts of multipurpose water management policy. The model is designed to simulate the monthly storage, flow, and diversion of water in a complex river basin. The prototype system is represented in the model by a network of interconnected nodes which can represent reservoirs, tributary inflow points, and diversion points in the basin. An important advantage of the model is that it does have some optimizing capability with respect to reservoir operating rules. It is also capable of simulating institutional structures governing water allocation, such as water right priorities, exchanges and trades. The basic model, called SIMYLD, was developed by the Texas Water Development Board, but a number of important modifications have been made. An interactive, conversational data management program has also been interfaced with SIMYLD to facilitate the rapid analysis of management alternatives, and encourage its use by water planners and managers with little background in computer programming.

The Cache la Poudre River Basin in northcentral Colorado is used as a case study to demonstrate the capabilities of the model. The problem addressed is to the availability of a firm water supply for the proposed Rawhide coal-fired power plant. By contract, this firm water supply must be composed of reusable foreign water diverted and first used by the City of Fort Collins. A detailed model calibration study is described in its entirety which clearly shows the model is capable of accurately simulating the important physical and institutional aspects of water allocation in the basin. Two management strategies are outlined for assessing opportunities for reused Fort Collins water to meet Rawhide Project needs, but detailed analysis is left for future work.

ACKNOWLEDGMENTS

We wish to offer our sincere thanks to Norman A. Evans, Director, Environmental Resources Center for his thoughtful consultation concerning the direction this research has taken. Also, we extend a note of thanks to John W. Neutze, Commissioner, Water District 3 for help in interpreting information obtained from the Colorado Water Data Bank.

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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.

In summary, 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, #7, and #9. 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.

The following report documents the structure of the model and then presents an indepth analysis of an actual case study. The emphasis in this report is on the calibration and testing phase of the case study, and will hopefully provide important insight into what is required to perform a comprehensive data analysis calibration for the model. 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.

Even though this report primarily addresses data analysis and model calibration, a final section of the report discusses the kinds of management alternatives that can be tested for this case study, and provides insight into how the model can be used to perform them.

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

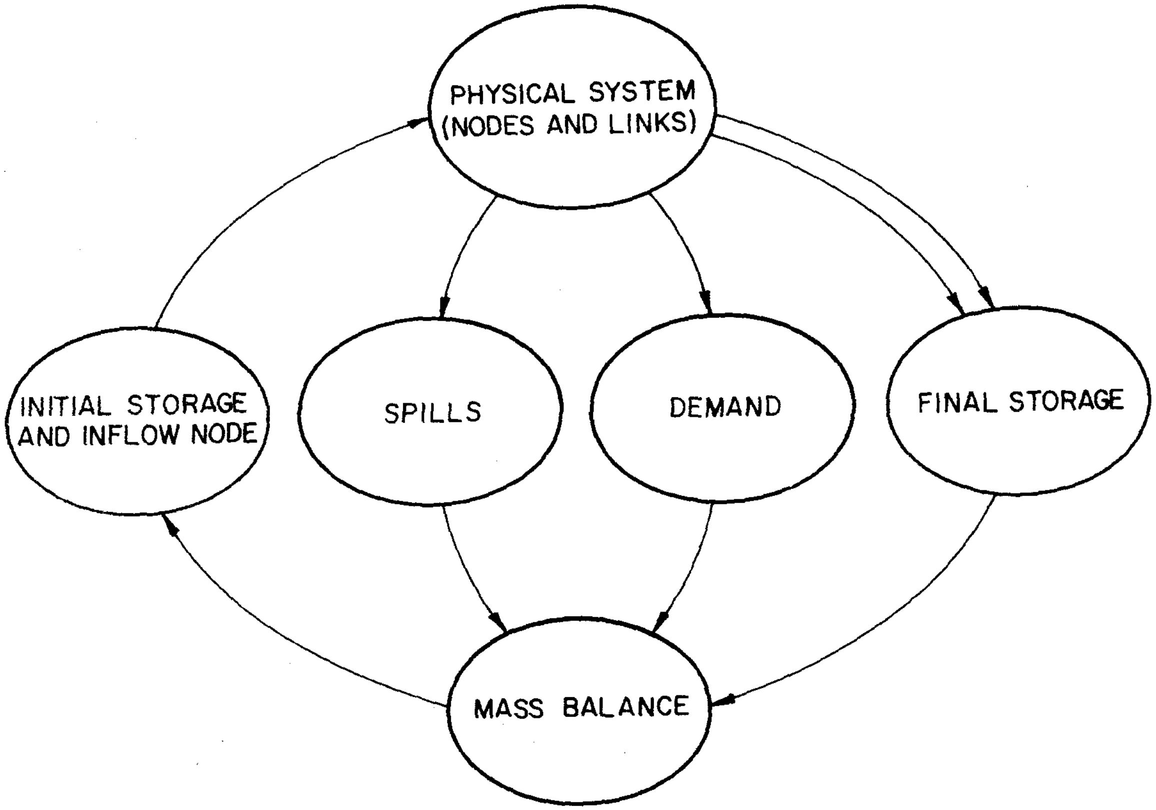

Figure 1. Link Configuration - Program SIMYLD

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:

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

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

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

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 SIMYLD

Expanded Capability: The modified code has expanded network 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). The modified code 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

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

 ** BEGIN FILE 0 **

 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 - TESTD13


 ** 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)

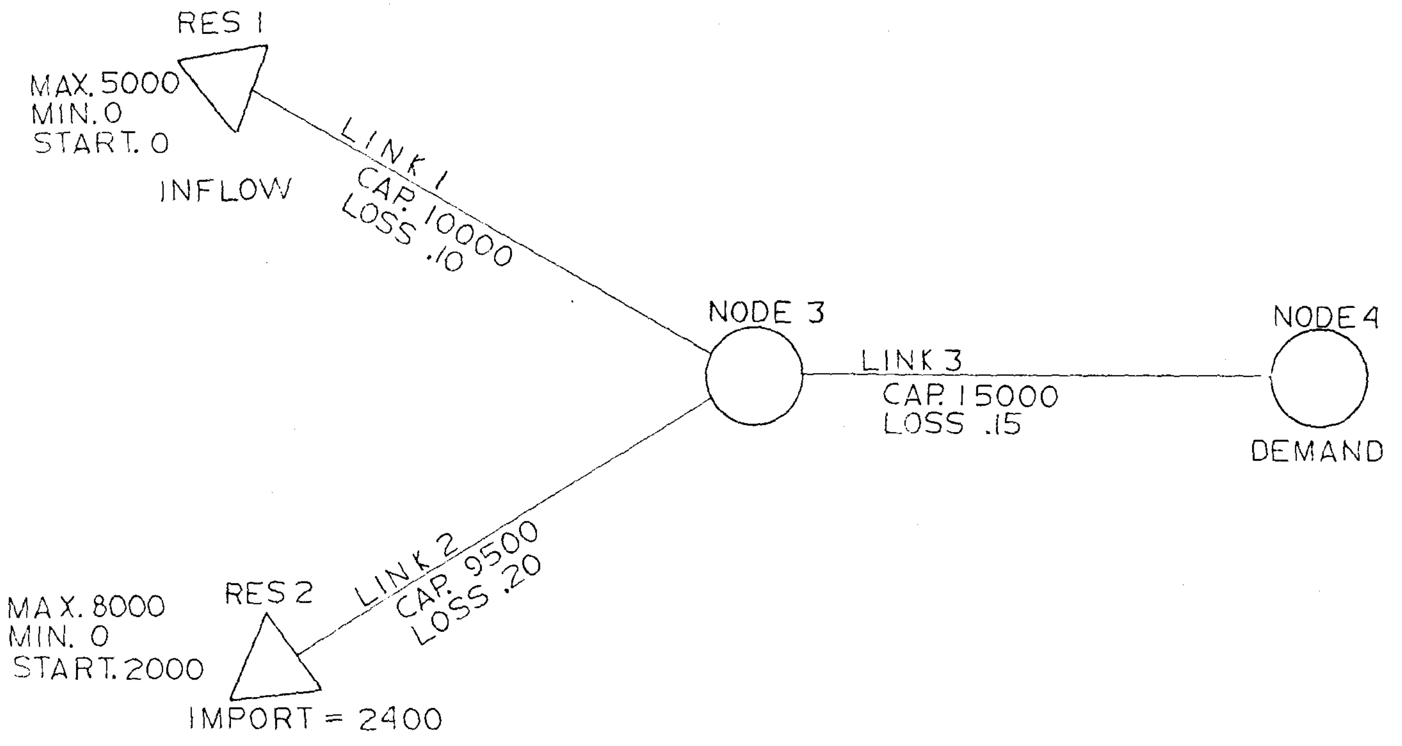

Figure 3. Example Node-Link Configuration

input via externally (to SIMYLD) 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.

III. CASE STUDY: RAWHIDE PROJECT

A. Introduction

Considerable thought was devoted to the selection of an appropriate case study that would be relevant, timely, and provide potential for actual use of the results. Therefore, several water resources planning and/or management problems currently concerning area (Northern Colorado Front Range) decision-makers were evaluated. These perceived problems were judged according to such factors as complexity, information requirements, potential cost (both time and money), urgency as related to other water allocation problems, and the degree of professional interest expected in the study.

The problem selected for 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 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.

A preliminary contract has been drawn up 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.

B. Background Information

To facilitate an overall understanding of the implications and circumstances concerning the proposed Rawhide Project, a section dealing with background information is presented. One must consider not only the physical setting, but the legal environment as well. Therefore, a physical description of the case study (location, hydrology, basin configuration, etc.) is provided, followed by a review of the preliminary contract as it pertains to the physical system.

B.1 Physical description of the study area

The Rawhide Project will be located in the Cache la Poudre River Basin in north-central Colorado (Figure 4). This basin comprises Water Division 1, District 3, one of the most productive agricultural areas in Colorado. It is also as complex a system of interrelated water storage and distribution structures and regulations as found anywhere in the Rocky Mountain Region.

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.

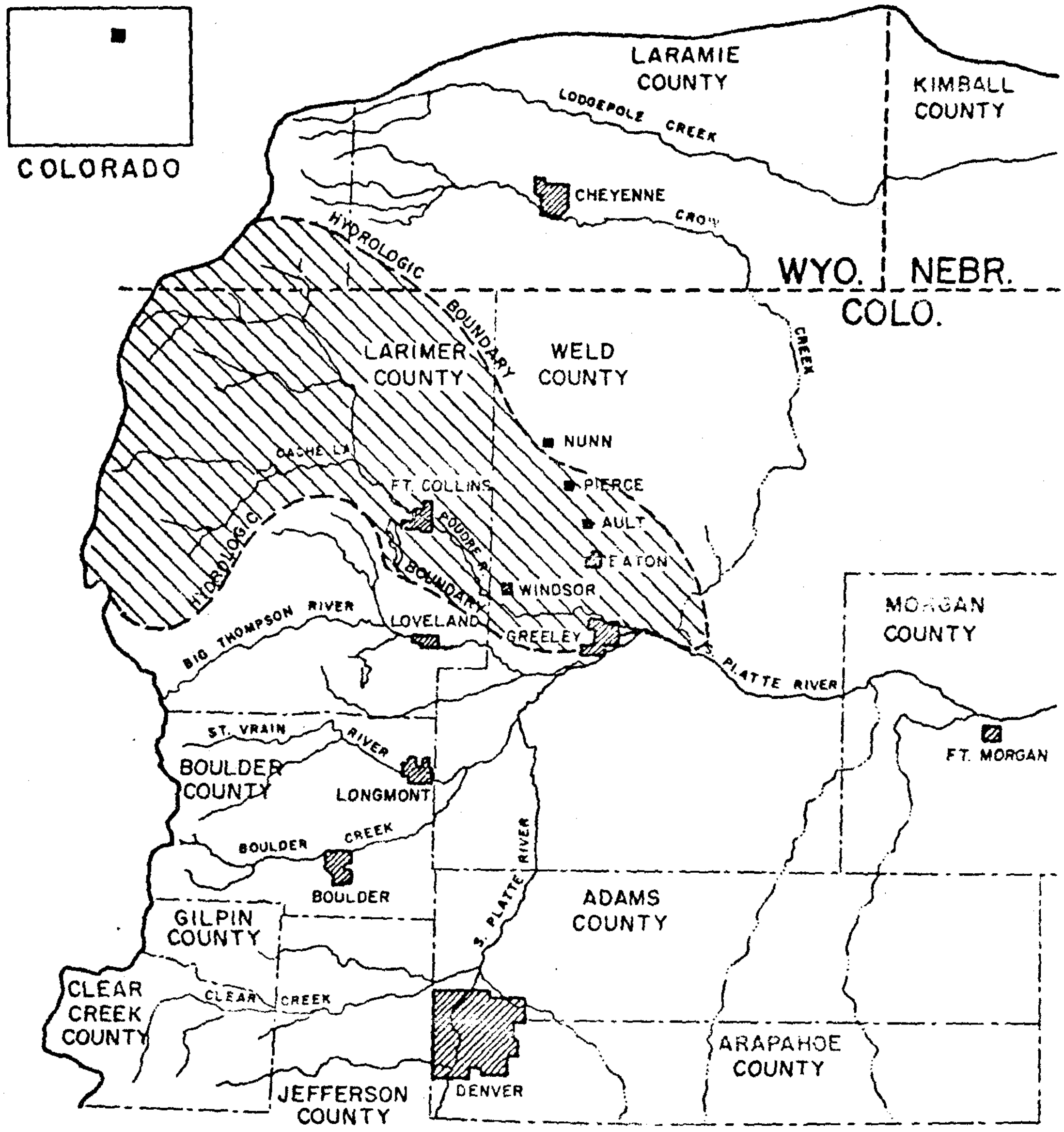

Figure 4. Location of Cache la Poudre River Basin (Evans, 1971)

Table 1 lists sources of water supply to the basin and their corresponding percentage.

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

Source	Percentage (%)
Natural Inflows (Snowmelt, Precip.)	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.

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 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 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 1976 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 Irrig. Co.	4,190
Direct Flow	10,000
Total	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 Spring 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. It is advisable to parameterize on these percentages to determine their influence on the final results.

Table 3. Consumptive Water Use Ft. 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	1.6
APR	881.8	378.7	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. As a result of cooperation between the City and North Poudre Irrigation Company the effluent can either be returned to the river or diverted to Fossil Creek Reservoir.

C. The Rawhide Project

As mentioned previously, the Rawhide Project is an electric generation facility designed to augment projected power demands of the municipalities of Estes Park, Fort Collins, Longmont, and Loveland.

The power plant is to be located 20 miles north of Fort Collins. 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 of the reservoir, the Rawhide Project will require no less than 4200 acre feet of firm water annually and a stable reservoir elevation within two to 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 6,474 acre feet of usable storage. 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.

D. System Decomposition

As previously discussed, the Poudre River system is extremely complex in both composition and operation. Figure 5 is a schematic diagram depicting the major components of this system (Note: many plains reservoirs are not included for reasons of simplicity). Fortunately, the system has two control points situated in advantageous positions. The State of Colorado has two gaging stations located on the Poudre River. The upstream gage is situated near the mouth 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 when the key components of the case study are individually considered, but the remainder of the

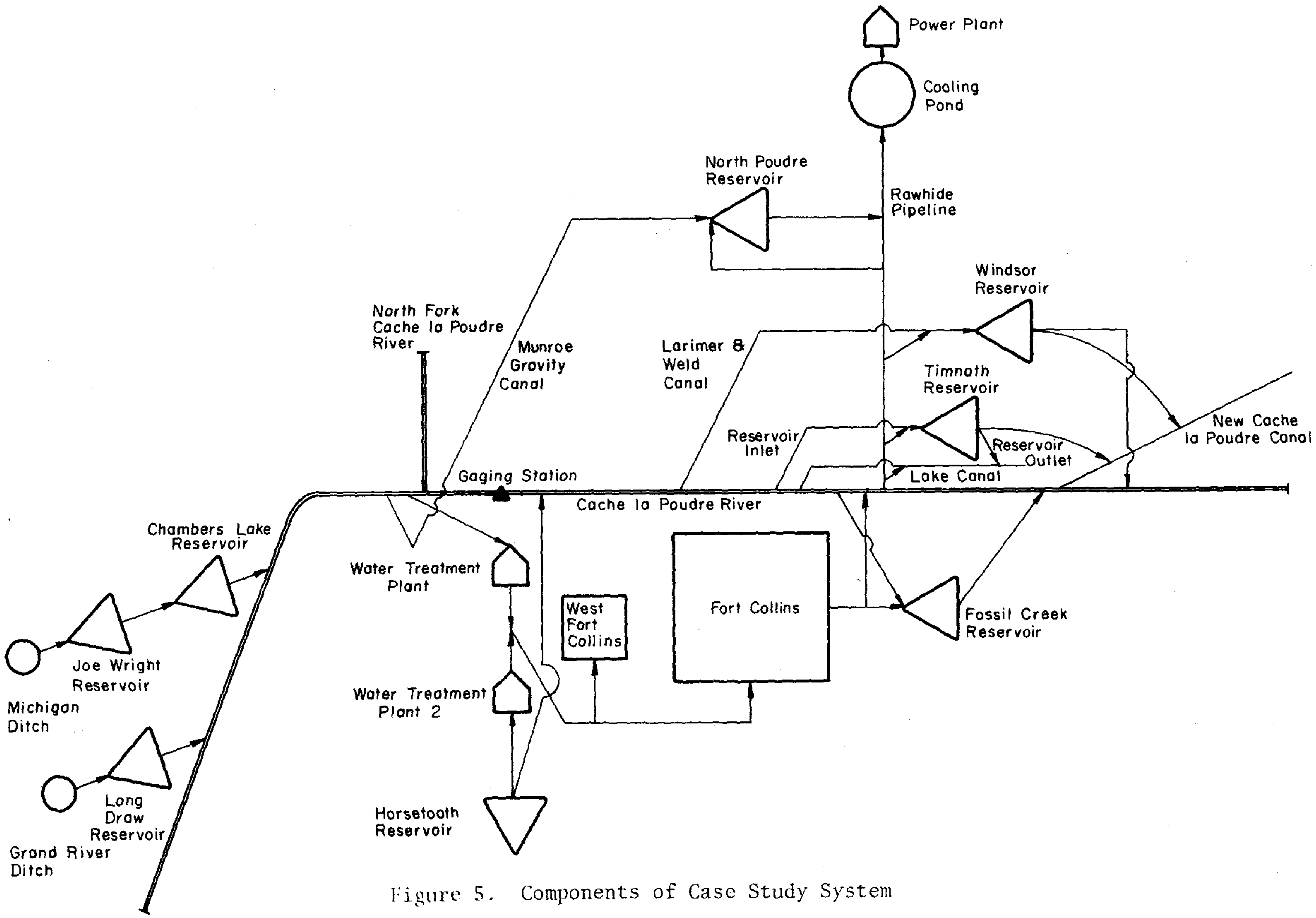

Figure 5. Components of Case Study System

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 (Figure 5) 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*.

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		

Once the physical system to be modeled has been delineated, it must be translated into a node-link network configuration. Particular attention must be afforded this phase of any study to insure that the essence of the system remains intact. Figure 6 shows the network system to be directly solved by SIMYLD. Notice that the Fort Collins water

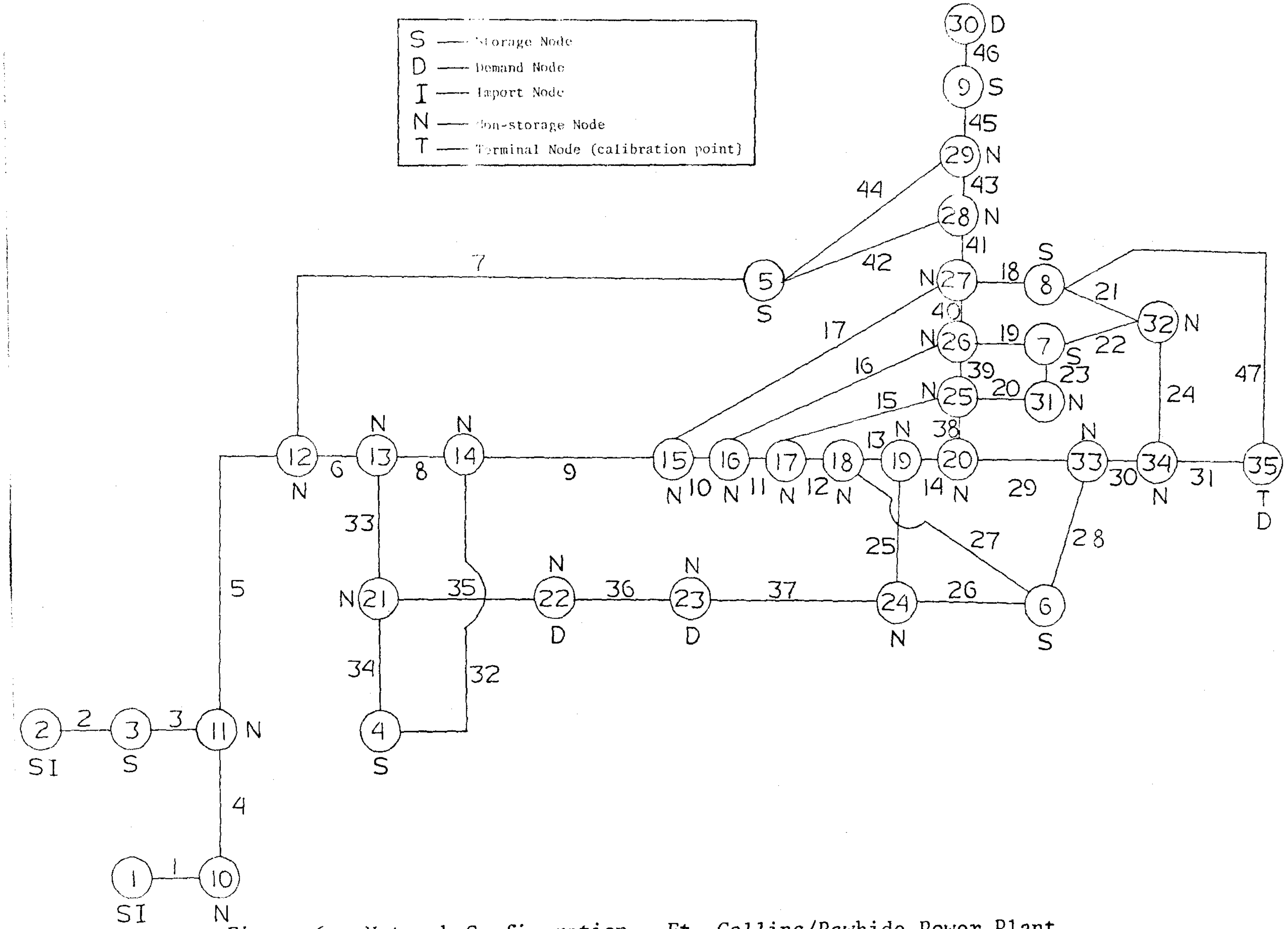

Figure 6. Network Configuration - Ft. Collins/Rawhide Power Plant

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		
18	Fossil Creek Reservoir Inlet	35	Terminal

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
19	10070	43	0
20	158	44	0
21	17689	45	0
22	10070	46	0
23	10070	47	17689
24	35490		

Figure 6. (Cont'd)

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. Model Calibration

Model calibration in this study is defined as the adjustment of certain model parameters until the model reasonably duplicates available historical records. Calibration is an extremely important task to be accomplished in a study such as this. Without successful model calibration, there can be no assurance of reliability in subsequent management alternative analyses. Success in this case is defined such that little further improvement can be made by adjusting model parameters. Discrepancies between the model output and the historical record are to be minimized and logically explained.

Irrigation years 1973-1975 (November-October) were used to calibrate the model. This period was selected for two reasons: 1) highly detailed information was available concerning daily ditch diversions and end-of-month reservoir storage volumes from the Colorado Water Data Bank (CWDB), and 2) this period represents a wet to dry trend, based on recorded river flow at Ft. Collins.

E.1 Data organization

This section contains the data necessary to operate the model on monthly time increments for the selected time period. Since all data must be compatible, 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.

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. These capacities, along with loss coefficients where appropriate, are provided in Table 5.

Table 5. 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

SIMYLD 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 6 contains

Table 6. Selected 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			

an example calculation of area-capacity points. Horsetooth Reservoir is not included for reasons which are discussed in the following section.

Evaporation rates were compiled from various sources. These data were difficult to obtain because of a lack of information specific to the area of interest. Rates were obtained from the Bureau of Reclamation (USBR), but were not oriented toward this particular geographic region. However, the monthly distribution of the annual total was considered acceptable (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 7 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. 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 7. 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 plains reservoirs and high country reservoirs (Figure 8).

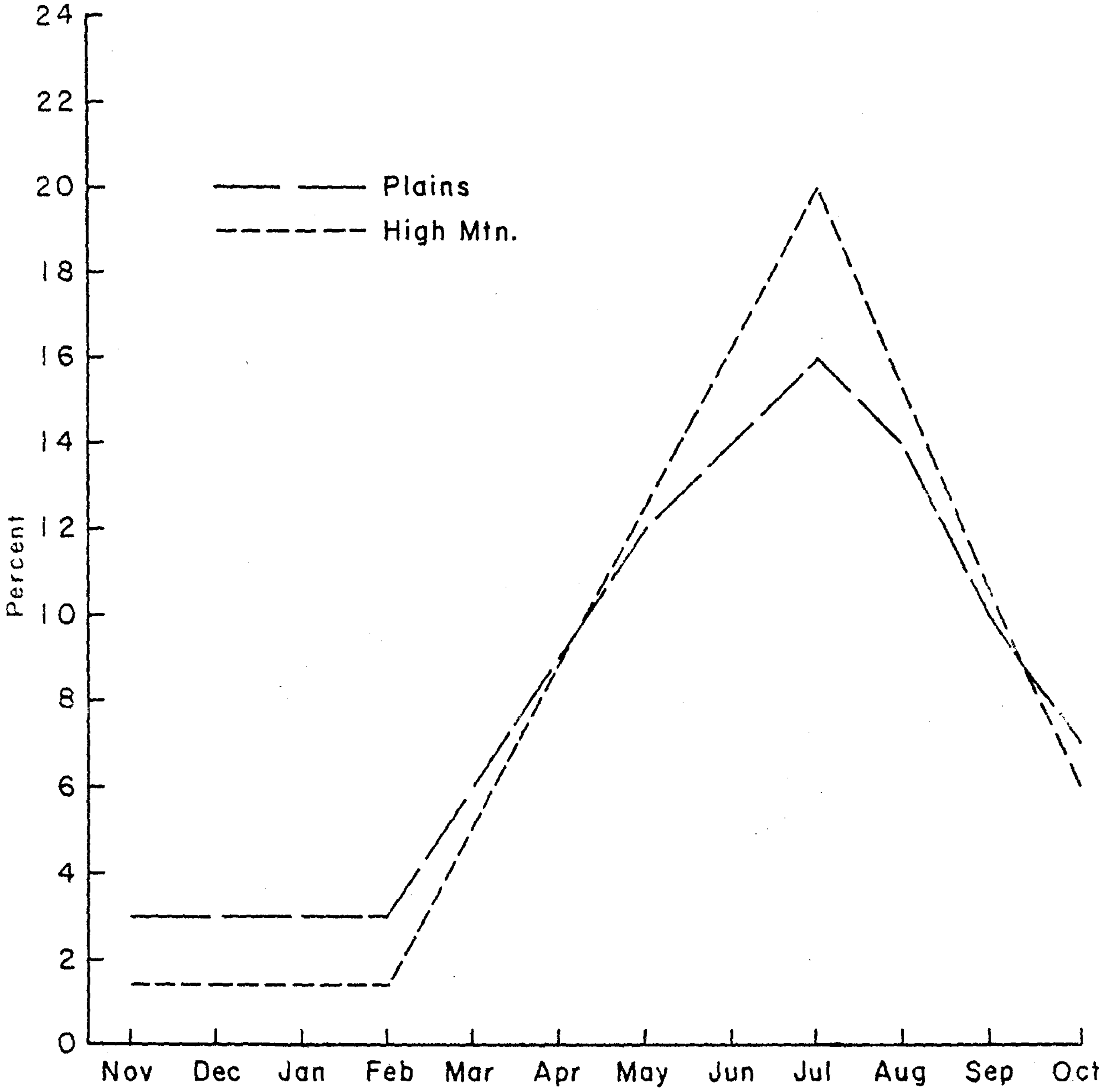

Figure 7. Monthly Distribution of Evaporation as Percent of Gross Annual Rate

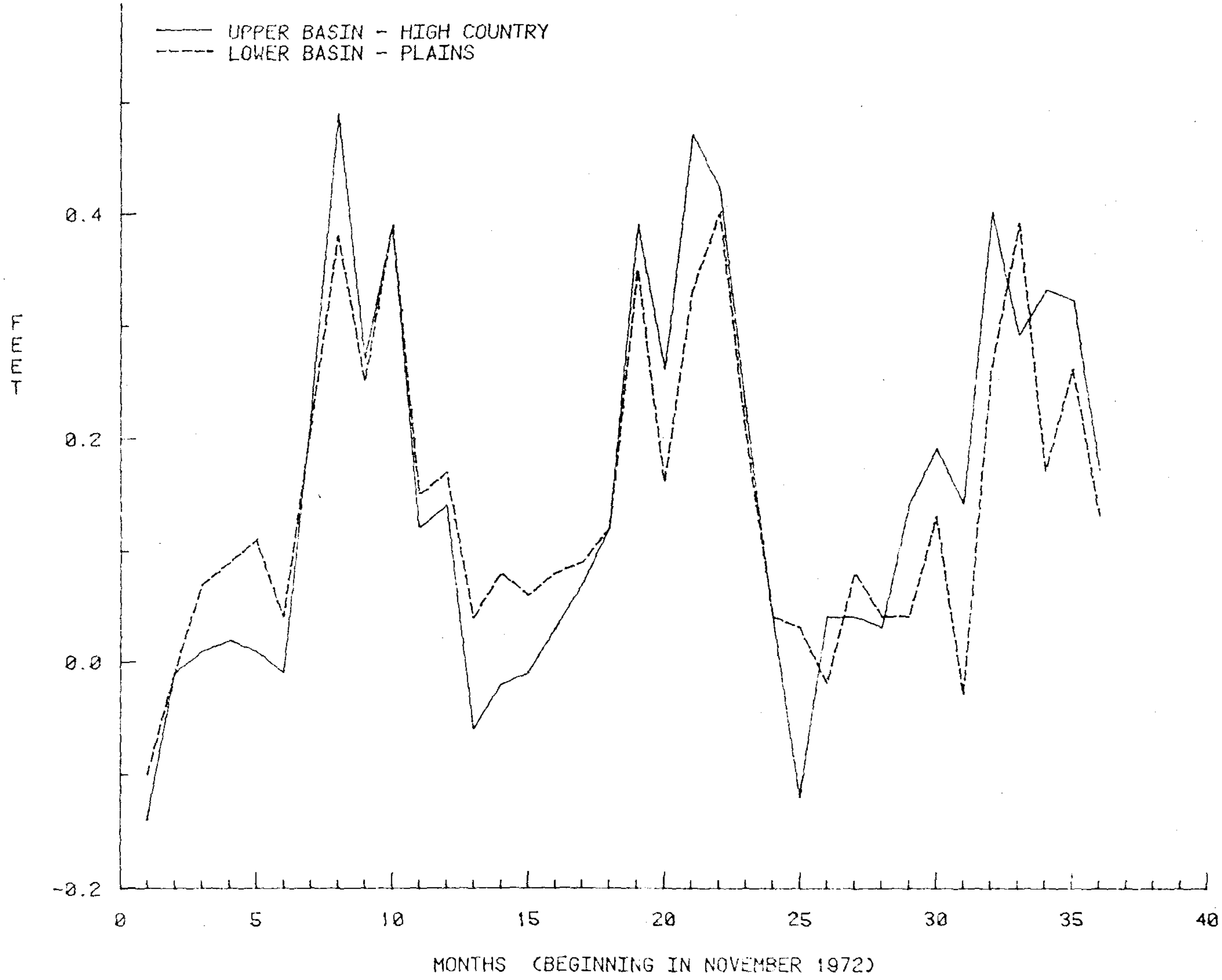

Figure 8. Evaporation Rate Irrigation Years 1973-1975

E.2 Methodology

The following step by step procedure was used to calibrate SIMYLD for the three year period 1973-1975.

1. Set the lower and upper bounds equal to zero for all links representing the Rawhide Pipeline.

2. Set desired monthly ending storage for Joe Wright Reservoir to zero for all months. Joe Wright was inactive during the calibration period.

3. Obtain initial storage volumes (November 1, 1972) (Table 7).

Table 7. Initial Storage Levels (November 1, 1972)

Reservoir	Water in Storage (acre feet)
Long Draw	1174
Chambers Lake	2192
North Poudre No. 6	6224
Fossil Creek	5837
Timnath	5455
Windsor	9805
Horsetooth	0

4. Set desired or target end-of-month storage values as historically observed end-of-month storage divided by reservoir maximum capacity (except Horsetooth Reservoir) (Table 8).

5. Determine unregulated and spurious inflows:

   i. Inflow to node 14 (confluence of North Fork Cache la Poudre River) equals monthly release from Milton Seaman Reservoir.

Table 8. Storage Targets % of Full

1973	CAP	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct
Long Draw Res.	10519	.112	.128	.128	.126	.129	.134	.000	.000	.000	.000	.000	.000
Chambers Lake	8824	.371	.399	.476	.501	.534	.580	.844	1.00	1.00	.546	.115	.225
No. Poudre #6	9968	.624	.624	.624	.624	.624	.624	.659	.703	.582	.495	.286	.503
Fossil Creek	11100	.652	.765	.759	.791	.843	.927	.797	.935	.892	.573	.658	.658
Timnath Res.	10070	.612	.774	.774	.774	.808	.928	.910	1.00	.973	.471	.449	.612
Windsor Res.	17689	.659	.680	.708	.734	.791	.888	.781	.697	.847	.466	.493	.500
1974													
No. Poudre #6	9968	.511	.511	.511	.530	.558	.534	.495	.484	.447	.407	.404	.659
Windsor Res.	17689	.550	.573	.607	.629	.646	.776	.720	.857	.421	.417	.236	.504
Timnath Res.	10070	.715	.715	.715	.741	.830	.836	.887	1.00	.628	.140	0.00	.434
Fossil Creek	11100	.658	.664	.664	.670	.850	.864	.772	.792	.658	.330	.525	.623
Long Draw Res.	10519	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Chambers Lake	8824	.261	.317	.373	.399	.370	4.90	.875	.976	.927	.700	.136	.208
1975													
Long Draw Res.	10519	.018	.018	.018	.018	.018	.018	.062	.993	.993	1.00	.811	.829
Chambers Lake	8824	.257	.293	.369	.369	.401	.440	.297	.962	.962	.281	0.00	.110
No. Poudre #6	9968	.659	.659	.681	.681	.681	.690	.676	.672	.522	.320	.286	.432
Fossil Creek	11100	.676	.685	.595	.595	.700	.617	.374	.857	.687	.353	.056	.079
Timnath Res.	10070	.662	.662	.662	.662	.662	.662	.436	.678	.569	.152	.271	.273
Windsor Res.	17689	.547	.547	.607	.607	.650	.715	.477	.939	.554	.178	.335	.431

ii. Inflow to node 10 equals Fort Collins gaged flow plus diversions to Fort Collins Pipeline and Munroe Gravity Canal, minus releases from Chambers Lake, Long Draw Reservoir, and Milton Seaman Reservoir, plus five percent to compensate for channel losses. This result is the gross amount of water available for subsequent diversion in each month from the headwaters of the Poudre River. It is also net of diversions to Poudre Valley Canal and assumes historical operation of high mountain reservoirs not directly modeled.

iii. For purposes of this study, Horsetooth Reservoir was considered an equalizing reservoir. The reservoir operates on a seasonal basis. In all but a few cases the reservoir only releases water between the first of April and the end of October. Its waters service the entire valley with supplemental irrigation water and also augment the supply of several municipalities, including Fort Collins. To avoid allowing more Horsetooth water to the system than actually was available, the Northern Colorado Water Conservancy District (NCWCD) records were used to delineate only those waters that were delivered to the river and also supplied to the City of Fort Collins. These monthly releases were then summed and entered as inflow to the reservoir in April. The reservoir level was allowed to freely fluctuate except that the storage had to go to zero in October. Evaporation was not deducted from the storage pool due to the fact the adjusted inflow is the net delivery to the City.

iv. Historical inflows to Long Draw Reservoir and Chambers Lake Reservoir were input monthly.

v. Additional inflows to certain plains reservoirs were included as a result of ditch transfers that did not originate from diversions

on the main stem of the river and non-stream inflows.
Table 9 lists the primary inflows to various nodes throughout the system for the simulation period.

6. Net added flow to the river was calculated. Due to irrigation activity in the valley, there is significant return flow accruing to the Poudre River between Fort Collins and Greeley. Also, tributary inflow, precipitation on the channel, and channel seepage are occurring throughout the year. This net additional inflow to the river can be reasonably estimated. The gaged Poudre River flow at Greeley (confluence with South Platte River), the gaged river flow at Fort Collins, and the monthly diversions and releases between these stations were used to determine the net added flow. Working upstream, diversions and releases to the river were added and subtracted from the gaged record at Greeley. This resulted in a calculated flow at the Fort Collins gage. Comparing this calculated flow with the observed flow at Fort Collins reveals that in each month the calculated flow at Fort Collins was greater than the observed, as expected. The difference between these values was assumed to be net return flow to the river. Figure 9 shows the Fort Collins gaged flow and the net added flow between Fort Collins and Greeley. These monthly values of net added flow were input to the model at node 14. Though the lumping of total return flow at this point is somewhat erroneous, the nature of the aggregated demand for water downstream of the system boundary (as well as other ditches within the system not explicitly included in the model), does not seriously detract from reality.

7. Determine historical demands:

i. The demand for raw water by the City of Fort Collins has been discussed previously. Using the aforementioned consumptive loss

Table 9. Unregulated Inflows (acre feet)

Month	Node 14 Release from Milton Seaman Res.	Node 10 Fort Collins Adjusted Gage Record	Node 4 Horse-tooth Res.	Node 1 Longdraw Res.	Node 3 Chambers Lake Res.
Nov 72	133	3274	0	0	1081
Dec	0	2409	0	150	248
Jan 73	0	2278	0	0	730
Feb	148	2068	0	0	230
Mar	50	2843	114	28	299
Apr	0	4175	66874	53	404
May	3950	92672	0	346	2547
Jun	0	144424	0	0	1584
Jul	184	83659	0	0	0
Aug	1647	26996	0	0	0
Sep	1059	7615	0	0	0
Oct	0	6512	0	0	993
Nov	1879	5576	0	0	345
Dec	154	3719	0	0	493
Jan 74	0	3188	0	0	489
Feb	0	3702	0	0	238
Mar	4	6702	0	0	339
Apr	661	7860	107189	0	461
May	3881	87129	0	0	3396
Jun	400	126667	0	0	1103
Jul	0	54024	0	0	0
Aug	1204	19390	0	0	0
Sep	287	8471	0	0	127
Oct	2208	7298	0	0	630
Nov	28	3715	0	0	434
Dec	170	2106	0	0	319
Jan 75	590	1094	0	0	303
Feb	129	1433	0	0	363
Mar	0	2010	64	0	291
Apr	0	3106	87210	0	343
May	3942	20168	0	1002	449
Jun	0	98256	0	9801	5869
Jul	0	94907	0	0	0
Aug	1449	25328	0	69	0
Sep	1119	10156	0	73	0
Oct	1190	3508	0	194	974

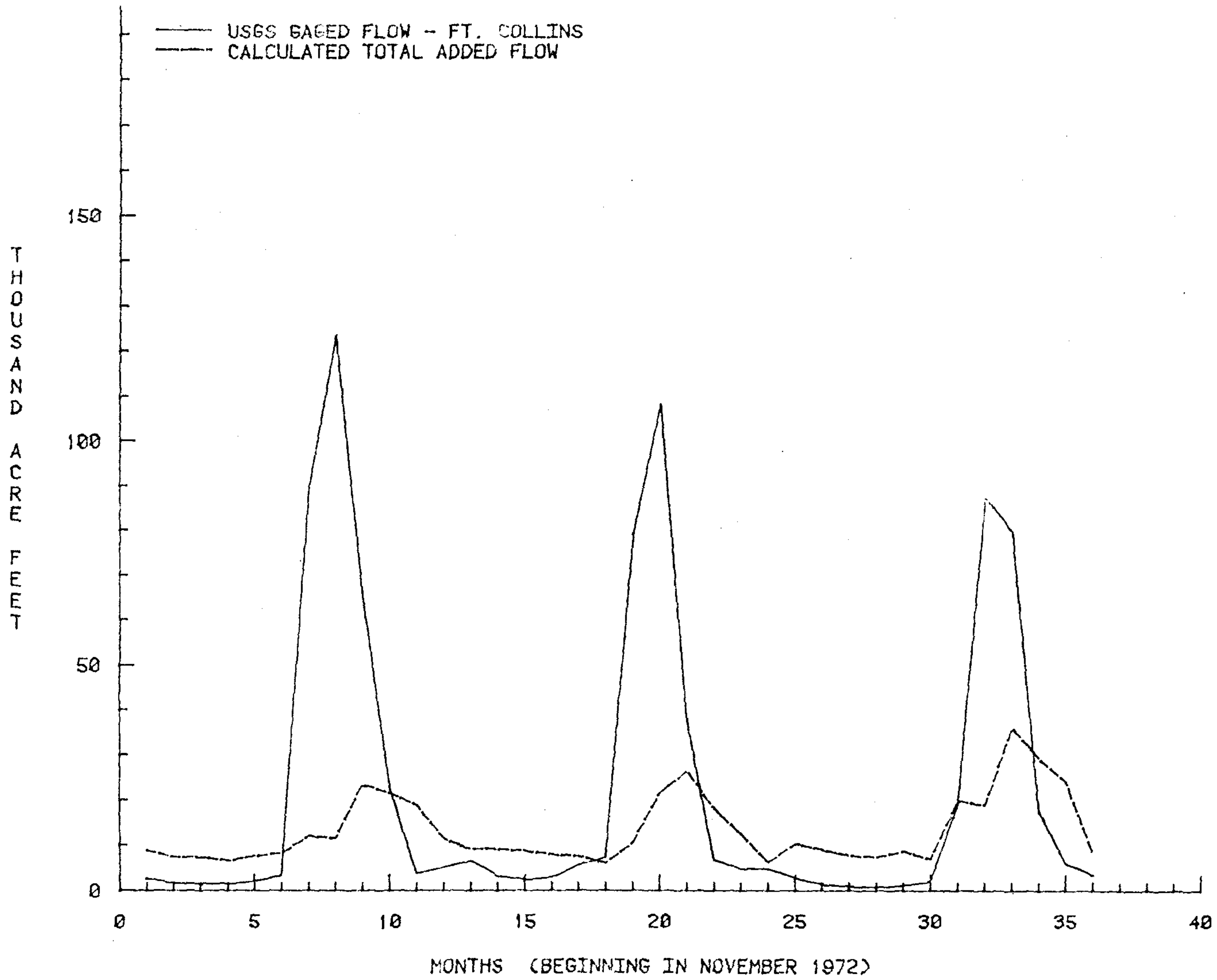

Figure 9. Ft. Collins Gaged Flow and Net Added Flow Between Ft. Collins and Greeley

percentages and a two percent diversion of treated water to West Fort Collins Water District, the resulting estimated losses were specified as model demands. Tables 10 through 12 display the monthly values for diversions to the Fort Collins treatment plants and associated consumptive losses.

ii. The historical river to ditch diversions (including Horsetooth water) as compiled from generated reports from the CWDB were input as demands for the specific canal systems modeled.

iii. To insure that the remainder of the system not explicitly modeled is realistically considered, a demand is established at the terminal node which takes into account all ditch diversions not directly analyzed. To do this, the flow normally passing the downstream case study boundary was calculated for the historical period in much the same fashion as the added flow. Beginning with the recorded streamflow of the Greeley gage, canal diversions were added (moving upstream) until the historical flow of the study boundary was calculated. To these monthly values were added the monthly diversions to ditches not directly modeled between the boundary and the Fort Collins stream gage. These total monthly figures were then input as the monthly demand at the terminal node. In this manner, the total historical requirement for river water in this reach is considered (Table 13).

E.3 Discussion and results of model calibration

The goal of the calibration procedure was to manipulate the priorities placed on individual reservoir storage and demand satisfaction until:

1. the calculated end-of-month reservoir storage volumes *reasonably duplicate* the historically observed end-of-month volumes.

2. shortages in calculated water diverted to meet demand are minimized and aggregated at the terminal node (if shortages occur,

Table 10. 1973 Demands at Fort Collins
(acre feet)

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Annual
River Diversion to Pipeline	621	704	710	668	708	506	748	1335	1396	1416	1010	920	10,742
Horsetooth					114	280	630	991	569	757	257	90	3,688
TOTAL (Demand at 21)	621	704	710	668	822	786	1378	2326	1965	2173	1267	1010	14,430
2% to West Ft. Collins (Demand at 22)	12	14	14	13	16	16	28	47	39	43	25	20	287
Available at Ft. Collins	609	690	696	655	806	770	1350	2279	1926	2130	1242	990	14,143
% Consumptive Loss	1.6	1.4	1.1	1.2	1.6	42.9	60.7	55.0	46.0	46.5	35.1	21.8	
Consumptive Loss (Demand at 23)	10	10	8	8	13	330	819	1253	886	990	436	216	4,979

Table 11. 1974 Demands at Fort Collins
(acre feet)

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Annual
River Diversion to Pipeline	826	796	636	586	587	877	1447	1611	1693	1731	1279	1184	13,353
Horsetooth	36	18	3	3	6	22	623	686	914	669	293	6	3,279
TOTAL (Demand at 21)	862	814	639	589	693	899	2070	2297	2607	2400	1572	1190	16,632
2% to West Ft. Collins (Demand at 22)	17	16	13	12	14	18	41	46	52	48	31	24	332
Available at Ft. Collins	845	798	626	577	679	881	2029	2251	2255	2352	1541	1166	16,300
% Consumptive Loss	1.6	1.4	1.1	1.2	1.6	42.9	60.7	55.0	46.0	46.5	35.1	21.8	
Consumptive Loss (Demand at 23)	14	11	7	7	11	379	1231	1238	1176	1095	542	254	5,965

Table 12. 1975 Demands at Fort Collins
(acre feet)

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Annual
River Diversion to Pipeline	776	796	816	750	748	834	1105	966	1196	1178	1034	1028	11,227
	50		6	4	16	26	69				238	178	587
											109		109
Transbasin							10		65	174	91		340
TOTAL	826	796	822	754	764	858	1184	966	1261	1352	1472	1206	12,263
Horsetooth					64	2	332	528	1077	738	483	173	3,397
TOTAL (Demand at 21)	826	796	822	754	828	860	1516	1494	2338	2090	1955	1379	15,660
2% to West Ft. Collins (Demand at 22)	17	16	16	15	17	17	30	30	47	42	39	28	314
Available at Ft. Collins	809	780	806	739	811	843	1486	1464	2291	2048	1916	1351	15,346
% Consumptive Loss	1.6	1.4	1.1	1.2	1.6	42.9	60.7	55.0	46.0	46.5	35.1	21.8	
Consumptive Loss (Demand at 23)	13	11	9	9	13	362	902	805	1054	952	672	294	5,096

Table 13. Calculation of Adjusted Demand at Terminal Node - 1974
(acre feet)

	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Annual
Calculated Flow at Terminal Node	13350	10380	9420	9060	7360	7476	13528	41842	20718	16807	8667	8568	167,176
Ditches Not in Analysis													
Boxelder							1744	1378	2265	1719	659	121	7,886
Chaffee							105	141	125	117			488
Coy						14	283	303	376	297	248	46	1,567
Arthur							1340	1169	1881	729	86		5,205
Larimer Co.#2							3429	3424	1307	1650	555		10,365
New Mercer							2482	1820	1627	1077	240		7,246
Little Cache La Poudre		1071	921	832	1154	719	3619	3289	3859	1184	545	89	17,282
Jackson							2170	1934	1632	988	376		7,100
Larimer Co. Canal	362				319	2109	20608	18970	23170	16490	4496	3838	90,362
Pleasant Valley and Lake							4536	4617	3357	3046	2481	818	18,857
Greeley Pipeline	760	719	709	630	739	744	251		1468	1702	1462	1303	10,487
TOTAL	14472	12170	11050	10522	9572	11062	54095	78889	61785	45806	19815	14783	344,021
Seeley Lake Release		125		59		166				311		82	743
Total Adjusted Demand at Terminal Node	14472	12045	11050	10463	9572	10896	54095	78889	61785	45495	19815	14701	343,278

they are only allowed to occur at the terminal node).

3. Fort Collins and ditch company allocations of Horsetooth Reservoir water were totally exercised each year.

4. calculated streamflow at the Fort Collins gage reasonably duplicates the historical record for the period.

As discussed earlier, the Poudre River basin is an extremely complex water resources system. Many water exchanges are not documented, since they originate in verbal agreements. Parameters such as channel loss coefficients are only estimates. However, these values are the best judgments made by persons involved with the river system for many many years. In some cases, the CWDB data are suspect (Shafer and Labadie, 1977). Also, the Out-of-Kilter Algorithm necessitates the conversion of real values to integer values, which introduces round off errors. For these reasons the term *reasonably duplicates* is employed. There is no substitute for good judgment and thorough knowledge of the system when evaluating the results of the calibration exercise.

The aggregate demand was given the lowest priority among demand nodes to insure all shortages would occur at the terminal node. The water requirement at this node is a conservative estimate of the actual aggregate demand due to the inclusion of reservoir to reservoir transfers of water that are impossible to separate from the data. Shortages which occur at the boundary should be limited to the non-irrigation months of the year when such transfers take place. This condition is exactly the response one finds from model runs with these data.

The criteria for acceptable model calibration was met after successive adjustment of model priorities. The final priorities or ranks are presented in Table 14. Reservoir storages calculated by the

Table 14. Final Rankings for Rawhide Project Calibration*

	Name	Network Node No.	1973	1974	1975
Demand	No. Poudre No. 6 Res.	5	10	10	10
	Munroe Gravity Canal	12	10	10	10
	Larimer & Weld Canal	15	10	28	10
	Fort Collins Pipeline	21	10	40	10
	West Fort Collins	22	10	42	10
	Fort Collins (consumptive loss)	23	10	44	10
	Lake Canal	31	10	48	10
	New Cache la Poudre Canal	32	10	50	10
	System boundary	35	18	55	15
Storage	Long Draw Res.	1	13	500	13
	Joe Wright Res.	2	500	500	500
	Chambers Lake Res.	3	3	3	3
	Horsetooth Res.	4	50	60	50
	No. Poudre No. 6 Res.	5	1	30	1
	Fossil Creek Res.	6	5	5	5
	Timnath Res.	7	13	3	13
	Windsor Res.	8	17	10	20
	Cooling Pond	9	100	100	100

*Rankings are translated into *pseudo-costs* of moving a unit of water from storage to demand satisfaction. For example, the rank of 1 in 1973 for holding water in N. Poudre Reservoir No. 6 takes precedence over all other storages and demands in 1973.

model corresponds surprisingly well with observed data. In every case (except Windsor Reservoir) the calculated storage identically matches observed, or varies by a few acre feet. The model calculates storage volumes for Windsor Reservoir in 1975 only which are below observed, except for May when the calculated equals observed. This significant deviation may be attributed to an underestimate of either non-stream inflow to Windsor Reservoir or failure to consider transfers within the ditch system itself to the reservoir, or both.

The results of the model calibration are presented in Figures 10 through 15. Clearly, good correlation between calculated and observed flows at the Fort Collins gage exists. Deviation between the calculated water available at the case study boundary and the historical requirement are only a small percentage of the total requirement, and occur in off-season months. All other demands throughout the system were totally satisfied.

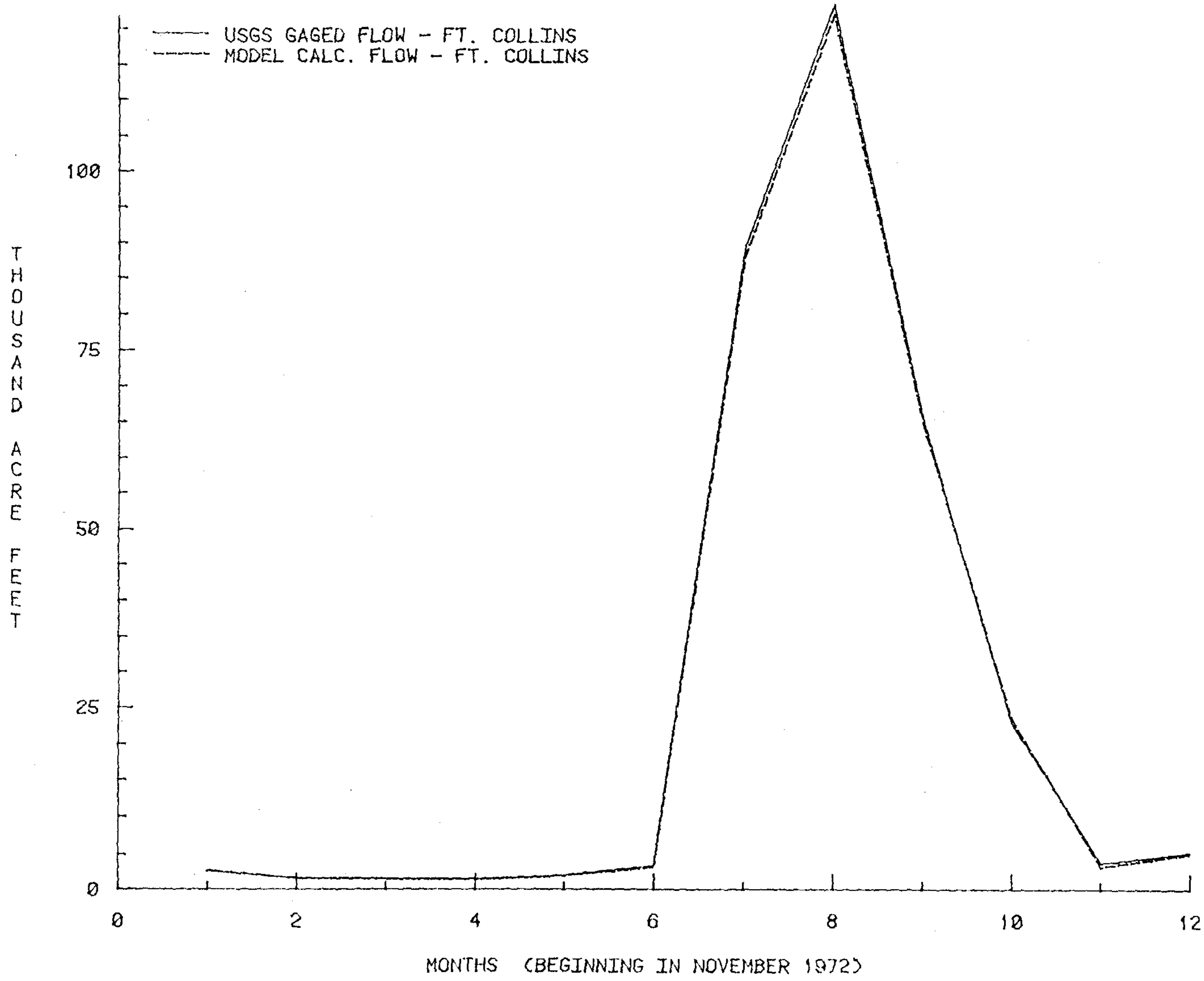

Figure 10. Calibration for Rawhide Project Irrigation Year 1973

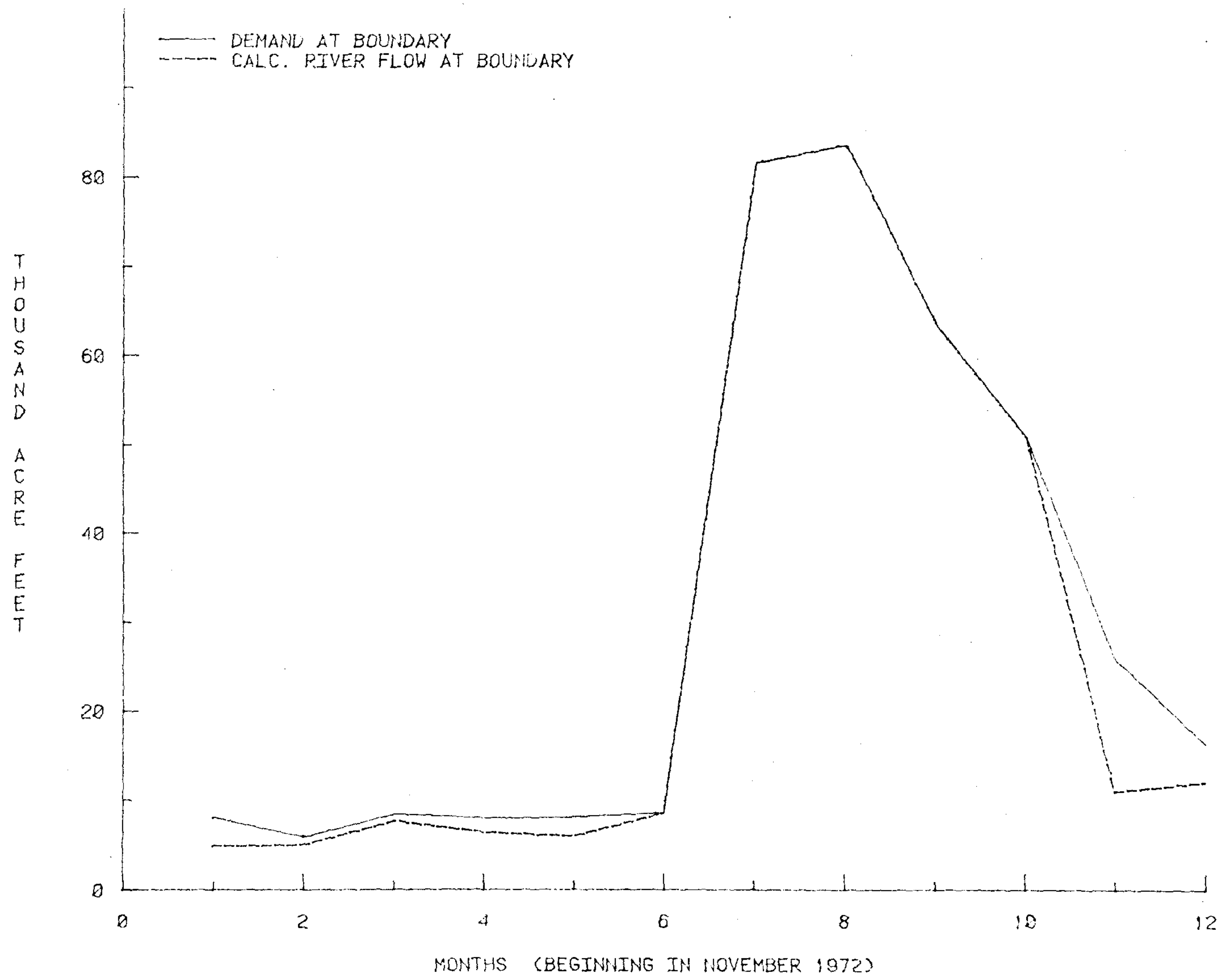

Figure 11. Calibration for Rawhide Project Irrigation Year 1973

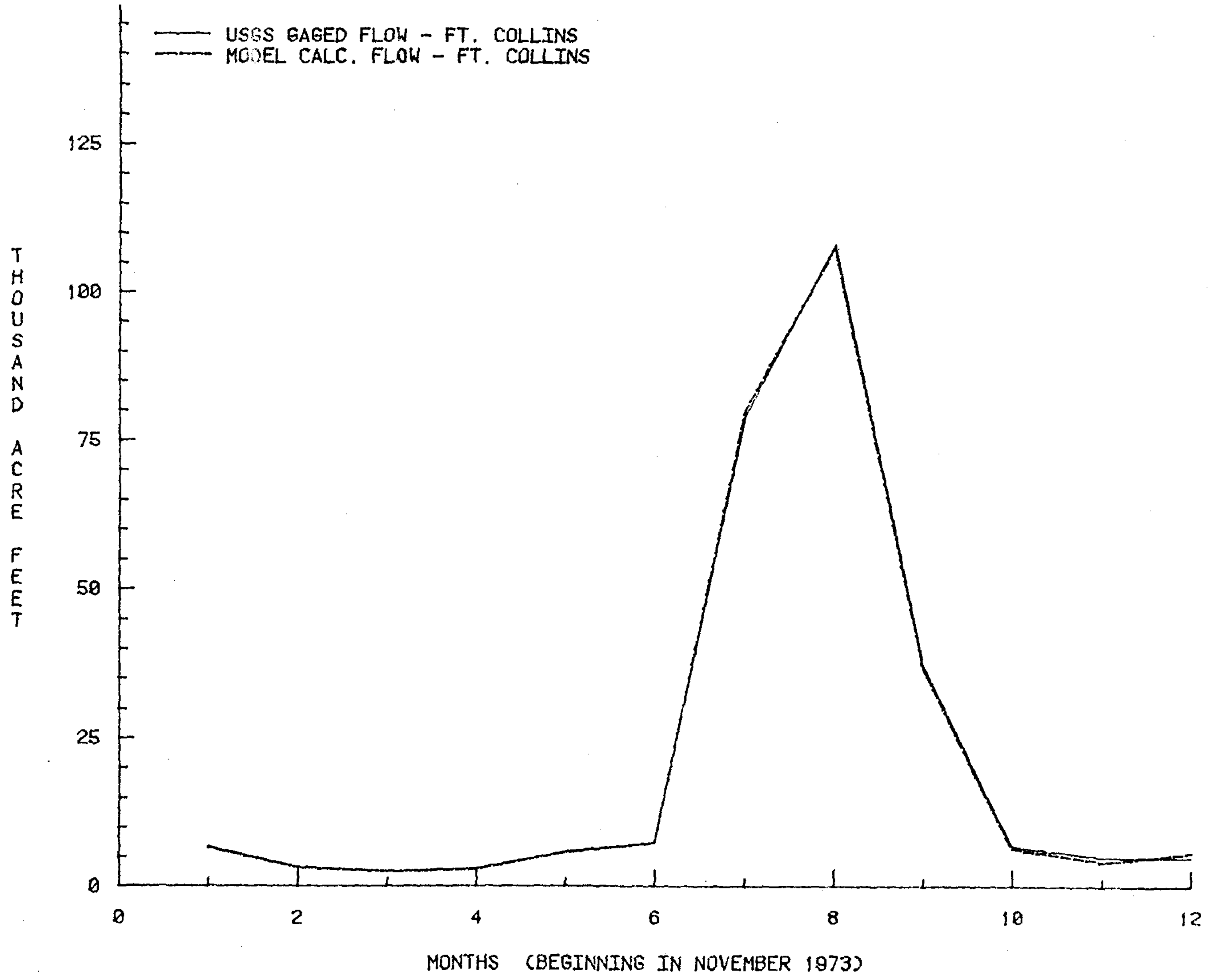

Figure 12. Calibration for Rawhide Project Irrigation Year 1974

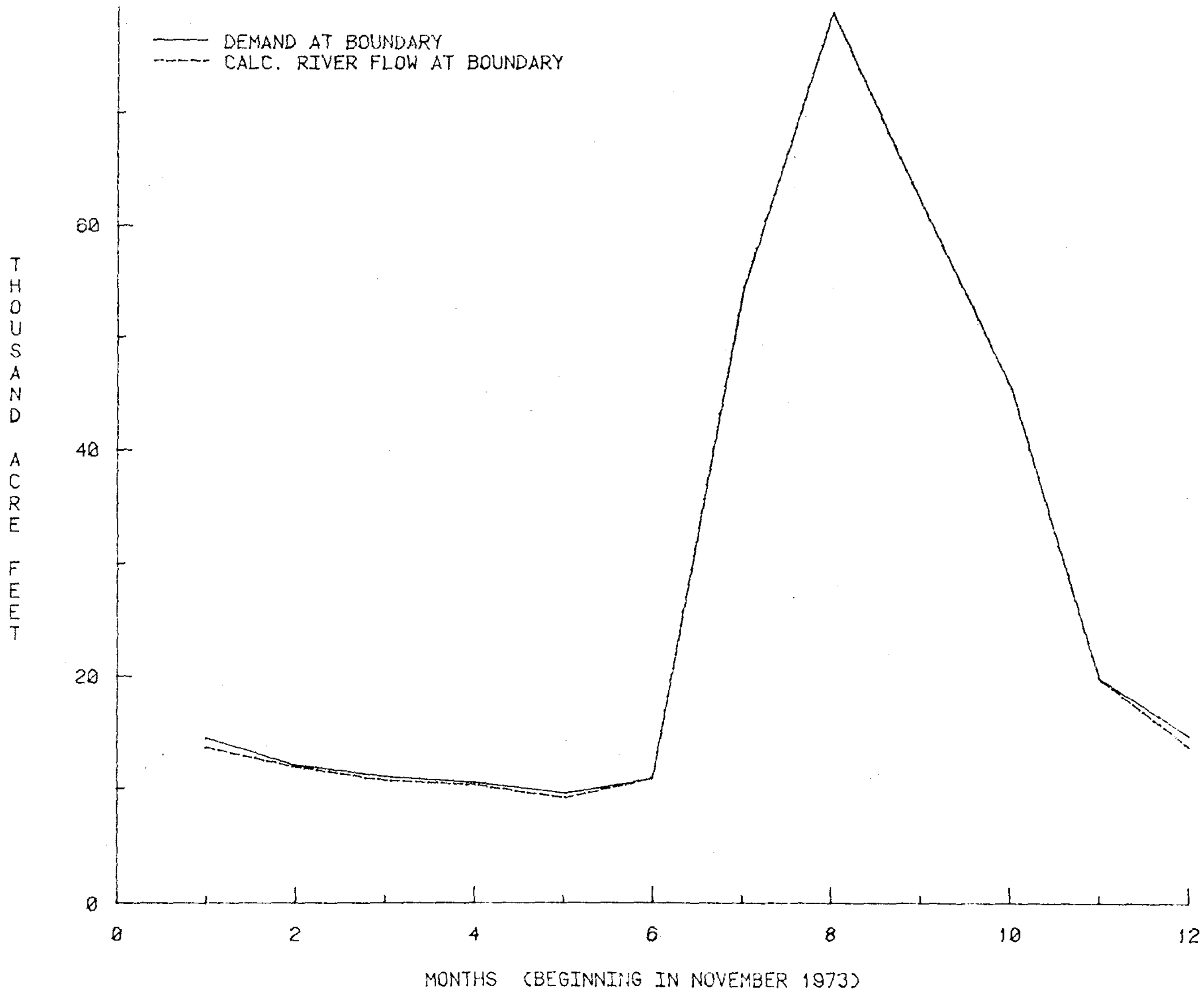

Figure 13. Calibration for Rawhide Project Irrigation Year 1974

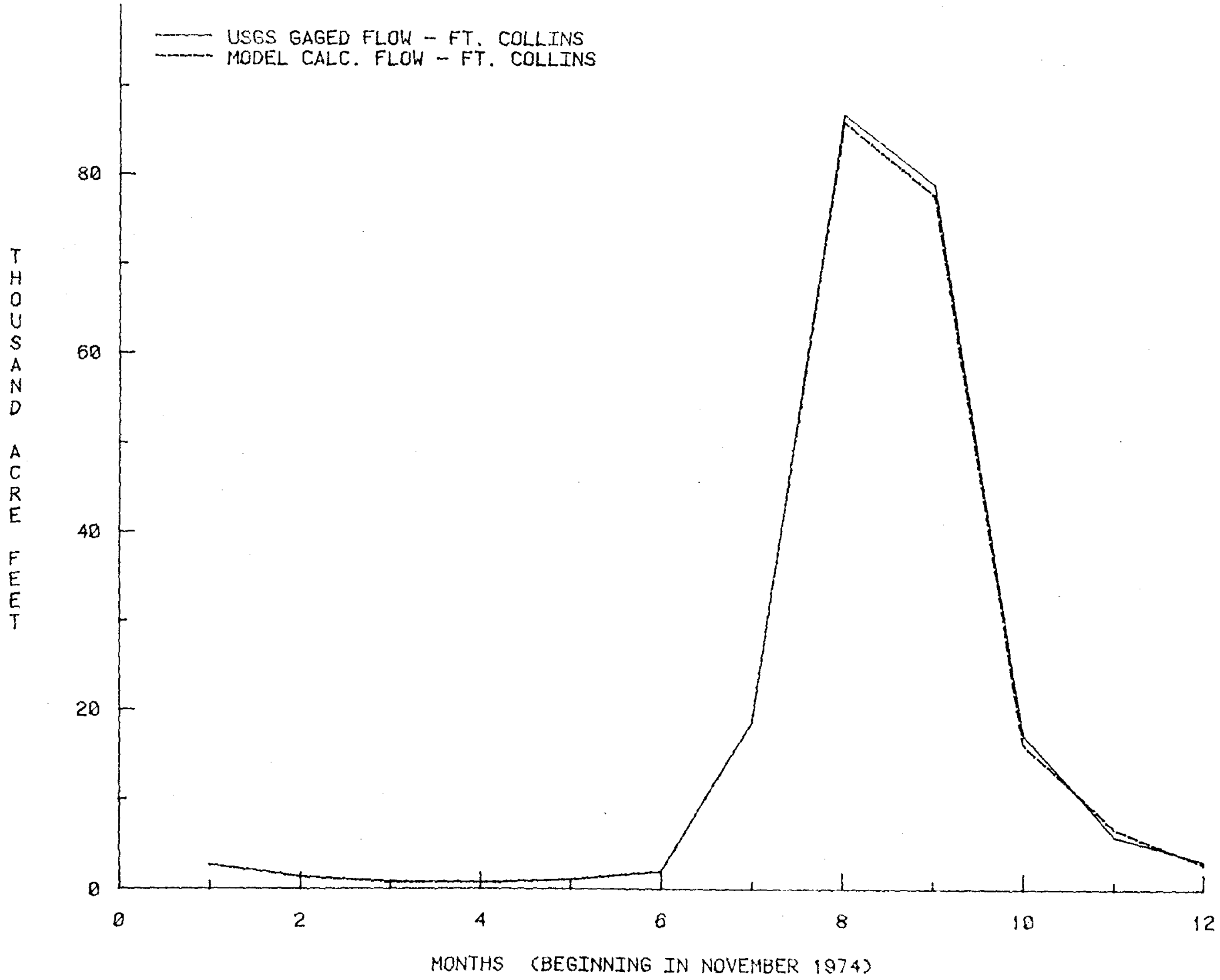

Figure 14. Calibration for Rawhide Project Irrigation Year 1975

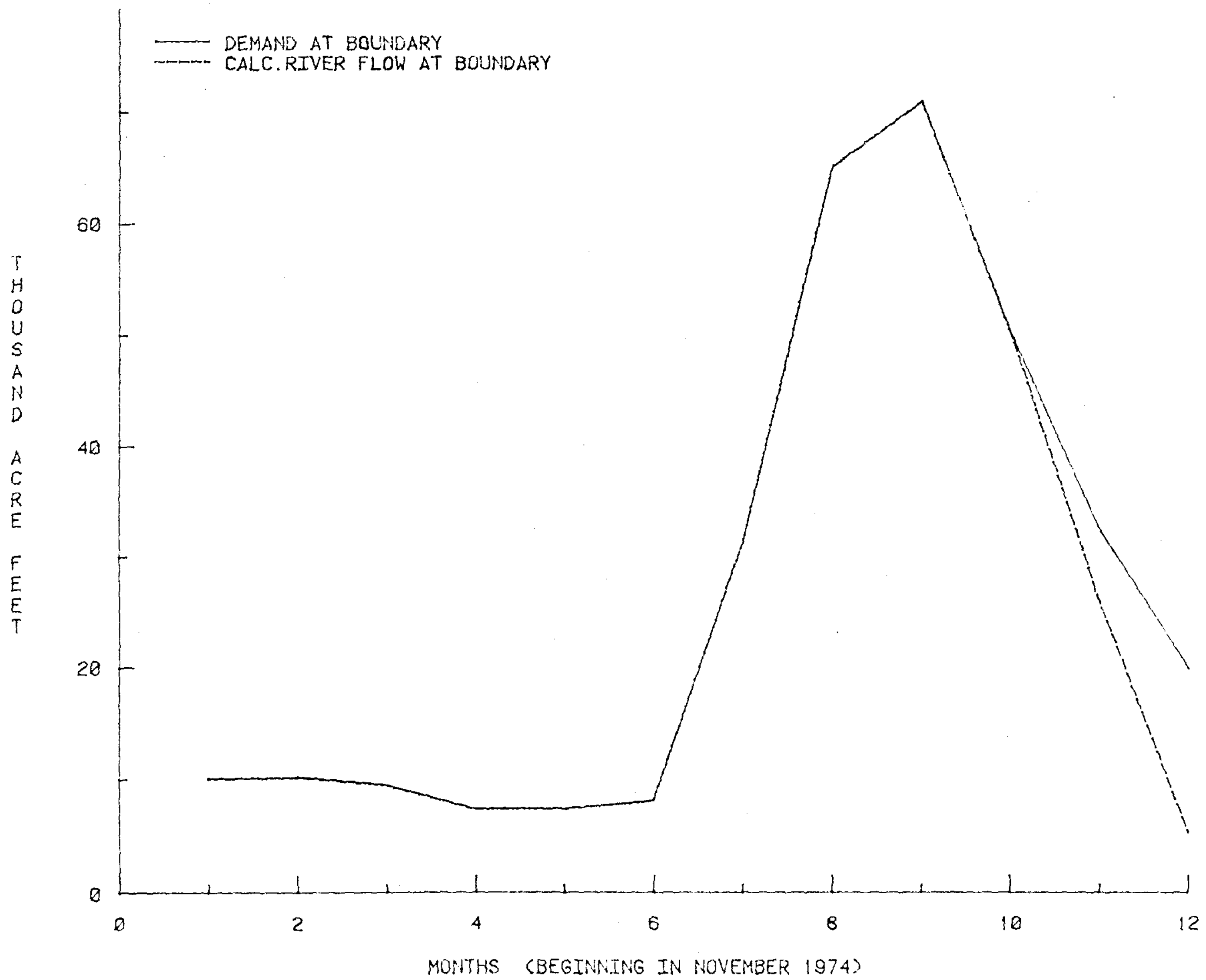

Figure 15. Calibration for Rawhide Project Irrigation Year 1975

IV. TESTING MANAGEMENT OPTIONS

There are several questions which must be answered concerning the availability of water for in-plant usage. Successfully calibrated, the model is now ready to use in evaluating various water supply management options. Two separate operational requirements must be met. The first is to fill the cooling pond beginning in 1981 and ending full in 1985. The second requirement is to supply 4200 acre feet annually of make-up water and to maintain a steady pool elevation in the cooling pond.

The water that is provided the Rawhide Project must be attributed (directly of indirectly) to treated effluent originating as new foreign water. It is unlikely that the time distribution of available flow for the Rawhide Project will coincide with the relatively uniform time distribution of demand.

Throughout the analysis, attention must be focused on the avoidance of injury to downstream (beyond outfall of Fort Collins wastewater treatment plant) users. The calculated flow at the case study boundary must be adjusted by subtracting ditch diversions upstream. This adjusted flow can then be compared with the calibration values obtained for adjusted demands at the boundary. It is assumed that the same diversions which occured during the historical period (1973-1975) will remain constant in the future. Since the historical period considered is a wet to dry cycle and diversions are a function of inflows to the system, this assumption is reasonable.

With the above conditions as a foundation, the following analyses can be made:

I. Filling of cooling pond
    1. estimation of Fort Collins demand (1981-1985).
    2. estimation of amount of diversion of new foreign water to Joe Wright Reservoir.
    3. operate SIMYLD with priority placed on filling the cooling pond.
    4. determine sensitivity of slight variations of Fort Collins demand and transbasin diversion on filling.
    5. determine impacts on remainder of the system.

II. Provision of make-up water
    1. estimate 1985 to 1995 Fort Collins demand.
    2. estimate transbasin diversions and distribution to Joe Wright.
    3. set priority on maintenance of stable pool elevation for cooling pond.
    4. operate SIMYLD with appropriate demand for make-up water.
    5. determine the sensitivity of slight variations in Fort Collins demand and transbasin diversions on the satisfaction of requirements for make-up water for PRPA.

During the testing of these management options, adjustment of the priority factors will be used to determine their impacts on the exchange system. The best management strategy for storage of flows in excess of Rawhide Pipeline capacity can be considered. It should also be remembered that the prevention of injury to downstream users (below pipeline intake) is of primary concern. The manipulation of priority factors allows the analysis of management options for satisfying downstream water rights. These priority factors reflect user preferences in the exchange of water among the various system components. For example, if holding water in storage in any particular reservoir is considered more beneficial than releasing that water for downstream demand satisfaction, the priority factor for that reservoir must be lower (ordinal scale) than the priority factors associated with demands.

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