MODELS FOR SYSTEM WATER PLANNING WITH SPECIAL REFERENCE TO WATER REUSE

by

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June 1978

Colorado Water Resources Research Institute
Completion Report No. 90

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DEPARTMENT OF CIVIL ENGINEERING
COLORADO STATE UNIVERSITY

Completion Report

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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF TABLES

PROJECT ORGANIZATION

This report is the final completion report for a research project entitled, The Role of Water Reuse in Meeting Regional Water Requirements. The project was sponsored by the Office of Water Research and Technology, Grant No. B-115-COLO, administered through the Environmental Resources Center, Colorado State University. It commenced July 1, 1974 and was granted extensions to April 30, 1978.

The extensions permitted another project, Water Supply Planning for the South Platte River Basin, 1970-2020, to be accomplished for the Corps of Engineers, Omaha District under the direction of D. W. Hendricks. The work for the Corps contract made application of a model to input-output water balance model--developed by the OWRT project in its early stages. In fact, it contributed to the model development in concert with the objectives of the OWRT project, and generated sufficient empirical data for more extensive demonstration of the model than would have been possible otherwise. Consequently the reports produced under the Corps contract are proposed as joint with the OWRT grant.

The co-principal investigators for the OWRT project were: David W. Hendricks, Associate Professor of Civil Engineering and Hubert J. Morel-Seytoux, Professor of Civil Engineering. The input-output water balance modeling was developed under the direction of Hendricks, while Morel-Seytoux directed the optimization work. The optimization model was based upon the input-output model as a framework, and upon the empirical data generated by it. Thus the two tracks of activity were interrelated.

A number of students obtained graduate degrees through whole or partial support from the project. For those students having partial support from the project, the Corps contract provided the other portion. The students involved are identified by their authorships indicated in the listing of theses. The importance of their work, their degree of involvement, and their contributions are recognized through the listing of publications produced by the project. The individuals were:

Roger W. DeHaan, Graduate Research Assistant
Brian A. Janonis, Research Associate
Steve Gerlek, Graduate Research Assistant
James L. Patterson, Graduate Research Assistant
Torkil Jønch-Clausen, Graduate Research Assistant
Bartolomeo Reitano, Graduate Research Assistant

The present report outlines the key contributions of the reports and theses generated by the project. Further detail and documentation can be obtained through the relevant reports.

PUBLICATIONS

The publications of the project are listed below under two categories: "reports" and "theses". There were no journal publications though several papers are being prepared now.

Reports

1. Hendricks, D. W., and R. W. DeHaan, Input-Output Modeling in Water Resources System Planning, Environmental Engineering Technical Report No. 3, Department of Civil Engineering, Colorado State University, Fort Collins, November, 1975.
2. Hendricks, D. W., Janonis, B. A., Gerlek, S., Goldbach, J. C., and J. L. Patterson, Water Supply-Demand Analysis, 1970-2020, South Platte River Basin, Main Report, Volume 1, Study for Water Supply Management Analysis and Alternative Development for the South Platte River Basin, Environmental Engineering Program, Colorado State University, Printed by U.S. Army Corps of Engineers, Omaha District, June, 1977.
3. Gerlek, S., Water Supply Analysis, South Platte River Basin, 1970-2020, Volume 2, Study for Water Supply Management Analysis and Alternative Development for the South Platte River Basin, Environmental Engineering Program, Colorado State University, printed by U.S. Army Corps of Engineers, Omaha District, June, 1977.
4. Janonis, B. A., Municipal Water Demands, South Platte River Basin, 1970-2020, Volume 3, Study for Water Supply Management Analysis and Alternative Development for the South Platte River Basin, Environmental Engineering Program, Colorado State University, printed by U.S. Army Corps of Engineers, Omaha District, June, 1977.

5. Patterson, J. L., Industrial Water Demands, South Platte River Basin, 1970-2020, Volume 4, Study for Water Supply Management Analysis and Alternative Development for the South Platte River Basin, Environmental Engineering Program, Colorado State University, printed by U.S. Army Corps of Engineers, Omaha District, June, 1977.
6. Patterson, J. L., Energy Water Demands, South Platte River Basin, 1970-2020, Volume 5, Study for Water Supply Management Analysis and Alternative Development for the South Platte River Basin, Environmental Engineering Program, Colorado State University, printed by U.S. Army Corps of Engineers, Omaha District, June, 1977.
7. Janonis, B. A., and S. Gerlek, Agricultural Water Demands, South Platte River Basin, 1970-2020, Volume 6, Study for Water Supply Management Analysis and Alternative Development for the South Platte River Basin, Environmental Engineering Program, Colorado State University, printed by U.S. Army Corps of Engineers, Omaha District, June, 1977.
8. Goldbach, J. C., A Guide to Input-Output Modeling and Users Manual for IOPLOT, Volume 7, Study for Water Supply Management Analysis and Alternative Development for the South Platte River Basin, Environmental Engineering Program, Colorado State University, printed by U.S. Army Corps of Engineers, Omaha District, June, 1977.
9. Reitano, B., and D. W. Hendricks, Construction of an Input-Output Water Balance Model for the Cache La Poudre River Basin, Environmental Engineering Technical Report No. 5, Department of Civil Engineering, Colorado State University, Fort Collins, April, 1978.
10. Jønch-Clausen, T., and H. J., Morel-Seytoux, Users Manual for LPTOR, a Fortran IV Linear Programming Routine, Hydrology Program, Colorado State University, Fort Collins, May, 1976.

11. Jønch-Clausen, T., and H. J. Morel-Seytoux, User's Manual for QPTOR, A Fortran IV Quadratic programming Routine, HYDROWAR Program, Colorado State University, Fort Collins, March, 1977.

12. Jønch-Clausen, T., and H. J. Morel-Seytoux, User's Manual for a Fortran IV Program of: Optimal Allocation of Water Resources in an Input-Output Framework, HYDROWAR Program, Department of Civil Engineering, Colorado State University, Fort Collins, March, 1978.

Theses

1. DeHaan, R. W., "An Input-Output Analysis of the Total Water System in a River Basin, M.S. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, 1975.
2. Gerlek, S., Water Supplies of the South Platte River Basin. M.S. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, 1977.
3. Goldbach, J. C., Input-Output Modeling of Water Resource Systems by Digital Computer. M.S. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, 1977.
4. Janonis, B. A., Characteristics of Municipal Water Systems in the South Platte Basin. M.S. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, 1977.
5. Patterson, J. L., Water for Industry in the South Platte Basin. M.S. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, 1977.
6. Reitano, B., An Input-Output Model of the Cache La Poudre Water System. M.S. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, 1978.

7. Jonch-Clausen, T., Optimal Allocation of Water Resources in an Input-Output Framework, Ph.D. Thesis, Department of Civil Engineering, Colorado State University, Fort Collins, 1978.

I. INTRODUCTION

1.1 Background

Water reuse is a concept advocated increasingly over the past ten years as an answer to problems of water shortages. The concept has not been implemented widely, however, for various reasons. First of all, planned water reuse is a serious alternative only when sources of virgin water are not easily available in the physical, economic and legal senses. Second, a de facto water reuse is already practiced widely, particularly in irrigated areas of the Western United States. Thus, a source of unappropriated used water may be difficult to find in such areas. Finally, there are a variety of forms of water reuse. These fall into two general categories: (1) recycle reuse, and (2) sequential reuse. The most appropriate form depends upon the context of the situation at hand. Usually the context is highly complex at this stage of development. And so the best form of water reuse is not clear cut. Also, water reuse must take its place among various other alternative modes of satisfying new demands for water, such as transfers from agriculture, developing new supplies, water conservation, etc. Thus, the problem is really one of comprehensive water planning. Bishop and Hendricks (1971) outlined the systems context of the problem and developed a linear programming methodology for determining a least cost system configuration (in terms of the array of water transfers needed and amount of treatment required). This is a realistic point of departure for further development of a water reuse planning methodology, accounting for its system context. This turns out to be a comprehensive water planning methodology and not one belonging exclusively to reuse planning. The latter is a part of the former. Further, the premise that the "best" water system configuration is one that satisfies a least cost "objective function", is too confining. Water rights and political concerns are equally important, and usually dominate considerations. The political concerns of course may reflect a host of societal concerns, e.g. environmental, social, growth, ecological, etc.

1.2 Purpose

The purpose of the research reported is to delineate methods for water reuse planning within the context of a complex system.

1.3 Objective

The specific objectives of the research are:

(1) to develop the matrix format for depicting a complex water system,

(2) to demonstrate the application of the matrix format and its application in water planning, with particular reference toward water reuse,

(3) to develop mathematical programming routines for a least cost objective function using non-linear cost functions, and to demonstrate the application of the routines.

1.4 Scope of Work

The research emphasizes the development of models for water planning which take into account all sources of supply and all sectors of demand. Two such models were developed: (1) a descriptive model for an overall water system, called here an input-output water balance model, and (2) a least cost computer optimization model.

Both models are demonstrated using empirical data from the South Platte River basin. The input-output model was used in fact to delineate alternative modes of water supply development to meet overall water demands in the South Platte River Basin to 2020. This was done in the Corps of Engineers' study. The model is also demonstrated at the sub-basin level, using the Cache La Poudre River Basin as the case situation. This work is reported by Reitar (1978). In addition, the optimization model used the Cache La Poudre River Basin for the case situation.

Because water reuse is tied into overall planning it is not appropriate to consider it apart as a separate concept. The subject of water reuse is addressed herein in this systems context. While the subject is not investigated exhaustively by itself, the present research provides the set-up for more explicit studies.

1.5 Methods

As noted, the research has two main thrusts: input-output modeling and least cost optimization. The methods used in both are described in this chapter. The two succeeding chapters outline the achievements of each activity.

1.6 Input-Output Modeling

The conceptual basis for the input-output water balance model was the economic input-output model of Leontief (1951). The development of the former model used the latter model as a pattern. Further, like Leontief's model, the water balance model is empirical in nature. A case study, the water system of the South Platte River basin, was developed, which provided the empirical data for the model. In addition, the case approach resulted in identification of the most critical questions in construction of the model and assurance that that procedures developed are immediately applicable (vis a vis, a theoretical, or deductive approach).

Future demands for water in the South Platte River basin were projected to 2020. Municipal water demands were based upon combinations of low, medium, and high series populations projections and low, medium, and high per capita water uses. Then a selected set of projected water demands from various use sectors were combined with assumptions about the hydrologic availability of water. Two such sets of assumed conditions, representing "stress" and "average" conditions, were the basis for input-output models constructed for 1980, 2000, and 2020. Proposed projects were assigned priorities, i.e. projects based upon presently held conditional decrees were first; water reuse by Denver was permitted if needed by 2000 according to stated policy and water rights for reuse; water transfers from agriculture were allowed next; finally the most questionable and politically controversial projects were given lowest priority. The roles of planned municipal water reuse in its system context is then, at this point, discernible. Also, so is the more extensive de facto reuse as practiced by the irrigated agriculture community.

From the overall basin-wide South Platte input-output water balance model, the interfaces with the water system of the Cache La Poudre River basin was clarified. A similar model was then constructed for the Cache La Poudre water system for 1970. This model was "nested" within the large South Platte model, but it had considerably more resolution.

The optimization model then utilized the data and the structure of the Cache La Poudre input-output model. The latter was aggregated considerably in order to develop a feasible demonstration.

1.7 Post-Mortem

It may be appropriate, and instructive, to review the project accomplishments as they occured actually, vis a vis what was contemplated. The goal of the study was originally and is yet to develop a better understanding of the planning context of water reuse. The problem was seen as one of least cost optimization within the context of a real system. So the tasks were to: define the system, develop cost functions, and optimize.

The empirical or inductive, approach would require a continuous confrontation with the dilemmas of real circumstances. Development of a model and its demonstration under such circumstances ought then to lead to results which would be more readily usable in practice than if the preoccupation was on theoretical exercises. Particular emphasis was placed on the development of optimization procedures for non-linear cost functions.

The plan was followed and the optimization work was accomplished. But a number of serendipitous benefits were derived in the process and resulted in a reformulation of the project objectives, which are stated under the objectives heading.

The original study was to utilize the Cache La Poudre water system as the case study. It was soon obvious, however, that one could not formulate the Cache La Poudre system exclusive of either the larger South Platte system, or the adjacent basins which provide "foreign" water. Thus, in order to understand a part of the system, one needs to understand the whole system. It became evident, too, that an empirical model study is difficult for two reasons: (1) a prodigious amount of labor is required, and (2) the model must face a rather stern discipline, thus requiring adjustements and revisions (i.e. it is an inductive process). Thus, the case study approach has more inherent problems than the deductive approach (which permits the luxury of contemplation without accountability). But it also has the promise of bigger payoffs since practitioners don't often have the time to go through the process of adapting elegant models to reality.

Also, the idea of a matrix was in mind from the beginning of the project--but only as a structure for the optimization model. This soon became an end instead of just a means. It was seen soon after some initial trials that the matrix provided a visual picture of a complex water system structure. This became the input-output model. While it can be and was used as a basis for least cost optimization, it has value itself from the fact that it is easy to use and that it has considerable utility as a system model. Using it, one can focus on legal or political questions, which may be of greatest interest. Further, within basin systems as complex and highly developed as those found in the Western United States, the merit of mathematical optimization approaches may have limits simply because there are very few alternatives available. Also, the political and legal factors are likely to be overriding anyway. This does not say that least cost optimization is not applicable. It says merely that one must use judgment in applying it.

The writing of this report reflects these new insights gained through the process of accomplishing the research. It reflects the fact that research often has serendipitous benefits.

II. INPUT-OUTPUT MODELING

The input-output water balance model is a matrix representation of selected water transfers occurring within a water resources system. The water resources system represented could be of any type and size (i.e., that of a factory, a city, a water district, an irrigation company, a sub-basin, a river basin, a state, a region, etc.). The South Platte River Basin is depicted in this study.

The strength of the input-output model is its quantitative display, in the matrix format, of the innumerable interactions of a complex water resources system. From this display, one can grasp either the overall picture of the whole system or the minute quantitative detail of any component part. Thus, the format makes readily accessible a vast amount of data concerning any single item or group of items (e.g., water use by a single city, water use by a group of cities). In addition, the graphic display of a complex set of interactions easily conveys the concept of a *system*. But above all, the matrix is a powerful tool for system water planning.

2.1 Construction of an Input-Output Model

The method of construction and use of an input-output model can be understood most easily by starting with a simple system depiction having only a few interactions. Figure 2-1 is a block diagram of selected components, and their relevant interactions, for the South Platte basin as it may have been at an early level of development (i.e., about 1890).

The input-output matrix that corresponds to Figure 2-1 is shown in Figure 2-2. As seen in Figure 2-1, each of the system components acts as either an origin of water (i.e., water is an "output" from that component), or a destination for water (i.e., water is an "input"

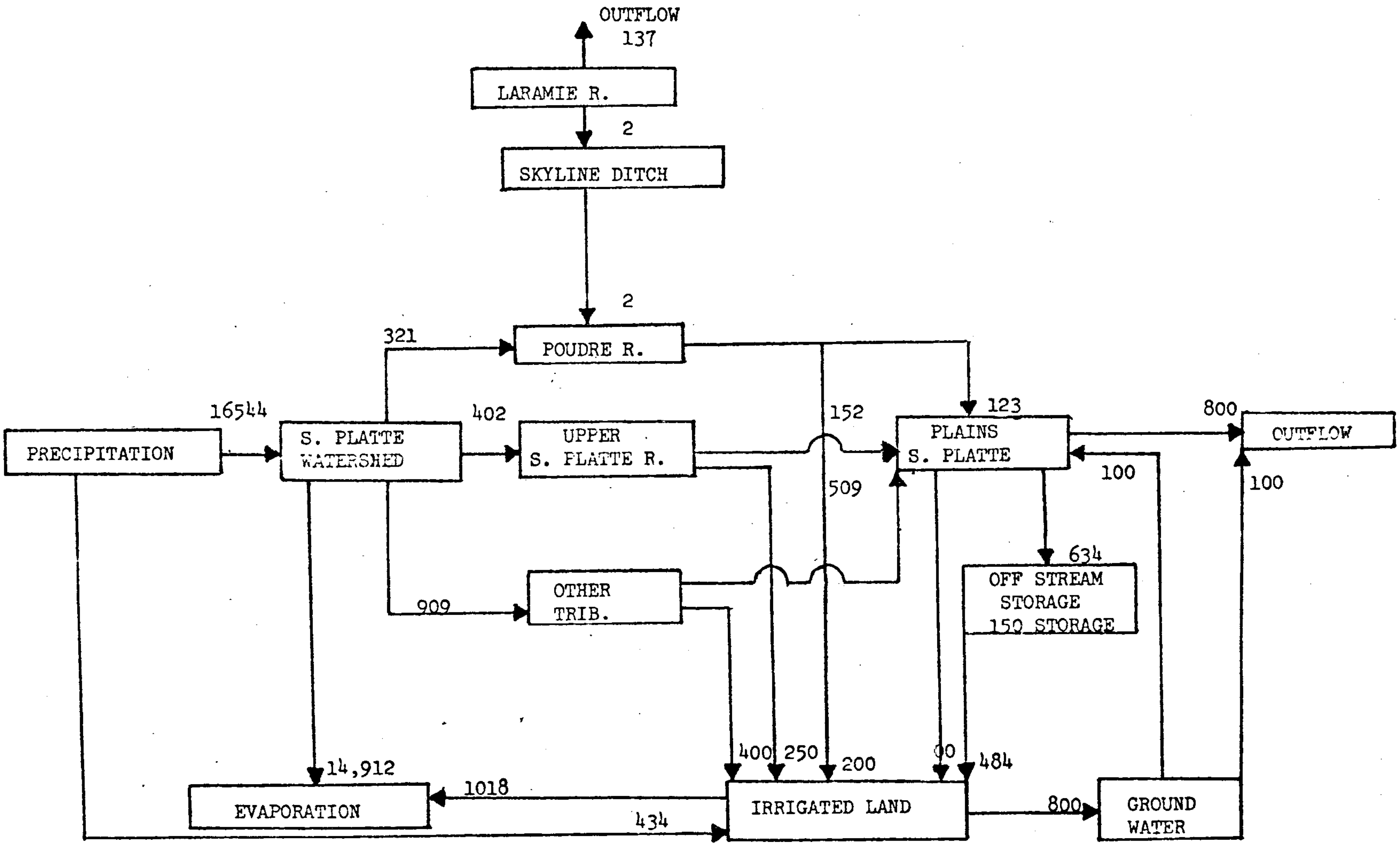


Figure 2-1. Block Diagram of Major Elements of Early South Platte Water Resources System Showing Roughly Estimated Annual Water Transfers in Thousands of Acre-Feet.

DESTINATION ORIGIN	SKYLINE CANAL	POUDRE R.	UPPER S. PLATTE	OTHER TRIBS	PLAINS S. PLATTE	IRRIGATED AREAS	OFFSTREAM STORAGE	G. W. RESERVOIR	EVAPORATION	OUTFLOW	TOTAL SUPPLIES
PRECIPITATION		321	402	909	0	434		0	14,912		16,978
LARAMIE RIVER	2									137	139
SKYLINE C.		2									2
POUDRE R.					123	200					323
UPPER S. PLATTE					152	250					402
OTHER TRIBUTARIES					509	400					909
PLAINS S. PLATTE						100	634			800	1,534
IRRIGATED AREAS					50			800	1,018		1,868
OFFSTREAM STORAGE						484				250	484
G. W. RESERVOIR					700					100	800
TOTAL DELIVERED	2	323	402	909	1,534	1,868	634	800	15,930	1,037	

Figure 2-2. Input-Output Model of the South Platte Water Resources System for about 1890. Water Exchanges Shown are in Thousands of Acre-Feet Anually and are Rough Estimates For Illustrative Purposes.

to that component)--or both. Most of the system components have both outputs and inputs. In Figure 2-2, each of the system components having "outputs" are shown as rows in the matrix, while all those having "inputs" are shown as columns. Since most of the components have both outputs and inputs, they are both rows and columns.

Any row in the matrix shows how the output from any system component is distributed to one or more of the various system components identified in the columns. The total supply available for distribution *from* any component is shown in the right hand columns. By the same token, the various water delivered *to* any component is given by the numerical entries in the respective columns. The total water delivery to any component is shown in the bottom row.

Also, just as the block diagram must have a numerical balance between outputs and inputs, so must the input-output matrix. For example, all inputs to the irrigation component in Figure 2-1 must be balanced by outputs from irrigation, i.e., both must add up to 1,868,000 acre-feet. These are seen as the column and row respectively in Figure 2-2. Also, for the overall system, precipitation plus imports must be balanced by system outflow, evaporation and storage (150,000 acre-feet is stored in "offstream storage"). Thus, the flows in both the overall system and each individual component within the system must be balanced.

Once one has learned to think in terms of the input-output model, it is easy to extract from the matrix any information desired. For example: What amount of Laramie River flow is exported to the South Platte basin? Answer: 2,000 acre-feet annually out of a total annual flow of 139,000 acre-feet. What is the annual native flow in the South Platte basin? Answer: 1,632,000 acre-feet (i.e., 321 + 402 + 909). What is the agricultural demand? Answer: 1,868,000 acre-feet. What amount of the agricultural demand is satisfied by precipitation? Answer: 434,000 acre-feet. What is the basin irrigation efficiency (i.e., ratio of evaporation to water applied)? Answer: 71 percent (1,018,000 acre-feet evaporated/1,434,000 acre-feet applied). What is the basin reuse factor (i.e., total water diverted for use divided by native supplies plus imports)? Answer: 1.14 (i.e., 1,868,000 acre-feet diverted/1.634,000 acre-feet native flows plus imports). The important point here is that one can query the matrix in any manner desired to answer any questions of interest.

The selection of system components for the matrix is probably the most perplexing task. There must be a balance between *resolution* and *aggregation* in order to keep the matrix meaningful, and yet tractable, in size. For example: How many tributaries should be displayed? How many stream reaches? Should irrigated land be disaggregated by subbasin? Which cities should be included, or should they all be aggregated (or "lumped") into a "municipal sector?" The answers to these questions are a matter of individual judgment, keeping in mind the purpose which the input-output model is intended to serve (e.g., to model a whole river basin, a municipal water system, etc.).

2.2 Planning

The input-output matrix can be utilized in planning in several ways. First, new demands by water utilizing components, i.e., cities, can be imposed by changing the bottom line entry for the respective column. To meet the new demand, a new entry for that column must be found from one of the rows--such that the new demand is satisfied.

Other questions related to the efficiency of certain policies, the role of new projects, schemes for water reuse, etc., can be ascertained by tracing the various water flows they cause through the rest of the system. Any change to any part of the system has "ripple effects" on other parts of the system; the input-output matrix is a way to trace these effects.

One of the major attributes of the model is its visual display of every possibility. Thus, the model permits an evaluation of various water planning alternatives in terms of any considerations which may be relevant (i.e., political, physical, economic, and hydrologic feasibilities, water rights, etc.). Such considerations must be integrated into the planning and evaluation process by personal knowledge (i.e., non-mathematically); the input-output matrix provides a vehicle for this purpose.

2.3 Construction of the South Platte Model

Figure 2-3 is a photograph of an input-output water balance model of the South Platte basin for the year 1970. The matrix consists of the major "sector groupings" which are common to most water resources systems. The "sectors" and the "sector components" on the other hand are unique to the South Platte basin. The broadest category in this taxonomy is the "sector group." This category consists generally of "Supply sectors," "transport sectors," "storage sectors," "use sectors," and "exit sectors." Most water resources systems would have these types of sector groups. The next level is the "sector." The labels in Figure 2-3 start at this level. The third level of disaggregation is the "sector component," all of the detailed side and top labels in Figure 2-3 are of this category. Table 2-1 illustrates the idea of such a hierarchical disaggregation with examples from the South Platte basin input-output model of Figure 2-3. The complete sets of sectors and sector components developed for the South Platte input-output model are seen in Figure 2-3. These are, of course, unique to the South Platte River Basin.

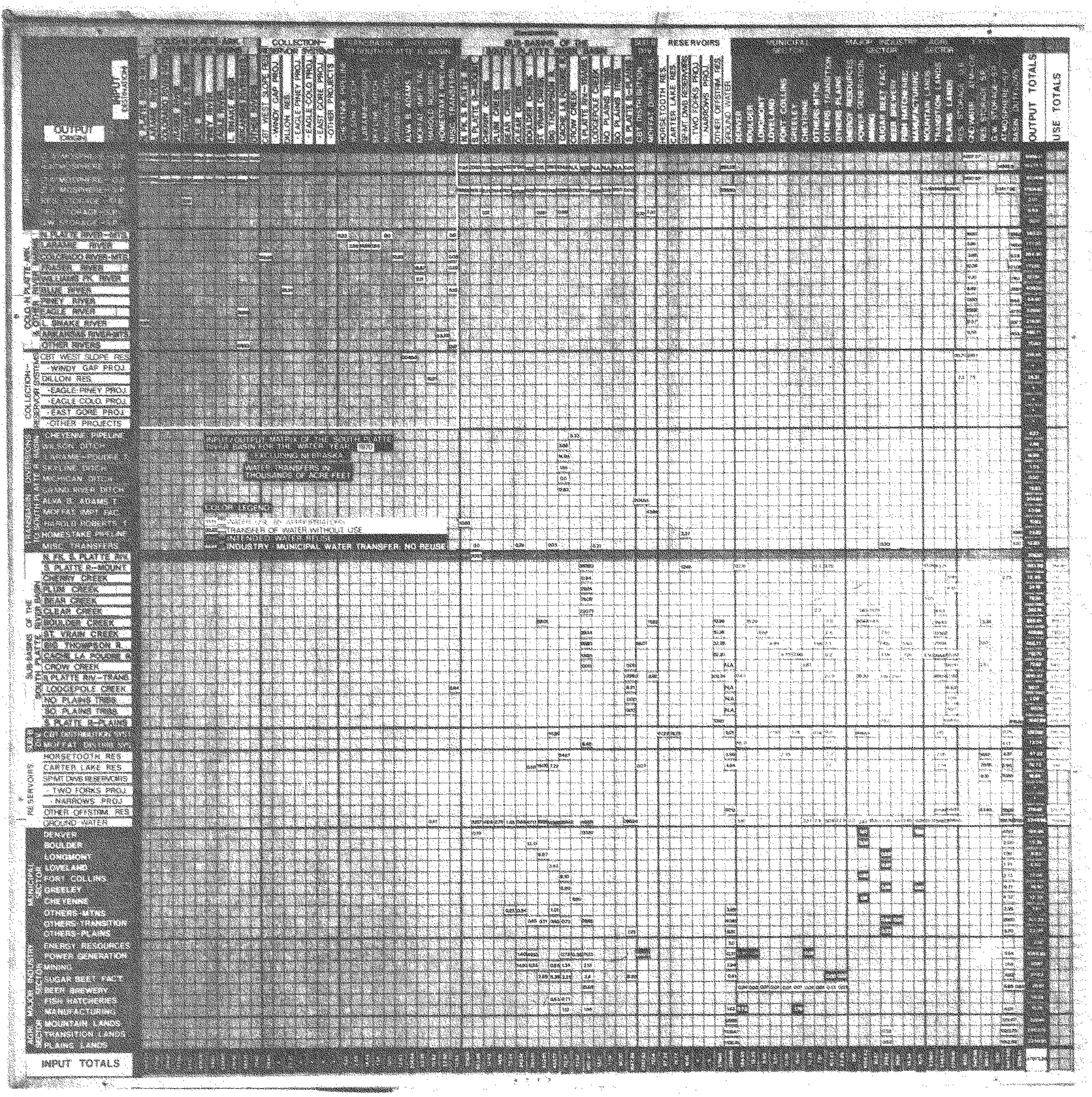


Figure 2-3. 1970 Input-Output Water Balance Model, South Platte River Basin

Table 2-1. Hierarchy of Sector Groupings for Construction of an Input-Output Matrix Using Illustrative Examples from South Platte Model, Figure 2-3

Sector Group	Sector	Sector Component
Supply Sectors	Origins	Atmosphere--Other Basins Atmosphere--South Platte Reservoir Storage
	Sub-Basins of the South Platte River Basin	Cherry Creek Plum Creek Bear Creek
Transport Sectors	Transbasin Diversions to South Platte Basin	Cheyenne Pipeline Wilson Ditch Laramie Poudre Tunnel
Use Sectors	Municipal	Denver Boulder
	Agriculture	Mountain Lands Transition Lands

The actual selection of sectors and sector components for a given input-output model is a trial and error process. One must first of all be intimately familiar with the system being modeled in order to identify the sectors and sector components which are appropriate. The sector components are then selected and aggregated, as necessary, to keep the size of the matrix tractable, and grouped into what seems to be the most suitable sector. This process is repeated until one finds a concise and articulate depiction of the system which seems the most satisfactory and suitable for the intended purpose. For some purposes a great amount of detail may be desirable. For example, creeks and tributaries of the main stream, stream reaches, individual canals, tracts of agricultural land, water treatment plants and wastewater treatment plants, etc., may be shown if these units are important to the planning process. An input-output model with such detail would be intractable in size if done for a whole river basin; a sub-basin, a water district, or some othe disaggregation sub-unit would be necessary to handle such detail. For the South Platte basin, input-output model of Figure 2-3, much of this detail is "lumped" into larger sector components. For example, water treatment plants and wastewater treatment plants are lumped into the cities identified within the municipal sector. Always there must be compromise between aggregation and disaggregation.

2.4 Media for Graphic Display

An input-output matrix can be constructed graphically on paper by typing or lettering, etc. The display media used for this study consisted of an eight foot by eight foot magnetic board, which had attached to it, one inch strips for sector and sector component labels and numerical data. This method works quite well in that it facilitates the trial and error process of determining the appropriate sectors and sector components and their arrangement for the water resources system depicted. Once the system is finalized, a photograph is taken of the board for permanent record. To make the board detail readable by photograph, the sector component labels were one inch colored strips; one inch squares were used for numerical data. These strips and squares are magnetic rubber which attach easily to the magnetic board. Color coding of sector labels and water transfer data was used to more easily identify the various types of information displayed. For example, all water transfers which consist of moving water to and from the various sector components were color coded yellow; if a water right (or by corollary, a use) is associated with the transfer, the color is white.

The grouping of data is facilitated further by the bold lines separating the major sector interactions. Figure 2-3 is a photograph of the 1970 South Platte basin input-output matrix constructed on the eight foot by eight foot magnetic board. The same magnetic board was used to construct the South Platte input-output models for 1980, 2000 and 2020.

Another tool which can facilitate construction of an input-output model display is the computer. A computer program, called IOPLOT, was developed to accomplish this. Goldbach (1977) has prepared a user's manual for IOPLOT. The program may be useful in several situations. First, in the early stages of model construction when decisions on which sector components should be included and their position in the matrix are all in a state of flux, changes can be accomplished merely by punching new cards or rearranging their order. Second, the input-output display from the computer output may provide a useful format for making changes by hand to the numerical data within the matrix. This method was used to work out future conditions for 1980, 2000 and 2020 in the present study. Third, the computer gives the capacity to perform various types of arithmetic on the vast amount of numerical data contained within the matrix. The program IOPLOT has subscripted some of the data within the matrix to facilitate this process. It is up to the user to add the statements to extract the information of interest. Finally, the matrix display constructed from IOPLOT is self sufficient as an input-output model display by itself. It was designed to provide such a display for those wishing to contruct an input-output model in a quick and easy manner.

2.5 Water Supply-Demand Scenarios for the South Platte by Input-Output Modeling

The input-output water balance model was used to depict the various water resource systems of the South Platte basin for 1970. Figure 2-3 shows the 1970 model. After the 1970 model was completed, two "scenario assumption sets" were developed for each of the years 1980, 2000, and 2020. Each scenario assumption set consisted of a different set of assumed conditions relative to water supply and water demand factors. From these scenario assumption sets the respective input-output models were constructed. These are shown as Figures 2-4 and 2-5 for 1980A and 1980B; Figures 2-6 and 2-7 for 2000A and 2000B; Figures 2-8 and 2-9 for 2020A and 2020B.

The input-output models for the scenario assumption sets were intended to provide an understanding on how the water transaction systems of the South Platte River basin might respond internally in adjusting to different future conditions of supply and demand. In this manner the role of water reuse could ascertained; i.e., it is one of the adjustments which could be made. *The problem is not to predict the future, but rather to understand how the system might respond, and whether it has the capacity to respond, to certain combinations of events.* These events might range from "expected" to situations which might severely stress the basin's water resource systems. This section describes the 1970, 1980, 2000, and 2020 input-output models and shows how they may be used to depict a manner in which the demands on water supplied within the basin might be satisfied as a result of selected future conditions (i.e., the scenario assumption set). Thus the model results for 1980A, 1980B, 2000A, 2000B, 2020A, 2020B are

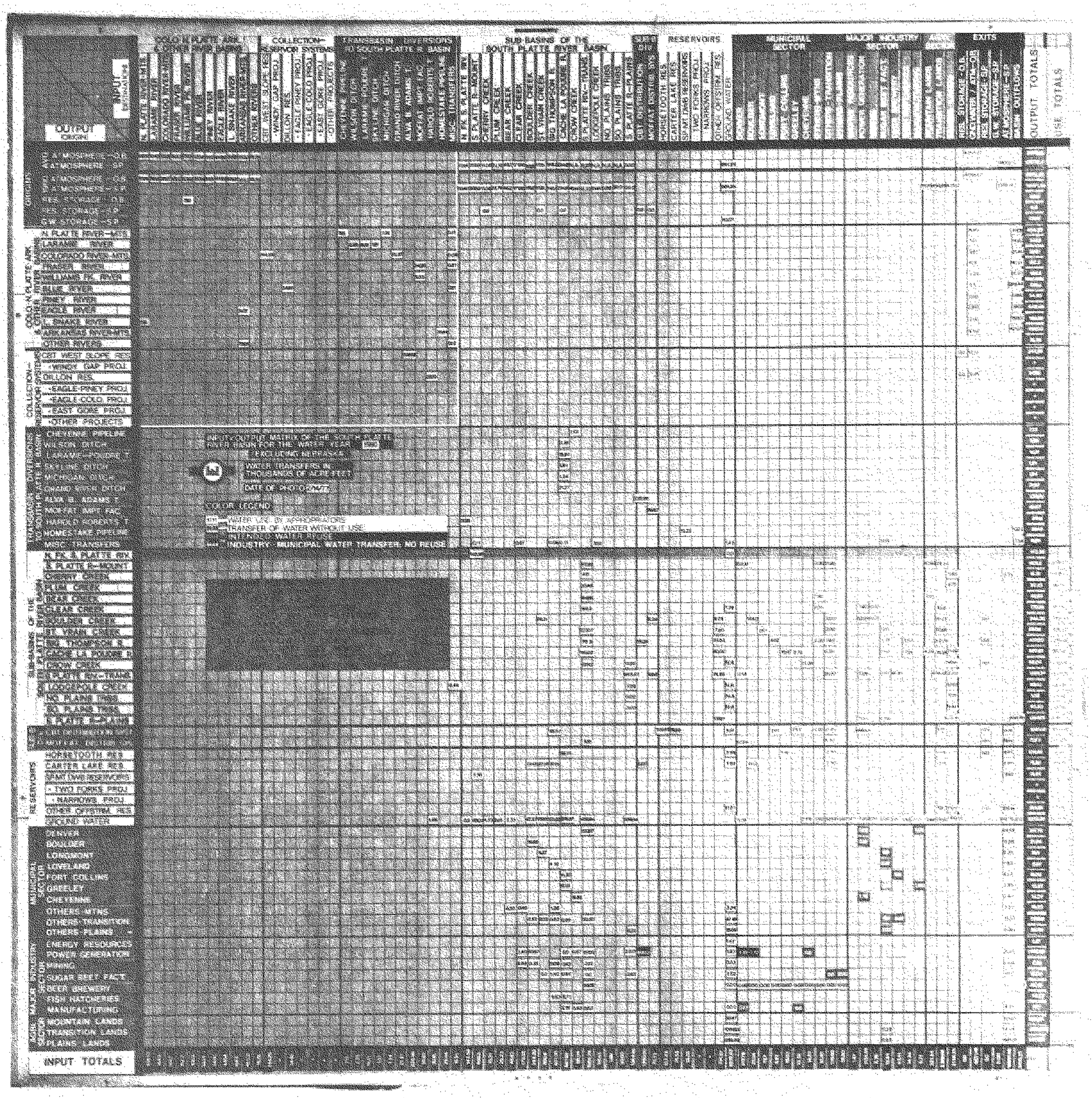


Figure 2-4. 1980 Input-Output Water Balance Model, South Platte River Basin. Scenario A: Average Runoff; Medium Series Population

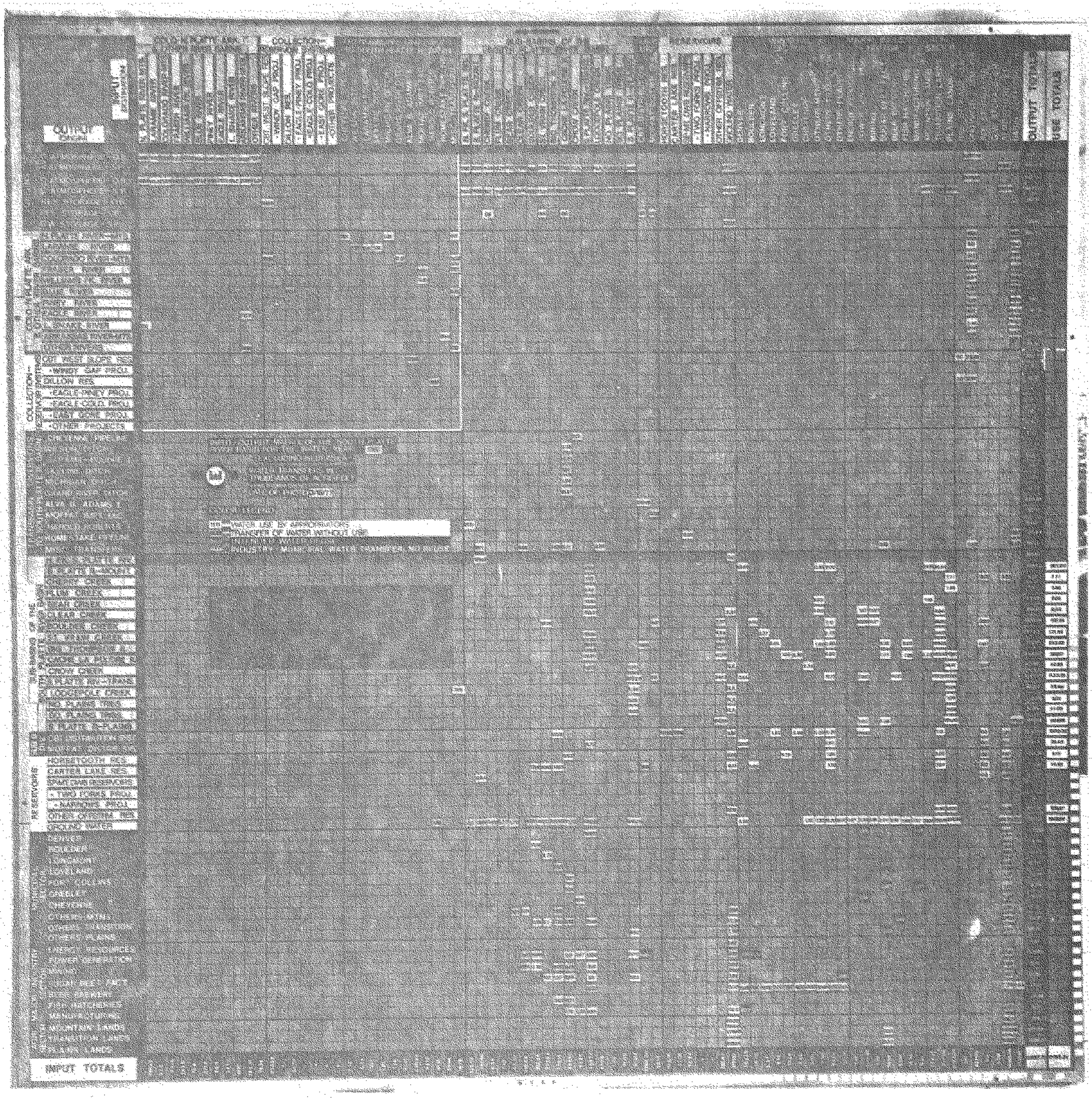


Figure 2-5. 1980 Input-Output Water Balance Model, South Platte River Basin. Scenario B: Drought Runoff; Medium Series Population

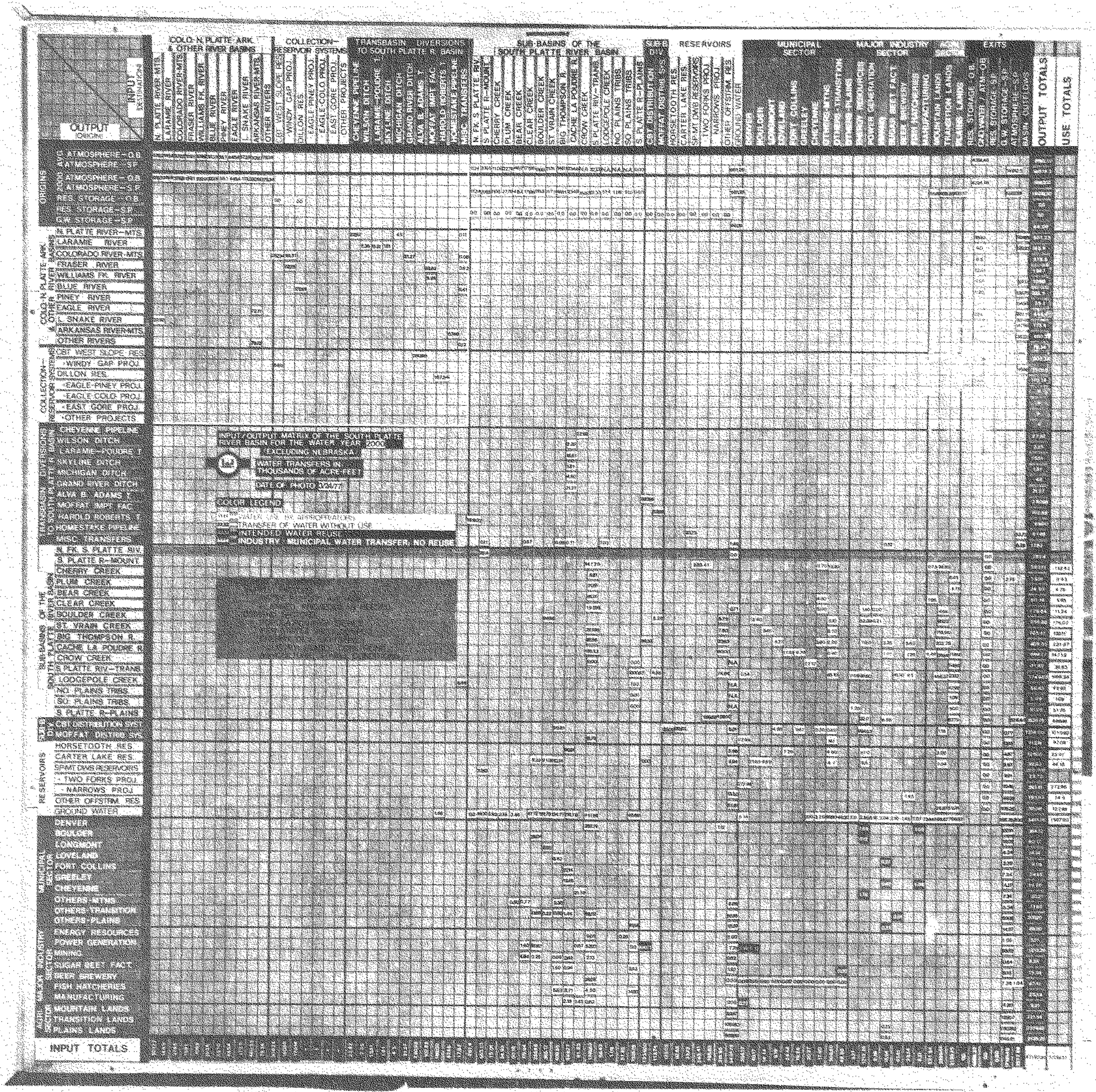


Figure 2-6. 2000 Input-Output Water Balance Model, South Platte River Basin. Scenario A: Average Runoff; High Series Population

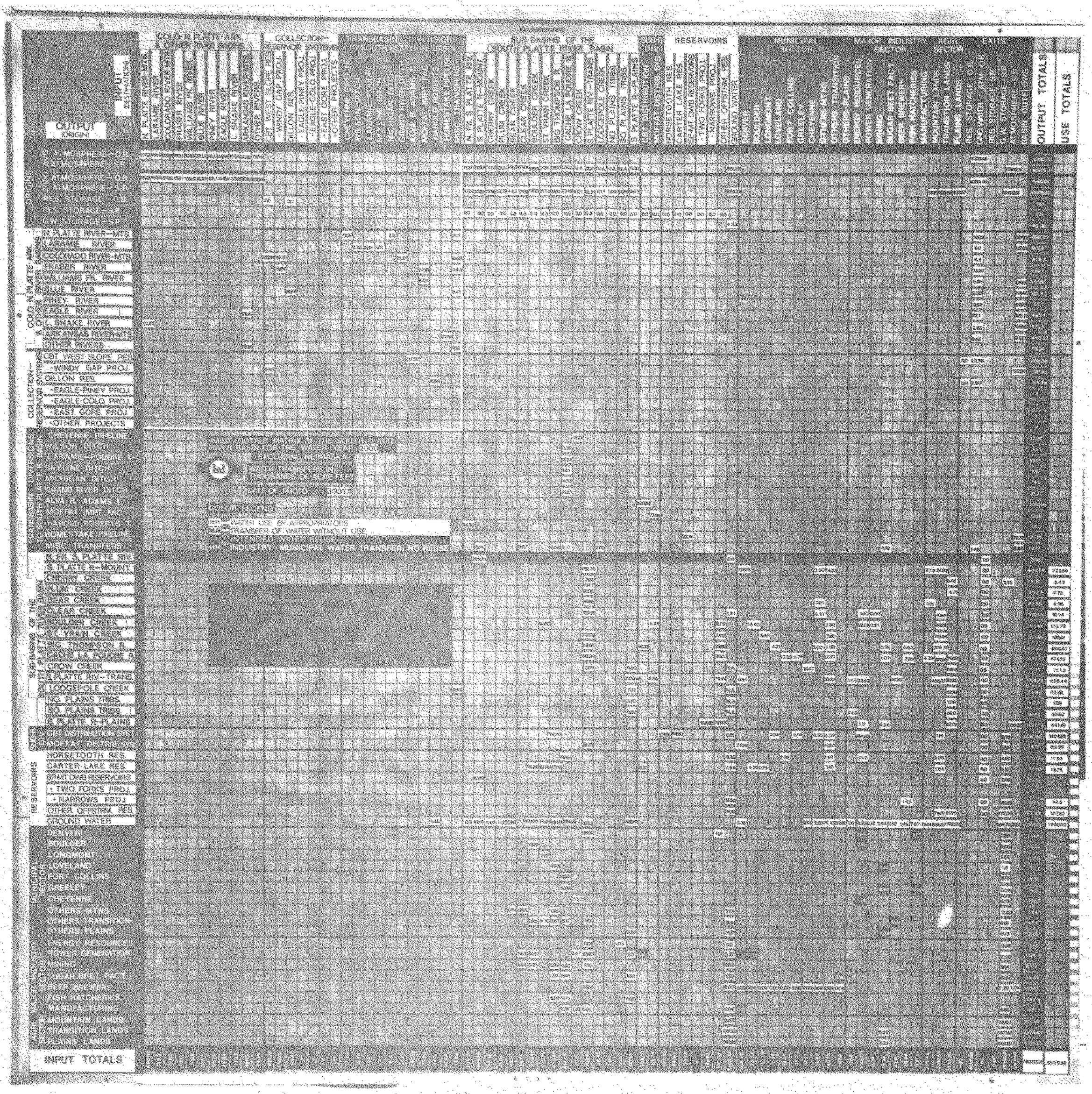


Figure 2-7. 2000 Input-Output Water Balance Model, South Platte River Basin. Scenario B: Average Runoff; Medium Series Population

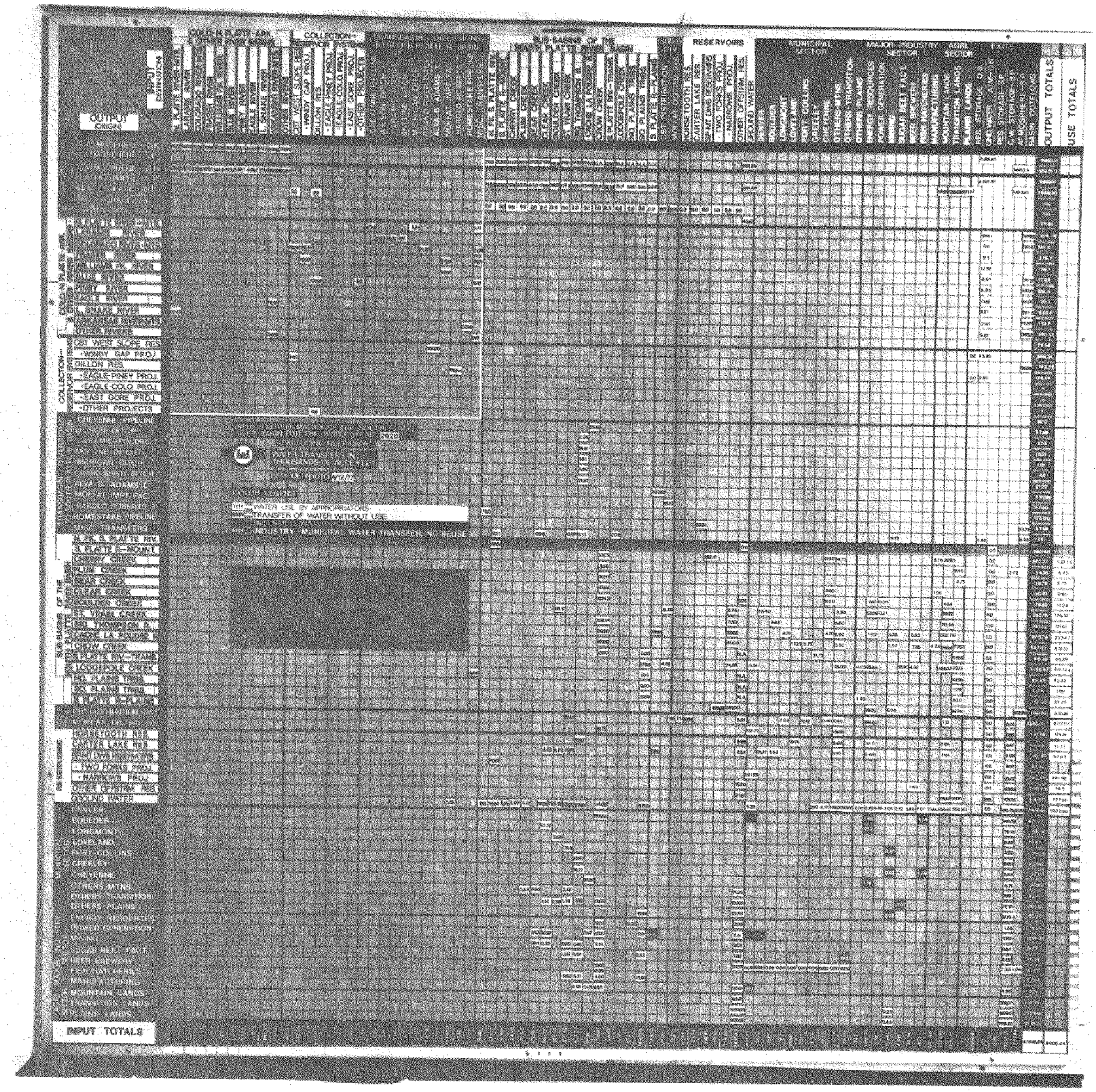


Figure 2-8. 2020 Input-Output Water Balance Model, South Platte River Basin. Scenario A: Average Runoff, High Series Population

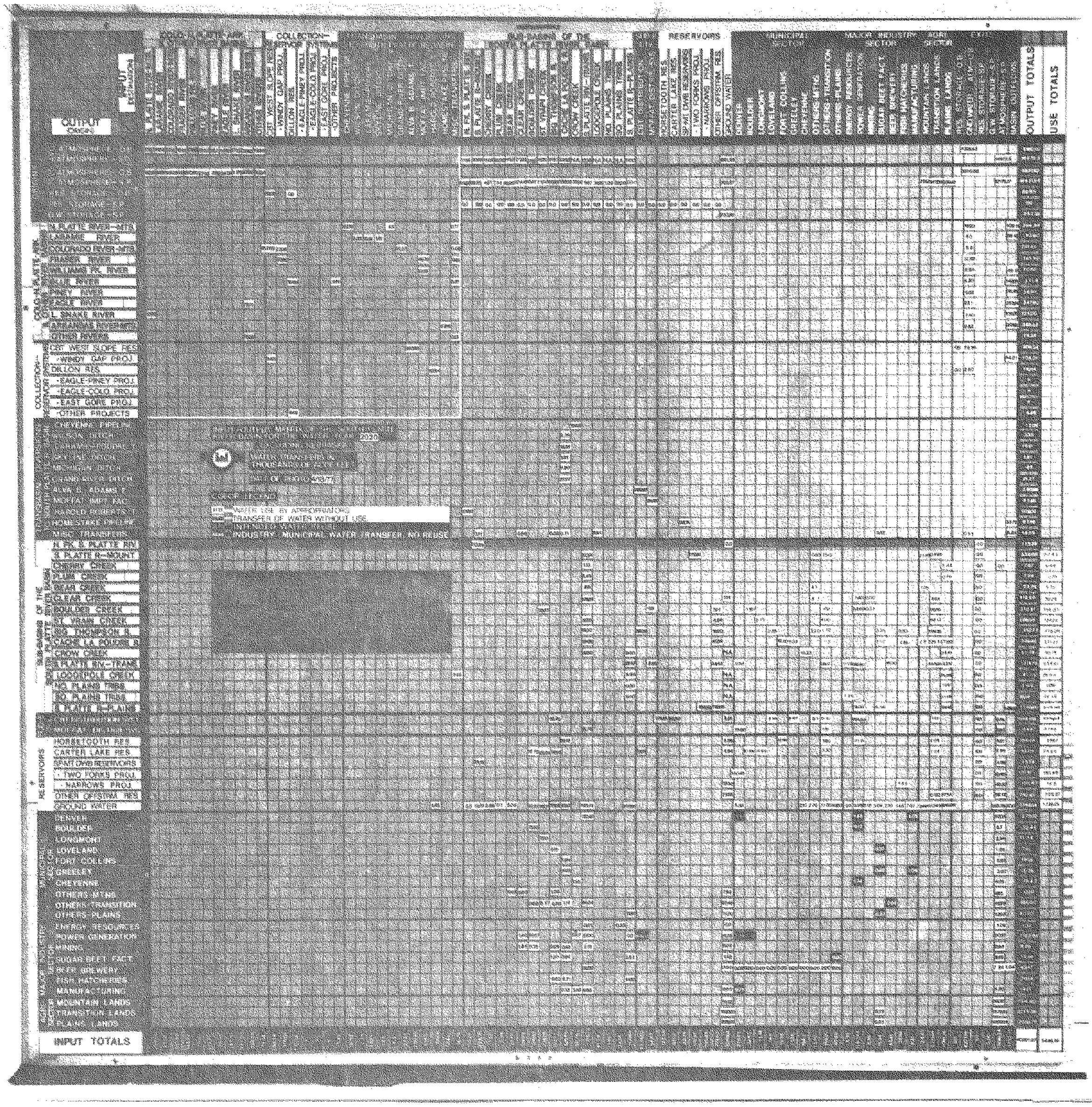


Figure 2-9. 2020 Input-Output Water Balance Model, South Platte River Basin. Scenario B: Drought Runoff; Medium Series Population

really the "scenarios"--albeit they are deterministic in nature vis a vis narrative. The "scenario assumption sets" selected for the respective models (or scenarios) are really assumptions about future ambient conditions and policies. While this is a limitation of the scenarios shown, it also illustrates the utility of the input-output model in exploring the efficacy of proposed projects and policies (i.e., relative to reducing per capita consumption, limiting further imports, building or not building certain projects, transferring water from agriculture, implementing planned water reuse, etc). The choices and their combinations in terms of a "scenario assumption sets" are infinite. Those chosen for this work were for both "average" and "stress" conditions for the future.

2.5.1. 1970 Input-Output Model. The 1970 water balance model for the South Platte basin is seen in Figure 2-3. The matrix was designed to delineate the relationships between the water supplies and uses within the basin. The sectors making up the rows and columns were chosen to show the flow of water transactions--both natural and manmade--from initial sources, through the water supply infrastructure, to the demand sectors, and finally to the atmosphere (as consumptive use) and basin outflow. The sector components were chosen to provide a meaningful amount of resolution and to fit the 82 x 80 spaces available for rows and columns respectively, on the magnetic board.

The construction of the 1970 matrix, as shown in Figure 2-3, required over two years of time and has involved two projects. The basic concept and methodology of the input-output water balance modeling was developed during 1974-75 under the present project sponsored by the Office of Water Research and Technology. The work is described by Hendricks and DeHaan (1975). The model developed was for the South Platte basin water supply-demand system. The second year has utilized the input-output model in the Corps of Engineers sponsored study. This latter study has developed the methodology of input-output modeling to a further extent (see Goldbach, 1977). In addition the Corp project, in Volumes 2-6 of the final report, compiled an extensive amount of data documentation for present and projected supplies and demands for water.

Documentation of data. The 1970 input-output model for the South Platte River Basin, as shown in Figure 2-3 involves some 400 items of data. Each required documentation. Many of the 160 "totals" rows and columns required such documentation also.

The documentation process was the most laborious phase of the input-output modeling. The division of labor for this task was by the major sectors (i.e., supply sectors, transfer sectors, use sectors, etc), identified within the 1970 matrix. Volumes 2-6 inclusive, of the Corps project, comprise the set of results for the documentation process. Each of these volumes is a self contained treatise on its respective subject. However, the primary purpose of each volume is to support the input-output model with needed data. In most cases the development of data necessitated the use of primary sources, including records from the files of plants, cities, and other entities. This was because published data were either not available or were aggregated in a form difficult to use for the input-output modeling.

The validity of the input-output model is no better than the data used and so it is advisable to have both an appreciation for the labor involved in developing good data and a respect for its importance. There are also numerous serendipitous benefits to developing and having good data. One of these is the familiarization with the systems involved in the input-output modeling. The modeling process is not a sterile seeking of abstract numerical data; continuous judgments and interpretations are a part of the process. From this it is possible to understand the systems involved in a very intuitive manner. In fact it would be possible to computerize some of the tasks of input-output modeling--such as mass balancing. However, it is felt that hand methods are more desirable in order to preserve a "feel" for the systems involved. Thus the *process* of developing an input-output model is as important as the result, as it develops the familiarity with the system.

Excerpts from 1970 South Platte Model. The 1970 input-output mdoel for the South Platte River Basin shows the basic structure of the existing system of water transfers. This structure is seen in both the selection of sectors and sector components and in the quantitative data within the matrix designating the specific water transfers.

The general structure of any water transfer system consists of hydrologic systems, water distribution systems, and various use systems. These are depicted for the 1970 South Platte basin model in Figure 2-3. The structure shown is the *context*, within which adjustments (i.e., new projects, cloud seeding, water rights transfers, water conservation, etc), will be made to meet future demands by the various use sectors and to handle any contingencies in supplies. The 1970 model provides a way to study the overall basin-wide system in order to ascertain the tradeoffs involved in responding to these future conditions. This requires an understanding of the 1970 model in terms of its internal details. Excerpts of this detail are given in the following paragraphs. They illustrate the type of information which can be extracted from the model. Also some of the information extracted is useful in itself in characterizing the water resource development state of the basin.

The 1970 model is best understood by tracing the flows of water through the various systems. The description of the 1970 model which follows is indicative of the types of information which can be extracted from the matrix.

Origins. The initial source of all water in the basin is precipitation from the atmosphere. This is seen in Figure 2-3 in two labels: "Atmosphere-Other Basins," and "Atmosphere-South Platte." The former includes 1970 annual precipitation falling on the Upper Colorado River Basin above selected gaging stations, the North Platte River Basin in Colorado, and the Laramie River Basin in Colorado. Precipitation for the long-term average is shown in the line above for comparison purposes. Figure 2-3 shows that the 1970 precipitation falling of the South Platte basin was 17,104,400 acre-feet. The evaporation back to the atmosphere amounted to 13,417,580 acre-feet. The balance is distributed to agriculture, groundwater recharge, and streamflow; the total water available to the hydrologic systems of the South Platte is the sum of these three categories; it amounts to 3,687,040 acre-feet. The native stream flows in the South Platte was 1,902,700 acre-feet. Reservoir storage and groundwater storage can be either sources of water (i.e., carry over storage from 1969), or destinations in the event storage is carried over to 1971. The native flow of the Colorado River basin, above those gaging stations nearest the points of diversion, was 1,901,800 acre-feet. All of these data are traceable in the matrix.

Transfers. The transfers of water from the other basins to the reservoirs and diversion structures are seen in the upper left corner of the matrix bounded by a white line. The surface water transfers to the South Platte basin from other basins amounted to 303,410 acre-feet. Thes west slope diversions from the Colorado River system totaled 272,390 acre-feet, or 14 percent of the native flows of the Colorado River, gaged at the high elevation stations for 1970. The diversions into the South Platte basin are seen by the sector given the label "Transbasin Diversions to South Platte R. Basin," which has red color in Figure 2-3. Some of the transfers are made to streams and others are made to the Colorado Big Thompson and Moffat distribution systems. The distribution of water from the streams is seen across the rows from the sector "Sub-basins of the South Platte River."

Use Factors. The intake of water by the various use sectors is seen in the columns, under the respective sectors. The total uses by each of the use sector components are given in the bottom row, called "Input Totals." The total uses amounted to 383,140 acre-feet by the municipal sector (including that given to industry); 106,580 by the industrial sector (self supplied); 92,830 power generation in thermal cooling; 995,790 acre-feet by hydro power generation (this high figure is due to the fact that several hydro power plants are associated with the Colorado-Big Thompson system); 4,952,150 by the agricultural sector, of which 3,397,640 acre-feet was delivered by irrigation (the balance was "effective precipitation"). The beneficial water use in the basin is color coded by the black on white squares; the total beneficial water use in the basin amounted to 5,570,670 acre-feet. The "reuse factor" for the basin was 2.5 [5,570,670/(1,902,700 + 303,410)]; in other words, the water reaching the basin was very well used--especially by agriculture. This is possible because the water not used consumptively is returned to the South Platte River or to recharge the groundwater aquifer, built up adjacent to the river over the last 100 years by irrigation. Groundwater was the source of 1,589,830 acre-feet of water. However, most of this came from the aquifers recharged from irrigation; they are really a part of the stream systems since much of the water, if not pumped, would return to the South Platte River.

Consumptive use by the various use sectors is of interest also. Consumptive use for the municipal sector was 105,140 acre-feet, or 27 percent of the water taken in. Consumptive use by agriculture was 2,606,220 acre-feet, or 53 percent of total water applied, which includes precipitation falling during the irrigation season.

Other Observations. The role of the streams in the South Platte basin is seen by examining the row and column vectors for any given stream. The Cache La Poudre River, for example, had a native flow of 321,220 acre-feet. However, the stream carried 712,000 acre-feet aggregated total. Of this imported water flow was 32,250 acre-feet. Deliveries from upstream reservoir storage were 960 acre-feet and Horsetooth Reservoir delivered 64,870 acre-feet. Return flows were 293,400 acre-feet, of which 259.420 acre-feet came from agriculture via "groundwater" in the matrix. Similarly the Cache La Poudre River distributed 501,500 acre-feet for beneficial use. The overall reuse factor for the sub-basin was 1.2 [501,500/(321,200 + 970 + 32,250 + 64,870)]. However, the stream also delivered 129,000 acre-feet of water to the South Platte River. The lower reuse factor reflects the fact that most of the agricultural lands in this sub-basin receive water from ditches diverting virgin water. The water delivered to the South Platte from this stream then is essentially all reused water.

The basin outflow from the South Platte River was 816,000 acre-feet, while the South Platte River Compact requires only 48,700 acre-feet. Thus, a considerable amount of water could be captured for use in Colorado if sufficient storage was available.

Further Notes on Using the 1970 Model. Further attention should be given to two procedural facets of the input-output modeling process which are demonstrated in the 1970 model. These are: 1) aggregation; and 2) mass balancing.

Aggregation. As noted previously, the input-output model would become too unwieldy without a considerable amount of aggregation of data. The system first must be disaggregated in enough detail at the data gathering state to discern the idividual elements which are to comprise an aggregation unit. These elements are recombined in the aggregation process. The final aggregation may obscure a great wealth of detail. If such detail is desired for the South Platte basin the Corps of Engineers report set volumes can be consulted. These volumes document in considerable resolution the data contained in the 1970 and the 1980, 2000, and 2020 models. A more disaggregated input-output display can be constructed from these data if desired. This can be done for any subsystem of interest such as an irrigation district, a municipality, a sub-basin, or a smaller unit such as a collection system. The idea is illustrated using the Homestake Pipeline as an example. Figure 2-10 is an excerpt from the 1970 input-output model, as seen in Figure 2-3, for the Homestake Pipeline system. Figure 2-11 is a schematic of the Homestake Pipeline Project in an expanded version. This more detailed diagram was developed in order to construct the input-output model of Figure 2-3, and the Figure 2-10 excerpt, which have less detail. The essential point is that one can see the amount of detail required in Figure 2-11 in order to construct a more aggregated depiction of the same system, as seen in Figure 2-10.

Mass Balancing. The mass balancing of the flows of water to and from each system and subsystem contained within the South Platte input-output models was rigorously adhered to in the construction of all of the seven models (i.e., 1970, 1980, 2000, 2020). In other words, for any system or sub-system:

$$\Sigma \text{ inputs} = \Sigma \text{ outputs}.$$

This principle is illustrated at three levels for the 1970 model: (1) the "South Platte basin-Other basins" combined systems: (2) the South Platte basin as a whole, (3) any sector component (except inputs and exits). Figure 2-12 shows the mass balancing for these three levels, using the City of Fort Collins as the example for the "sector component" level. The diagrams shown were constructed from data contained in the 1970 input-output model, Figure 2-3. In each case, the sum of the inputs equals the sum of the outputs.

	ARKANSAS RIVER--MTS		HOMESTAKE PIPELINE		S.P. MTS DWB RESERVOIRS		GROUNDWATER/ATM-OB		BASIN OUTFLOWS		OUTPUT TOTALS
EAGLE RIVER	30.38										
ARKANSAS RIVER-MTS			22.82				9.59		453.3		
HOMESTAKE PIPELINE					3.37				19.45		22.82
INPUT TOTALS			22.82								

Figure 2-10. Homestake Pipeline Excerpt from 1970 South Platte Input-Output Model

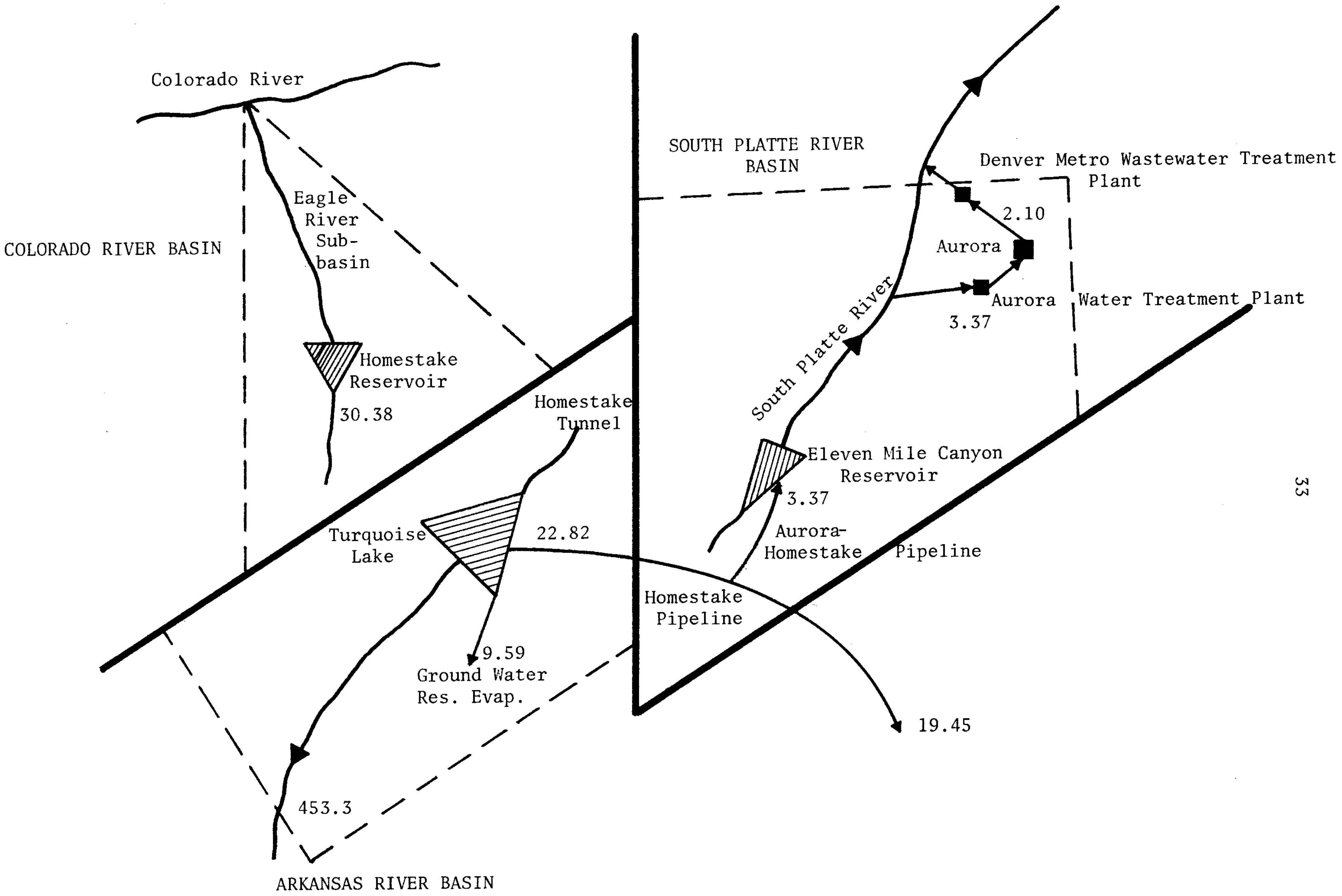
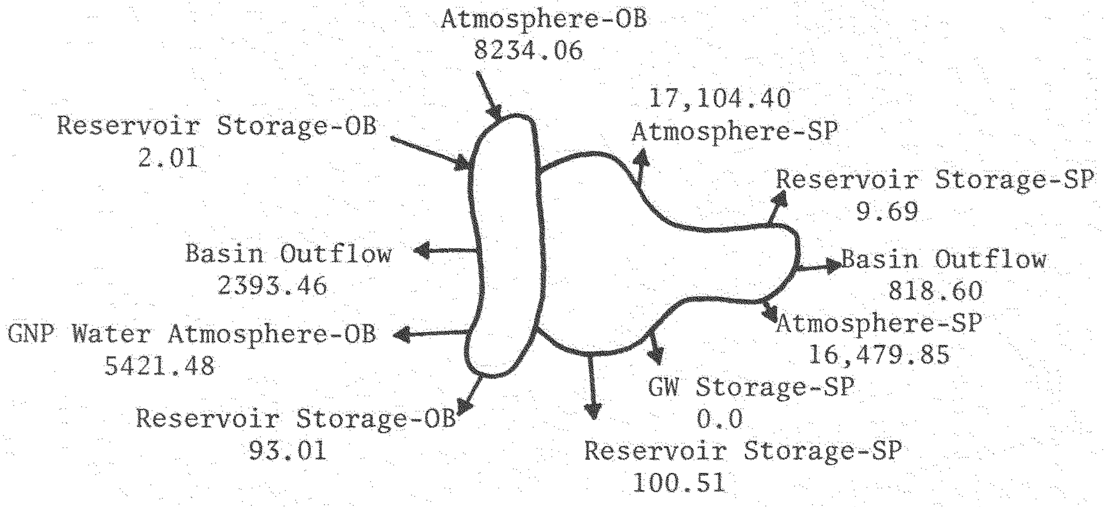
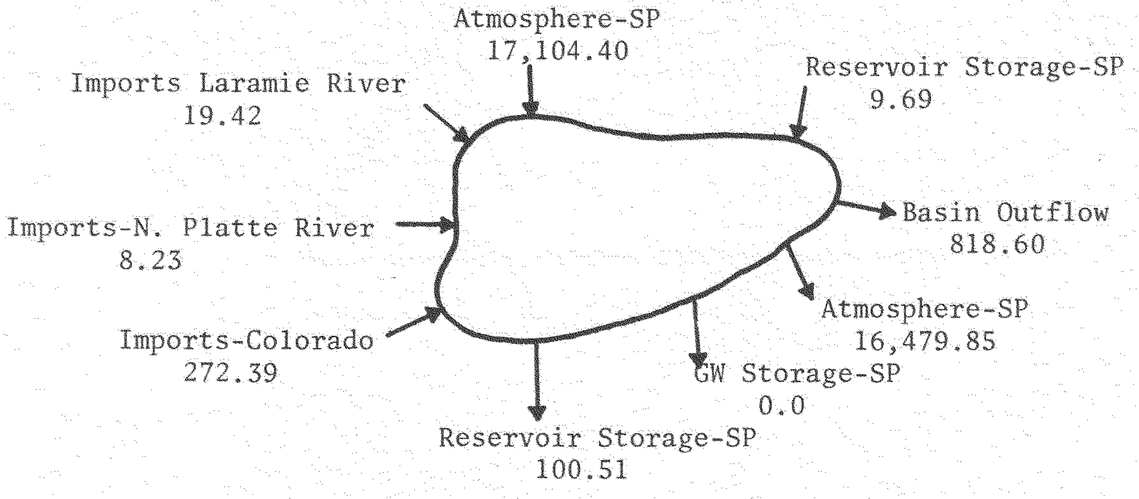


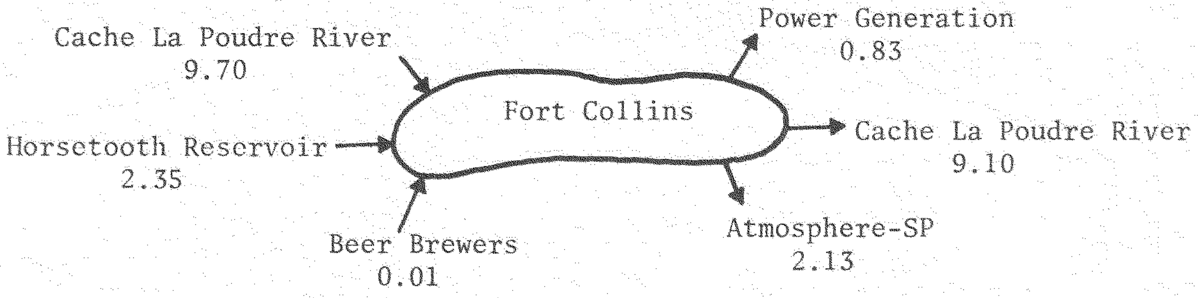
Figure 2-11. Homestake Project Schematic Diagram.



(a) South Platte Basin Combined with Colorado, North Platte and Laramie Basins.



(b) South Platte Basin



(c) City of Fort Collins

Figure 2-12. Illustration of Application of Mass Balance Concept for Three Levels of Resolution (Data from 1970 Input-Output Model, Figure 2-3)

Planning With the 1970 Model. The 1970 model shows, or can be modified to show, any of the possible "fits" between supply and demand, which may be proposed as planning alternatives. For example, several proposed diversion and storage projects are shown in the 1970 matrix, Figure 2-3. These are indicated by an asterisk and indentation of the respective labels. The matrix can show the sources of water for these projects, the proportion of annual flow from the streams utilized as sources of supply for the project, and the proportion of demand which the project will satisfy in the sector component utilizing the project's water. In addition, the disposition of the return flows can be traced as they are utilized by other sector components. The project's functioning can be ascertained for drought years by determining its yield when flows are lower, and when higher priority water rights need to be taken care of first.

On the demand side, the future annual water demands of any sector component can be imposed on the bottom row in the appropriate sector component column. One can then explore how this demand may be satisfied from various possible sources of water. These include such diverse sources as direct water reuse of wastewaters, indirect reuse through exchanges, purchase of agricultural water rights, or the development of a new project.

From the point of view of state level planning, the matrix can show what policies ought to be imposed to better match supplies and demands of a whole basin of a whole state. Such policies might have several objectives, such as: (1) maintenance of sufficient water supplies to meet agricultural water demands while at the same time meeting the rising urban demands; (2) reducing basin outflow toward the minimum outflow required by the South Platte River Compact; (3) assessing the effects of water exports on the basin of origin; (4) determining what kinds of trades could be made to maintain minimum streamflows; (5) assessing the basin-wide potential of water reuse. The key point is that the 1970 model provides a means to explore and evaluate these possibilities. Some of these questions are explored in the 1980-2020 scenarios.

2.5.2. Assumptions: 1980, 2000, 2020. The 1970 input-output model of the South Platte basin depicts the system structure for innumerable transfers of water. These transfers give the "fits" between the sources of supply and demand sectors shown (i.e., in Figure 2-3). The structure, implicit in the matrix is formed by the water rights priorities and the commensurate physical facilities for water storage, conveyance, and distribution.

Future water demands will occur and be met within the basic structure shown in the 1970 matrix. The future demands will be largely by the same sectors (i.e., municipal, industrial, agricultural) and sector components (i.e., Denver, Loveland; sugar beet factories, etc) shown. A new sector which could emerge is "environmental preservation and recreation"; this sector would related to minimum stream flows primarily. Water rights for maintenance of minimum in-stream flows are currently being procured by the Colorado Water Conservation Board. This sector was not considered in the water demand projections, i.e., for municipal, industrial, and agricultural water demands.

Scenario Assumption Sets. The magnitudes of demand by each of the water use sectors are actually dependent upon a wide variety of factors, many of which are mutually interactive. Figure 2-13 identifies some of these factors. It also attempts to illustrate the idea that many are mutually interdependent; their interactions are much more extensive and complex than indicated, however. A particular combination of these and other factors would comprise a "scenario assumption set."

It is most important to understand, when projecting supplies and demands for the whole basin, all of the factors indicated in Figure 2-13 will interact. Also they can interact at any level of supply and demand (i.e., low, medium, high). Thus the number of combinations of factors, or "sets", is very high.

A selection of a particular set of factors is designated here a "scenario assumption set." Two scenario assumption sets were chosen for each of the years 1980, 2000, 2020. Table 2-2 is a summary of the scenarios assumption sets used for the 1980, 2000, and 2020 projections. The table shows many of the major factors which influence water supply and water demands. It is a more tractable form of the relationships shown in Figure 2-13.

Table 2-3 is a recompilation of some of the essential features of Table 2-2, in a more succinct format. The far right column attempts to capture the key idea of each scenario assumption set. Both normal, or "expected," and stress types of scenario assumption sets were constructed. The two means of imposing stress are high population and drought; the two are not used concurrently, however. It should be noted also that the A and B scenario assumption sets for 2000 and 2020 permit additional projects as needed; also transfers from agriculture

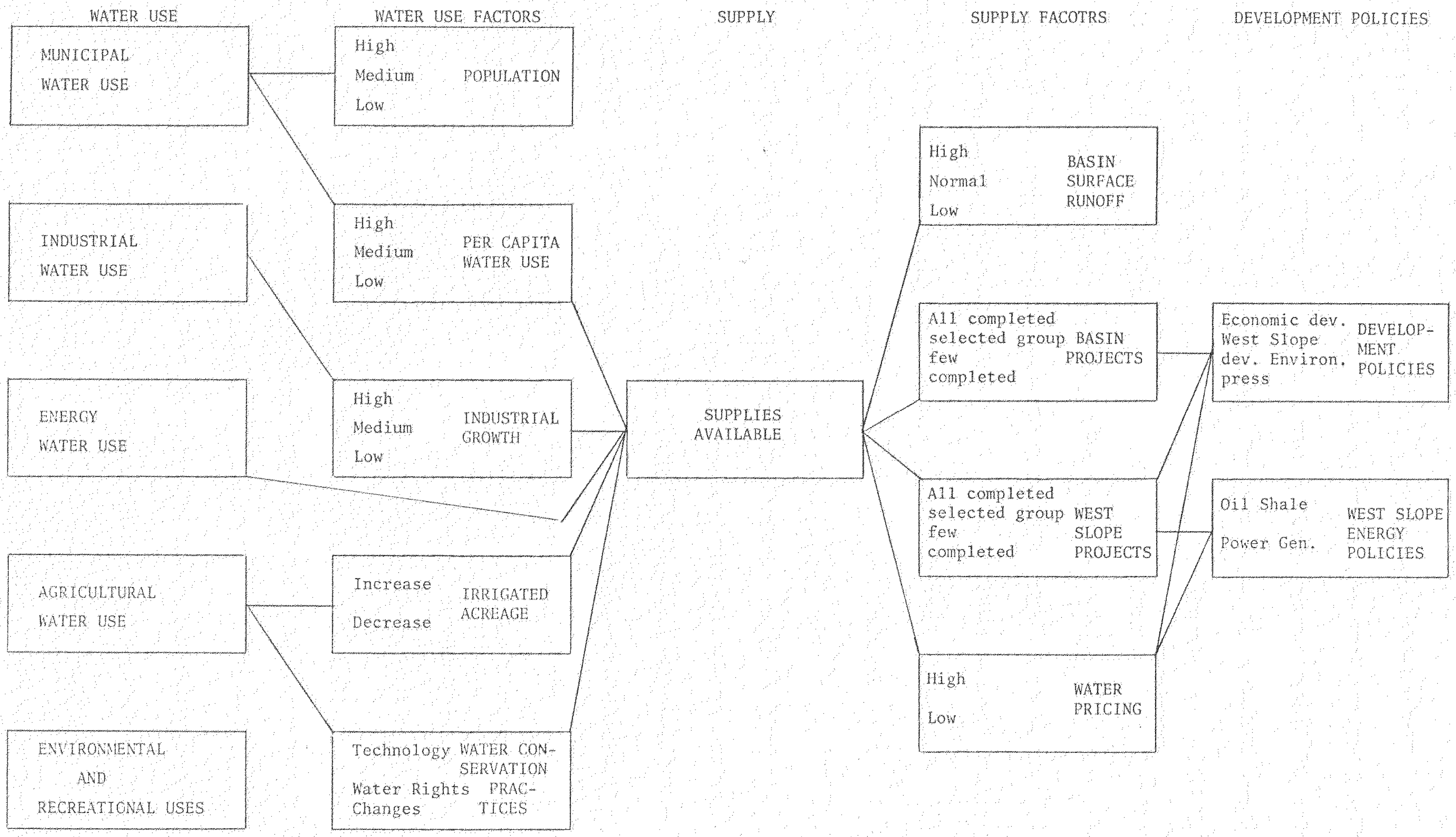


Figure 2-13. Factors Related to the Supply and Demand of Water in South Platte Basin and Choices for a Scenario Factor Set.

Table 2-2. Scenario Factor Sets: 1980, 2000, 2020.

SECTOR	DEMAND FACTOR	1980		2000		2020	
		A	B	A	B	A	B
Popu-la tion	Low Series						
	Medium Series	X	X	X	X		X
	High Series				X	X	
Per Capita Use (gpcd)	220				X	X	
	214	X					
	191			X			
	167						X
	150		X				
Indus-trial Sec-tor	1975 Activity Level (less 3 sugar factories)	X	X	X	X	X	X
Energy Sector	Pawnee No. 1	X	X	X	X	X	X
	Fort St. Vrain No. 1	X		X	X	X	X
	Rawhide			X	X	X	X
	Pawnee No. 2				X	X	
	Fort St. Vrain No. 2				X	X	
	Two Coal Strip Mines				X	X	X
	One Underground Mine				X	X	
	One Coal Gas Plant				X	X	X
	Fort St. Vrain No. 3						
	One Add. Nuclear						X
	Four Add. Coal Fired Plants						
Agriculture	Medium Lvl. Urban Encroachment	X		X	X	X	X
	Medium System Efficiency	X		X	X	X	X
	Average Precipitation	X		X	X	X	
	Average Sub-Basin Transfers	X	X	X	X	X	X
	Drought Level Precipitation		X				X
	Transfers from Sector Permissible, as necessary		X	X	X	X	X

SECTOR	SUPPLY FACTOR	1980		2000		2020	
		A	B	A	B	A	B
Exogenous Projects	Long Draw Expansion	X	X	X	X	X	X
	Aurora takes its 50% of Homestake water		X	X	X	X	X
	Windy Gap			X	X	X	X
	Joe Wright			X	X	X	X
	Homestake Expansion			X	X	X	X
	Williams Fork Expansion			X	X	X	X
	Straight Creek					X	X
	East Gore					X	X
	Eagle-Piney					X	X
	Eagle-Colorado					X	X
Endogen-ous Projects	Two Forks			X	X	X	X
	Narrows			X	X	X	X
	Denver Reuse						X
	Other Minor Projects			X	X	X	X
	Other Cities Reuse Exchanges						
Native flows	Average Precip. and Runoff	X		X	X	X	
	Drought (1953-57 4-Year Average)		X				X

Table 2-3. Summary of "Scenario Factor Sets" for 1980, 2000, 2020.

Scenario		Scenario Factor Choices						
Year	Scenario Set	Population Projection	Per Capita Use (gpcd)	Energy Projects	S. Platte Water Projects	Colorado R. Water Projects	Native Flows	Scenario Features
1980	A	M	214	2	0	1	Average	Normal projections
	B	M	150	2	0	2	Drought	Stress, i.e., drought
2000	A	M	191	3	3	6	Average	Normal projections
	B	H	220	8	3	6	Average	Stress, i.e., high population
2020	A	H	220	8	3	6-10	Average	Stress, i.e., high population
	B	M	167	7	3	6-10	Drought	Stress, i.e., drought

M = Medium series population projection.

(i.e., purchases of water rights) are permitted as necessary. The latter was a second priority method of meeting municipal and industrial demands in the input-output modeling, after presently conceived water projects were utilized.

Scenarios. The *scenario* is the outcome caused by imposing certain assumptions about the future for a particular system of interest. Usually, a scenario is thought of as a narrative future history. The term is used here with this connotation, but the "future" is given in terms of the input-output model. A particular "scenario assumption set" is imposed on the input-output model and the internal adjustments which must be made, as depicted on the model, is the "scenario." In a mathematical sense, the assumptions are the "boundary condition" for the model. In other words, the scenario is the resulting configuration of water transfers for the basin as a whole, depicted by the input-output model. While the input-output model outcome is both necessary and sufficient as the scenario, the model output may be supplemented by a narrative interpretation of the numerical configuration--if desired (as noted, the narrative is the more usual idea of a scenario).

A most critical point is that there is no *prediction* of the future. Rather, the scenario is a device to *explore* how the system may respond to possible future conditions. In other words, the key question is not: what is the future? but, does the system have the capacity to handle stress conditions? or normal conditions? etc. Whether the system response is satisfactory or not is a matter of *evaluation.* This takes place against expectations, i.e., whether objectives are met, the prevailing norms of society, etc. If these norms are not codified then they must be established by the political process. The basic goal of the input-output modeling of the South Platte is to permit a planning exploration to ascertain whether, and in what manner, the South Platte can adjust to possible future conditions relative to demand and supply. In other words: Are presently conceived projects adequate? If they are blocked, can the system still adjust? or, Are they necessary in the first place?--etc., etc.

2.5.3. Interpretation of Scenario Results: 1980, 2000, 2020. The outcomes of the scenario assumption sets--the scenarios--for 1980, 2000, and 2020 are seen in Figure 2-3 to 2-9 inclusive. These matrices contain the information relative to the flow of water throughout all segments shown of the important subsystems of the South Platte River basins. Thus they can be queried to provide whatever amount and type of information is desired about water balances.

While the matrices can be studied in order to glean a desired understanding of how the system may respond to the particular "scenario assumption set" imposed, some of the essential questions may be abstracted from the matrices in the form of selected "index questions." Table 2-4 shows a set of numerical indices about the South Platte system which were abstracted from the seven input-output models developed, i.e., in Figure 2-3 to 2-9. The indices of information seen in Table 2-4 were selected to provide a way to discern some of the essential differences in the 1980, 2000, and 2020 scenarios. The indices are identified in the rows of the table. Their numerical comparisons for different scenarios are seen under the respective columns. The indices are grouped into two general categories: supply and demand. The "scenario assumption set", i.e., whether A or B, is shown also.

Table 2-4. Summary of Selected Water Information from Input-Output Model Scenarios, 1970-2020.

YEAR	1970	1980	1980	2000	2000	2020	2020
SCENARIO ASSUMPTIONS		A	B	A	B	A	B
Native Runoff	1,826,510	1,354,000 (Avg)	672,060 (Drought)	1,350,650 (Avg)	1,350,650 (Avg)	1,350,650 (Avg)	672,060 (Drought)
Population	1,531,600	1,887,200 (Med. Series)	1,887,200 (Med.Series)	2,617,100 (Med. Series)	3,112,000 (High Series)	3,980,300 (High Series)	3,118,180 (Med.Series)
Per Capita Use	220	214	150	191	220	220	167
Energy Development		Self-Suff.	Med. Series	Med. Series	High	High Series	Med.Series
Industry		No Change	Stable	Stable	Stable	Stable	Stable
Irrigated Acreage		Free Market	Elastic	Stable	Stable	Stable	Elastic
IMPORT SOURCES							
N. Platte	-0-	1,360	1,350	4,610	4,610	4,610	4,610
Laramie	19,420	19,670	19,670	19,670	19,670	19,670	19,670
Colorado R.	327,320	285,310	248,330	302,310	302,310	302,310	302,310
Fraser R.	42,160	54,930	47,220	145,590	146,490	102,540	130,760
Williams Fork	2,110	5,550	5,510	6,650	9,260	25,080	12,160
Blue	31,410	42,460	68,080	101,250	146,490	193,950	121,440
Piney	-0-	-0-	-0-	-0-	-0-	-0-	-0-
Eagle	3,370	13,220	13,220	33,740	33,730	33,740	13,220
L. Snake	8,230	7,130	7,130	12,220	22,920	27,480	12,080
Arkansas	-0-	-0-	-0-	-0-	-0-	-0-	-0-
Other Rivers	470	120	120	-0-	-0-	120	120
Total Exports	434,490	429,750	410,630	626,040	685,480	709,520	609,720
PROJECT WATER							
CBT (brought over)	204,640	226,960	226,980	280,960	280,980	280,980	280,980
Moffat (brought over)	43,960	59,870	52,120	73,880	102,880	127,000	61,480
Roberts (brought over)	10,620	30,160	59,670	92,840	167,540	176,500	107,540
Windy Gap	-0-	-0-	-0-	54,000	54,000	54,000	54,000
Eagle Piney	-0-	-0-	-0-	-0-	-0-	-0-	-0-
Eagle Colorado	-0-	-0-	-0-	-0-	-0-	-0-	-0-
East Gore	-0-	-0-	-0-	-0-	-0-	-0-	-0-
Other Projects	30	-0-	-0-	-0-	-0-	9.0	5,490
NATIVE RUNOFF IMPORTS	2,261,000	1,783,750	1,082,690	1,976,690	2,036,130	2,060,170	1,281,760
SECTOR WATER USES							
Agriculture	3,997,840	3,781,690	3,651,350	3,781,690	3,781,690	3,781,690	3,636,800
Industry except thermal cooling	112,200	92,760	85,020	106,470	113,600	113,600	108,100
Thermal Cooling	93,990	141,050	141,050	151,050	207,650	221,630	168,250
Municipal (water rights only)	383,270	458,210	316,980	559,490	766,510	983,020	593,010
Total Basin Demand	4,587,300	4,473,640	4,194,400	4,598,700	4,879,450	5,099,940	4,506,160
REUSE FACTOR FOR BASIN (does not include groundwater or precipitation	2.03	2.51	3,87	2.33	2.40	2.48	3.52
SOURCES OF WATER							
Stream Diversions	2,779,440	2,707,800	2,303,400	2,786,810	2,360,110	2,621,040	2,295,970
Imports	434,490	429,750	410,630	626,040	685,480	709,520	528,770
Transfers from Agriculture	-0-					-0-	
Water Conservation	-0-	-0-				-0-	
Direct Reuse	-0-	-0-	-0-	-0-	-0-	78,370	72,570
Groundwater	1,589,830	1,531,260	1,688,840	1,550,100	1,587,900	1,627,900	1,726,750
BASIN OUTFLOW	816,600	484,480	177,970	550,820	524,440	492,280	127,490
SECTOR CONSUMPTIVE USES							
Agriculture	2,606,220	2,582,310	2,284,490	2,582,310	2,582,310	2,582,310	2,408,180
Industry	17,360	20,250	20,250	20,800	21,300	21,300	21,300
From Reservoirs 1970	9,540	25,870	25,870	37,580	98,620	102,500	50,520
Consumptive Uses	105,140	132,960	90,590	88,320	225,460	289,710	170,390
Total	2,738,260	2,761,390	2,421,200	2,729,010	2,927,590	2,995,820	2,650,390

The first major index in Table 2-4 is IMPORTS. Imports from other basins have been and will continue to be an important source of water for the South Platte basin. At the 434,490 acre-feet level in 1970 this is not likely to increase in 1980 due to the time required to develop a new project. In the 2000A and 2000B and the 2020A and 2020B scenarios, imports are shown increased by some 200,000 acre-feet, to the 600,000 acre-feet level (709,000 acre-feet for 2020A). Planned projects and the perfection of existing water rights were the physical and legal means of increasing the levels of imported water. This was one of the rules assumed in the scenario development: Colorado River water would be developed only as needed, as provided for by planned projects and by perfection of existing water rights, or purchase of the necessary senior rights. How the water is obtained is seen in terms of both surface water sources (i.e., streams) and selected proposed projects for development of some of these sources. The trends in Table 2-4 show that the Blue River is relied upon most heavily for future development. For example the 2020A scenario would utilize 193,950 acre-feet from this source; this compares with 31,410 acre-feet presently taken from the Blue River. This increased diversion level is enabled by perfection of present conditional water rights, which are subject to the limitations of the Blue River Decree. The present Harold D. Roberts tunnel would transport the water from storage in Dillon Reservoir to the North Fork of the South Platte River. Two Forks Reservoir would be required also to provide adequate storage. Because the time resolution of the input-output model is the year, the role of storage is not evident. Other major sources of additional water for import include the Colorado River, the Fraser River, the Eagle River and the Little Snake.

Of particular interest is: what portion of the annual streamflow (as measured at the nearest gaging station) will be diverted from a given stream? Two streamflows were used in the modeling: long-term average annual, computed from the available records; and a "drought period" as determined by the 1953 to 1956 four year period. The 1980B and 2020B scenarios used drought streamflows, while the 1980A, 2000A, and 2000B and 2000A used average streamflows; 1970 used actual streamflows. These virgin streamflows, average and drought, are shown in Figures 2-3 to 2-9. Comparing them with the average annual diversions for each scenario shows that presently and in the future about 80 percent of the flow of the Upper Colorado River, i.e., near Granby, is diverted. Also under the 2020 scenarios about 64 percent of the average annual flow of the Fraser River and 60 percent of the Blue River would be diverted. Diversions from the other streams would be much less.

The second question is: what projects can be used to develop the necessary water? Although several combinations are possible the scenario rule was: use existing projects and facilities and imminent projects to the extent possible. Under this rule, the Windy Gap project was assumed to go on line by 2000 since it already has a considerable momentum. Also, it was assumed that the Joe Wright storage project of Fort Collins would be on line, that the City of Aurora would utilize its full entitlement of the Homestake Project, that the Narrows project would be completed, and that Denver would first perfect its conditional decrees on the Blue and Fraser Rivers. With these assumptions, it is seen in Table 2-4 that many of the proposed projects are not utilized in the scenarios developed, i.e., 2020A and 2020B in particular. This is significant, because the 2020A assumes average streamflow and the high series population along with the high per capita municipal use, while the 2020B scenario assumes drought level streamflows and the medium series population. These are both "stress" conditions for the basin. The first is with respect to demand and the second is with respect to supply--albeit they are not the most stressful scenario assumptions which could have been used.

The role of groundwater in the scenario is seen in Table 2-4 also. The use of groundwater in 1970 was about 1,589,830 acre-feet; most is used by the agricultural sector. In the drought year scenarios, i.e., 1980B and 2020B, this is increased to about 1,700,000 acre-feet. At the same time the municipalities will utilize their purchased surface water rights, calling back the water leased to agriculture. Thus the groundwater under these scenarios would act as a drought year buffer. For this scenario to be workable a certain portion of the groundwater aquifers would have to be held in reserve to be utilized as "buffer" during drought years. If development of groundwater proceeded to an even higher limit than presently such management flexibility to handle drought conditions may be lost. Also groundwater models would be required to ascertain whether this was feasible (i.e., whether the riparian aquifer of the plains South Platte River could indeed be managed in such a manner).

The uses of water by each use sector is seen in the lower portion of Table 2-4. Agricultural water use falls off from the 3,997,840 acre-feet used in 1970 to 3,600,000 to 3,800,000 for the various scenarios. The lower range is in response to the drought scenarios; the free market transfers of water were assumed, to permit the municipal sector to meet its demands by taking agricultural water in times of stress. This is possible now for several Front Range cities, i.e., it is common practice presently for municipalities to have "water in the bank" with agriculture, which they draw upon when needed; they purchase agricultural water rights, lease the water back to agriculture, and use it as required to meet the demands of growth or drought. Industrial water use is assumed to remain rather constant for all scenarios. However, the demand for thermal cooling nearly doubles from the 1970 levels. Municipal water goes up from near 383,270 acre-feet in 1970 to 983,000 acre-feet for a per capita demand of 220 gpcd. Using this same per capita demand for the 2020A scenario (instead of 220) results in a municipal demand of 670,000 acre-feet, a saving of some 300,000 acre-feet. Along with groundwater and the "water in the bank" with agriculture, this is another method to maintain a resiliency for contending with contingencies (i.e., droughts). From this point of view, it may not be wise to impose a low per capita use (i.e., by metering) except during time of drought (the savings in water treatment costs is, of course, another consideration relative to this question). Total basin water uses vary with scenario assumptions. It ranges from 4,194,400 acre-feet in the 1980B scenario to 5,099,940 acre-feet for the 2020A scenario. The 1970 basin use was 4,587,300 acre-feet. This range is not large relative to the total water use, although squeezing even a little bit more water use out of the system, when the system is near the limit of development, if difficult.

The consumptive use by the various use sectors, seen also in Table 2-4 ranges from 2,421,200 acre-feet to 2,995,820 acre-feet, with agricultural consumptive use accounting for over 80 percent of this amount.

This exceeds the native flow plus imports to the basin; the difference is made up by precipitation and groundwater; which is seen in the input-output matrices. This large quantity of consumptive use is essentially unavoidable although it could be reduced by selective capital investments to reduce exposures of water to the atmosphere (i.e., phreatophyte growths, seeps along canals, excess application of irrigation water, etc.). It does say quite a bit about the intensity of water use and reuse within the basin.

Another index of water use within the basin is "basin outflow." This varies from a low of 137,490 acre-feet for the 2020B drought scenario to 816,600 of actual outflow in 1970. Since only 47,116 acre-feet of flow across the Colorado-Nebraska border is required, the difference could be captured for use in Colorado (this is true in a legal sense). The Narrows Project will capture some of this (i.e., about 122,000 acre-feet net). Regardless of what is captured of this outflow, the amount is low relative to the native flows and imported water.

Another index of the basin water activity is a "reuse index." It is defined as the ratio of total water uses (i.e., as permitted by water uses) (i.e., as permitted by water rights) to the sum of the native water plus imports; groundwater use and precipitation are excluded from this definition. The ratio varies from 2.03 to 3.87 for the different scenarios. Again the drought scenarios result in the highest reuse factors. All of this reuse is of a fortuitous nature. Direct reuse in the 2020A scenario is 78,370 acre-feet; a similar amount is used in the 2020B scenario. A direct reuse project is planned by the Denver Water Department which would come on line after 2000 and deliver much more than indicated in the scenarios; the present vision of the size is 100 mgd.

2.5.4. Conclusions from the Scenarios. The physical infrastructure to produce and deliver water in the South Platte basin and then return it for further use has developed over the period since 1858 when the first water right was established on Clear Creek. Today it represents an aggregate capital investment of many millions of dollars. Involved are dams and reservoirs for storage, tunnels for transbasin water transfers, miles of pipelines and canals, and distribution facilities as required by farm, city and industry, and finally wastewater treatment facilities. The management or institutional infrastructure too has evolved over the same period and in fact guided the physical infrastructure. The cornerstone of the institutional infrastructure is, of course, the appropriation doctrine. But the management operations are handled by a multitude of state and federal agencies, cities, irrigation districts, and other forms of organization.

While both the management entities and the physical systems have been developed as autonomous units to serve specific use entities (i.e., cities, industries, agricultural areas) there is extensive interlinkage in both management arrangements and physical interdependencies. For example, purchase of agricultural water rights and lease back to agriculture until needed is a common management arrangement. So too is the "point of diversion" stipulation of Colorado water law. The physical interdependencies may involve sharing storage or conveyance facilities, or the hydrologic interdependence between wastewater production by a city and its downstream use by agriculture.

These many physical interdependencies and institutional arrangements constitute, collectively, a *system*. The input-output matrix is a model of this system--albeit it lacks the detail described above. However, individually each of the linkages of each arrangement, is a *fit*. And so the system is a collection of *fits*. The complex system which has evolved is a collection of these fits. The framework for their evolvement has been the appropriation doctrine which, combined with a laissez-faire entrepreneurial ethic, encourages the development and use of new water.

The key point is that the present system has evolved "spontaneously," satisfying the multitude of individual fits between available water supplies and the economic and survival needs of the basin. Any deliberate comprehensive basin-wide planning would have difficulty in achieving such well serving fits. One might assert that these particular fits represent the highest level of "happiness" in the use of basin water resources.

However, there are continuing inexorable stresses on the basin's water resources. No longer is it relatively easy to build a new project, to divert water from another basin, or to fulfill the entrepreneurial spirit and find "new" water. There is some hydrologic upper limit to this activity. The development state of the South Platte River Basin is near that limit. Earlier, this was called the *apex stage* of development. In addition, for Colorado, there are legal limits concerning what may be done in terms of interstate compacts, also there is developing a clouded legal interpretation of some of these documents (e.g., with respect to federal reserve water rights, Indian water rights). However, for particular parties within the basin the priority of one's appropriation is still the legal limit prescribing what one might do.

But, in addition, there are new sensitivities about the environment and commensurate demands about how public sector resources should be used. Such concerns reflect a broader range of values than in former years. No longer are economic development and regional development the only accounts to be satisfied. Social well being and environmental preservation are the new accounts required by law. They must be incorporated in the planning process for federal water resources projects and by the political process for other projects. In any water short region all of these accounts are profoundly affected by how water is allocated. This is true also in the South Platte River Basin.

The basin has developed thus far maximizing the economic and regional development accounts. It may be postulated that any unrestrained tampering with the present context of water use systems may have profound effects on these two accounts and, by corollary, on the social well being account. Thus there are certain social equilibria built up over the years which are dependent upon present patterns of water use.

However, there are now evolving demographic and development forces which will give a new context to the water supply-demand *forms* which must evolve. One can speculate on these possible new contexts by the process of creating a scenario (i.e., a description of the *context* which results from a given set of assumptions about a situation). However, we really cannot predict the future and it is rather meaningless to do so since the number of combinations of conditions which create the future or influence it is vitrually infinite. Our basin interest is: do we now have or can we develop appropriate water resources *forms* (i.e., management options, adequate physical facilities, new water, etc) to accomodate whatever future might emerge. We explore this question by selecting those assumptions about the future (e.g., population, hydrologic availability of water, per capita use, etc), which will provide the most stressful context. Given this context we then ask, what *forms* (i.e., water resources management alternatives) will work? And second, the political question can be posed: are they acceptable? The input-output model was devised to handle the former question. The second question is a value judgment. However, the whole point of the input-output matrix is that we can explore different forms and their acceptability can be judged on the basis of knowledge--because the matrix displays all the facts about the situation (i.e., both the assumed context and the corresponding scenario form).

The results of the input-output modeling for future supply-demand contexts within the South Platte basin indicate that there are forms (i.e., water resources planning and management alternatives) which can permit the appropriate fits between supplies and demands for both *expected* future contexts and also those contexts which are the most stressful. Probably, however, there are no forms which are mutually acceptable to all parties (i.e., west slope interests, environmentalists, agricultural green belt advocates, those who want to maintain a viable agriculture, city water department officials, trout unlimited, etc., etc). Thus the forms which emerge are politically determined. The forms explored here by means of the input-output modeling process provide a basis for such evaluations. The particular forms to be chosen are value laden and it is the political process which must handle this.

2.5.5. *Context and Form, 1970-2020.* The natural situation in the South Platte River basin with respect to water supply--i.e., limited native surface water runoff, variable annual discharge of the mountain streams, accessibility of additional supplies from other basins, etc.--is its *water supply context.* The population in the basin which used domestic water, the industries, agriculture, and the various interests are called here, collectively, the *water demand context.*

The *forms* devised over the past one hundred years to provide the present *fits* between supply and demand fall into two major categories: (1) the institutional infrastructure, and (2) the physical infrastructure. The cornerstone of the former is the appropriation doctrine, while the latter consists of the accumulated capital investment in storage dams, canals, water and wastewater treatment plants, etc.

The water demand context is variable; it changes with population influx, factors related to economic development (e.g., agriculture, industry, energy), and various social conditions (e.g., environmental ethic, growth policies, etc). However, the water supply context is essentially fixed by the hydrologic conditions of the basin.

The forms devised thus far to find the needed fits between supply and demand have been based largely on the appropriation doctrine and upon the laissez-fair search for new water. The result has been the appropriation of virtually all free water. A very high degree of sequential water reuse has been a fortuitous by-product.

Alternative forms for the future to permit the required supply-demand fits can be displayed by an input-output model. The selection of a particular form from among the alternative is a value oriented question having to do with the allocation of public goods. Therefore, the decision is inherently political in nature.

The political character of the form chosen not withstanding, several criteria or characteristics can be specified with respect to the consequence resulting from the particular form chosen. Some of these criteria and associated alternative forms are outlined broadly in Table 2-5.

The criteria listed in Table 2-5 are indicative only of the kind of system needed. The present system probably has these characteristics already to a large degree. The appropriation doctrine, combined with the free-market transfer of water, permits both a system of priorities for water use and a mechanism for transfer to meet changing demand situations. While this does not insure the highest and best social purpose, this seems to happen fortuitously in the South Platte River Basin. For example, the natural stream flows are maintained in most of the mountains streams where recreation use if most important; municipal water procurement is essentially price inelastic and so this need can be taken care of by the market mechanism; agriculture can and does survive on used water and so is able to cope with further municipal demands.

Table 2-5. Examples of Broad Policy Criteria and Associated Alternative Forms

Criteria	Alternative Form
Flexible management strategy	Appropriation doctrine. Free market transfers of water. Central planning. Secure additional amounts of water (e.g. new storage projects to limit flow into Nebraska to compact amounts. Water exchanges (in lieu of direct water reuse to meet new demands.
Resiliency of system to withstand droughts	Reserve storage (i.e. groundwater, surface water) and conjunctive use. Priority in accordance with highest social good (e.g. water rights ownership by cities with lease back arrangement to agriculture. Secure additional virgin resource (e.g. west slope water). Conservation by pricing or rationing.
Accommodate new social priorities (e.g. minimum streat flows, new regional growth, etc.)	Provide zones for maintenance of minimum streat flows through acquisition of water rights. Work out symbiotic arrangements with agriculture. Encourage viable advocate institutions for the social priorities of interest.

The particular forms suggested in Table 2-5 are all controversial, and the list certainly is not exhaustive. They are not necessarily mutually exclusive of one another. But they all characterize the "final development" or "apex" stage of alternative supply-demand fits.

III. OPTIMIZATION

3.1 Background

This chapter reviews the work of Jønch-Clausen (1978) and Jønch-Clausen and Morel-Seytoux (1977, 1978) who developed quadratic programming procedures to handle the optimization of regional water supply-demand planning for the case of increasing water demand with fixed supply and non-linear costs. Broadly stated, the objective of the planning effort is to best satisfy growing demands for water in a planning area with available supplies, "best" being an expression of some measure of social desirability.

The planning problem is as follows: a multitude of future demands for water in an area--for agricultural, municipal, industrial, recreational and other purposes--must be satisfied from a number of existing or potential sources: natural precipitation falling within the area, streamflows entering the area, groundwater, imports from adjacent areas and various forms of reuse of water. Demands as well as supplies have certain spatial, temporal and quality characteristics which must be reconciled in this demand-supply "matching" process. Obviously, regardless of whether the planning area in question has water in abundance or is in very short supply, an infinite number of such demand-supply combinations exists, each with a different physical and social impact in the area. Given certain societal goals and objectives, it is the job of the planning authority to identify and select the most appropriate and desirable out of this large number of combinations.

As the number of alternative planning strategies grows very large, it is no longer possible for the planner to compare alternatives and select the best without the aid of some systematic methodology, which usually involves the use of a digital computer capable of performing a large number of operations in a very short time. One such methodology, a quadratic programming optimization model, is presented here.

A more detailed user-oriented description of the methodology and the computer program can be found in a separate user's manual (Jønch-Clausen and Morel-Seytoux, 1978). Also documented in a separate user's manual is the quadratic programming routine which forms the basis for the otpimization approach in this methodology (Jønch-Clausen and Morel-Seytoux, 1977). The dissertation of Jønch-Clausen (1978) provides a more comprehensive treatment of the application of the optimization model applied to the Cache La Poudre River Basin, demonstrating how the model is used to determine optimal water supply-demand configurations for 2000 and for 2020.

3.2. Optimization Techniques in Water Resources Planning

The relatively simple optimization techniques, *linear programming* and *dynamic programming* caught on in the 1960's and were applied to a limited extent. They remain very popular. Both of these techniques are conceptually and mathematically simple, and easy to teach and apply. Also standard computer codes are available in most computer software packages. However, both of these techniques have limitations: true linear objective functions are very rare in water resources problems, and dynamic programming becomes computationally infeasible if more than a few constraints are imposed.

In cost minimization problems linear programming can be applied only if economies of scale characteristics are neglected, i.e., if constant unit costs are assumed. Non-linear cost functions can be piecewise linearized, however, thereby translating a non-linear programming problem into a linear one. This of course is a popular approach since it allows planners to use the available very efficient linear programming codes in solving non-linear problems. A disadvantage of this *separable programming* approach is that the linearization process involves the introduction of a large number of additional variables and constraints which may result in very high computer costs.

But the mathematical complexity and computational inefficiency of the more general non-linear programming algorithms tend to restrict their applicability to fairly small size problems. Special non-linear programming techniques are *quadratic programming* (quadratic objective function and linear constraints) and *geometric programming* (posynomial objective function and constraints). Through these techniques a least cost objective function can be handled for non-linear cost functions.

3.3. Multiple Objective Water Resources Planning

Obviously, the optimal solution with respect to economic objectives (e.g., least cost), do not adequately consider all important aspects of water resources development, such as environmental, social and political consequences of the "optimal" plan. In fact, this "optimal" plan may not be optimal at all, at least from the point of view of some segments of the affected population. Most of the studies in the literature concerned with regional water resources planning consider just one objective, usually the least cost objective, and all other societal objectives ans aspirations are considered as constraints. The sensitivity of such constraints are in some studies investigated by means of dual variables (e.g., Bishop et al., 1975b), a technique that allows the decision maker to at least realize how much economic benefit must be sacrificed in order to achieve a higher level of one or more of these other "objectives", or vice versa.

Whereas single objective optimization problems have a definite solution, namely *the* optimal solution, there is in fact no optimal solution to a multiple objective programming problem. A set of non-inferior solutions is generated, and in some way--which depends on the particular technique--a *best-compromise solution* is chosen from this set.

Keeping these limitations in mind, this study considers only a least cost objective function. The model construction does incorporate those social values (e.g., minimum stream flows) which may be expressed quantitatively. They are introduced into the model as constraints.

3.4. Present Study

This research builds upon the *total regional water resources planning* study by Bishop and Hendricks (1971), who formulate regional water planning as a transportation problem. An interaction matrix--or *input-output matrix*--is used to portray origins and destinations for water in the system, and linear programming is used to minimize the overall costs associated with transportation and treatment of water between origins and destinations.

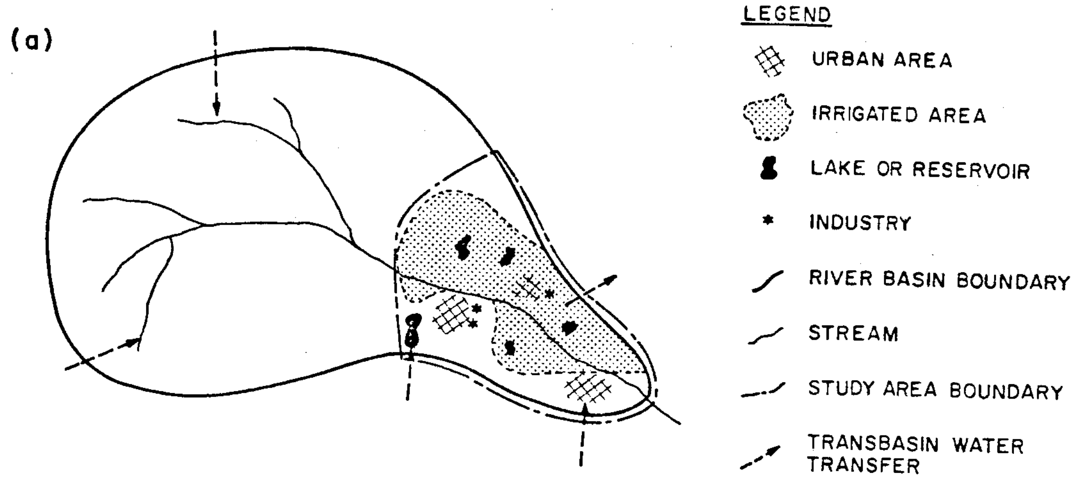
This work also utilizes the framework of the input-output model described in the previous chapter. This framework is used in order to aid understanding of the overall problem.

The quadratic programming optimization model is applied to a simplified depiction of the Cache La Poudre water system for least cost and minimum cost variance objective functions. The model is demonstrated for both annual and seasonal levels of resolution.

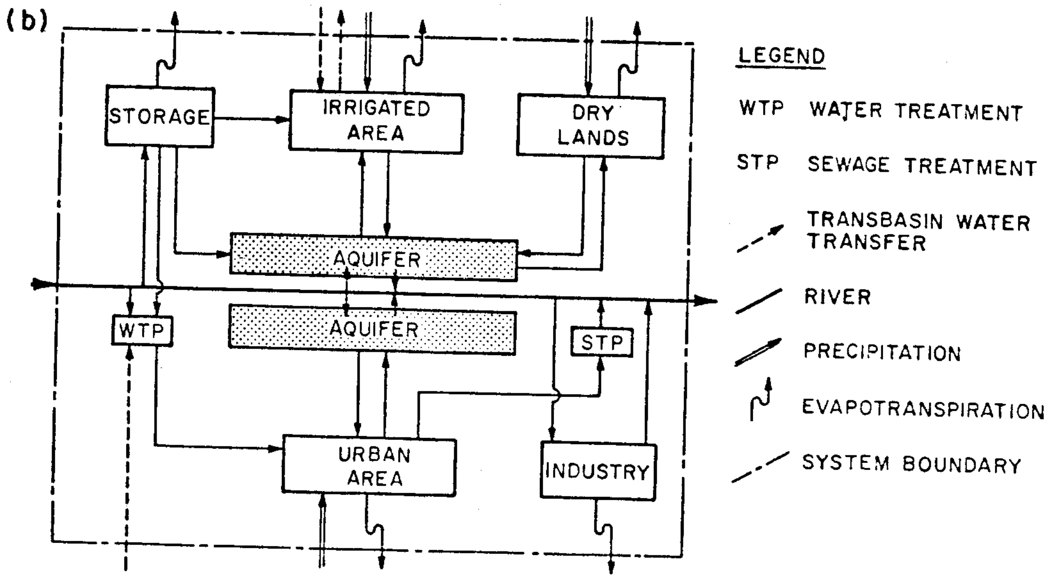
3.5 System Definition

The water system is defined in terms of inputs, outputs, and water consuming and/or transferring sectors within. For a river basin the basic system inputs are natural precipitation and imports from other systems. Water storage may provide another input to the system. System outputs are evapotranspiration, surface and subsurface outflow, and exports. Water consuming and/or transferring sectors within the planning area may include: urban areas, irrigated agriculture, infrastructure facilities, etc. The input-output model described in the previous chapter describes these sectors in more detail.

Figure 3-1 is an example of the conceptualization and aggregation process involved in system description. The hypothetical real system, as it would appear on a land use map, is shown in (a), and a conceptual planning system at a high level of aggregation is shown below in (b). Areas of human habitation are either omitted (rural population) or consolidated into one city which is supplied through a water treatment facility, or from private wells. The water treatment facility may draw water from the river, from imports or from storage. Effluent from the city passes through a sewage treatment facility. Other sectors represent storage facilities (reservoirs and lakes), irrigated agriculture, and undeveloped land within the system boundaries. The irrigated agricultural area has a variety of supply sources: natural precipitation, direct diversion from the river, pumpage from the ground, withdrawal from storage or imported water. Some water may leave the system in irrigation canals to adjacent areas (exports). The groundwater reservoir is



REAL SYSTEM



CONCEPTUAL SYSTEM

Figure 3-1. Conceptualization and Aggregation.

depicted as a separate sector. Industries in the planning area are consolidated into one sector which is assumed to have its own treatment facilities. Arrows in the diagram (b) indicate water flows in the system, both natural and man-caused. These flows include evapotranspiration from vegetated or free surfaces, deep percolation to the acquifer, and stream-aquifer interactions.

It is important to recognize, however, that water is being used and reused within the system; effluents or return flows from one sector are supplies for other sectors. A thorough understanding and conceptualization of this interdependence between sectors within the system is of crucial importance in the planning approach presented here, and it is particularly in this context that the input-output formulation described earlier contributes to the understanding and conceptualization (modeling) of the system.

Following the procedure outlined above, the lower plains portion of the Cache La Poudre water system is conceptualized and aggregated in Figure 3-2. Reference is made to the description of the basin's water system outlined in Appendix A.

The planning area represented in Figure 3-2 is divided into two sections, each being represented by a reach of the river, an agricultural sector, an urban sector, and a section of the aquifer underlying the area. About 60 percent of the irrigated area falls in the upper section, and 40 percent falls in the lower section. Of the total 55 river miles in the plains, 20 miles are in the upper section, and 35 miles in the lower section. The urban areas are represented by the City of Fort Collins in the upper section, and the City of Greeley in the lower section.

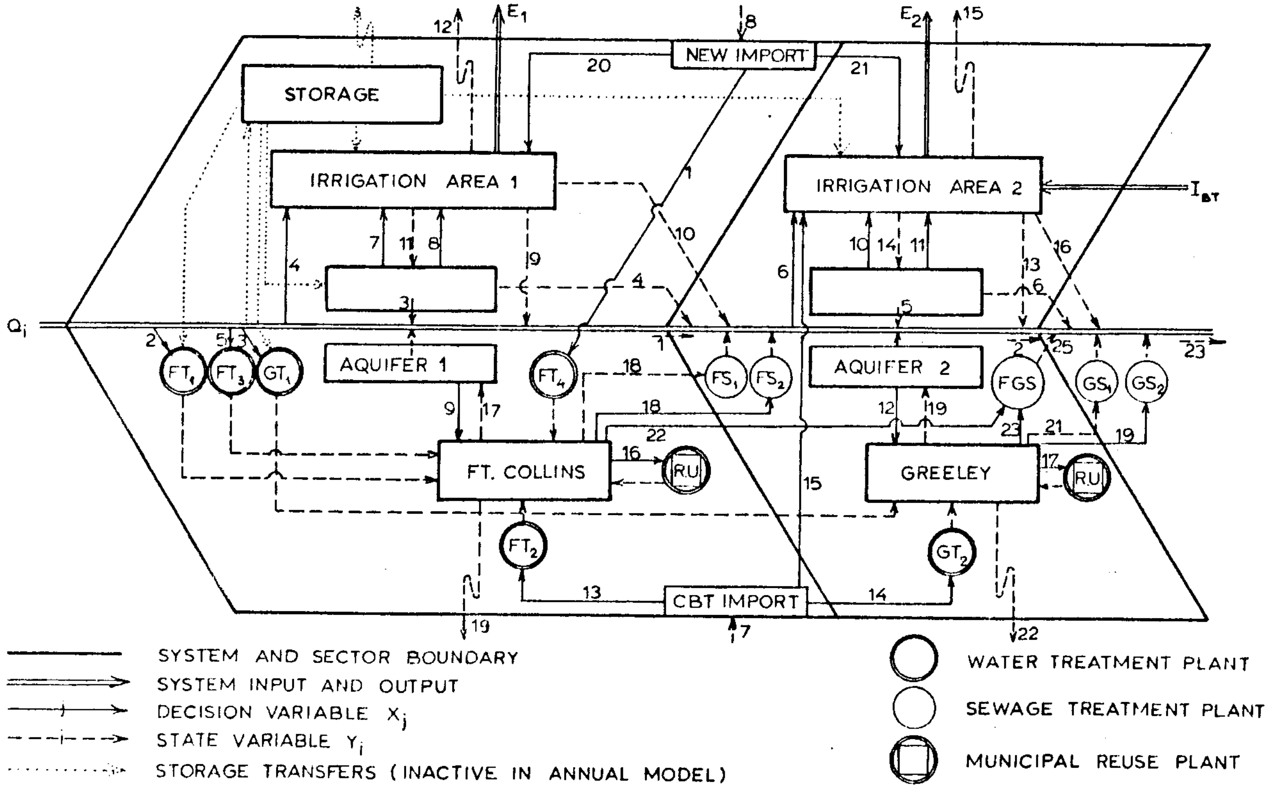


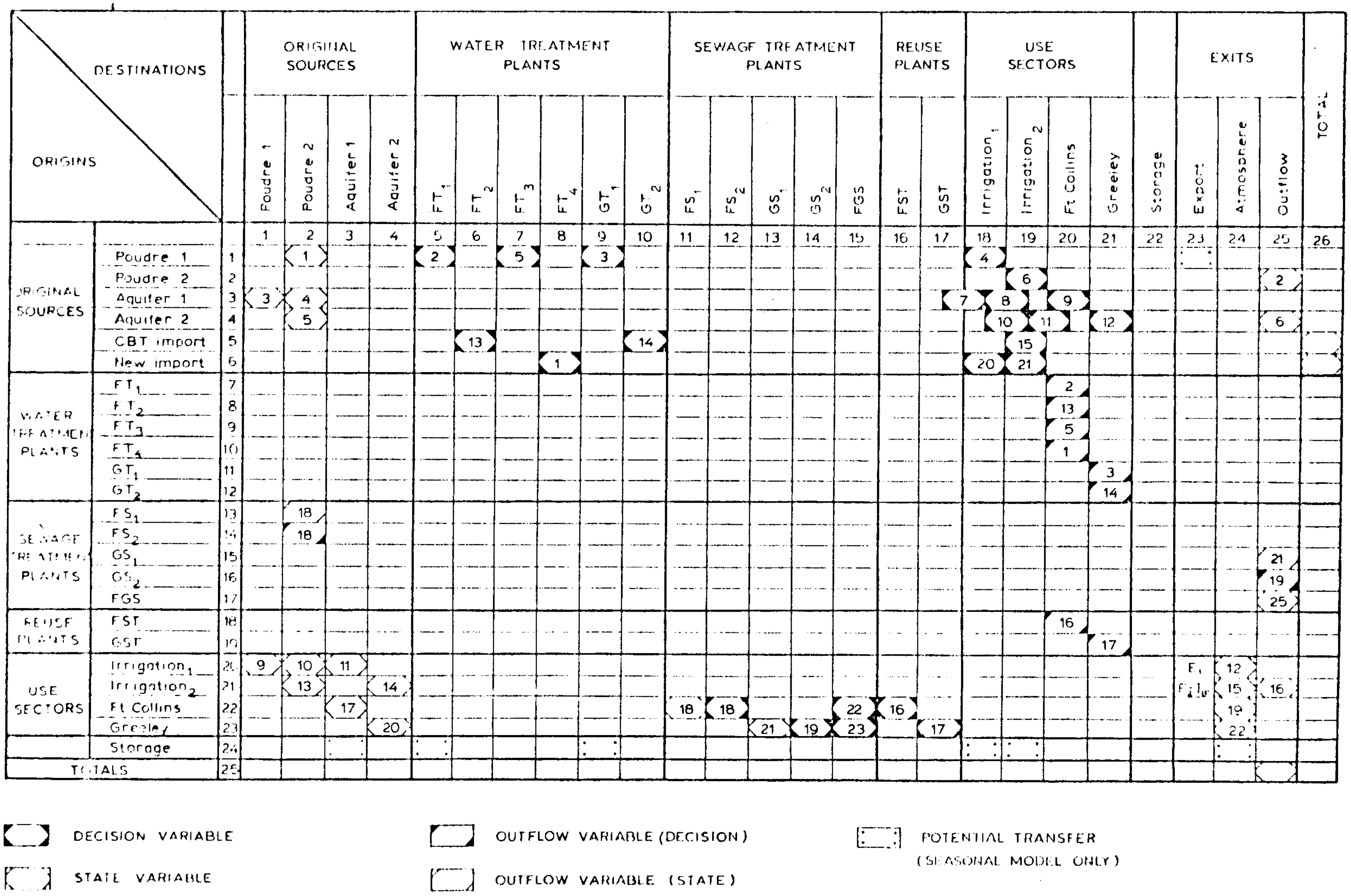
Figure 3-2. Aggregation of Sector Components for the Cache La Poudre Water System

Alternatives considered for future urban water supply and wastewater disposal are the following: (1) potential expansions of existing treatment facilities; (2) additional imports from exterior sources through a new water treatment facility; (3) construction of municipal water reuse facilities; and (4) construction of a regional sewage treatment plant to handle wastewater from Fort Collins and Greeley. Furthermore, groundwater is considered a potential municipal-industrial water supply source. Other alternatives could have been included; however, those listed here should provide an adequate and realistic basis for the case study.

Figure 3-3 is the input-output matrix which corresponds to the line diagram of Figure 3-2. The diagram illustrates the use of two categories of variables: decision variables, and state variables.

3.5.1 Reduction of Data. In order to formulate and analyze the planning problem mathematically the information and data on the Cache La Poudre system (Appendix A) is organized and expressed in a number of coefficients and parameters. This is done in Table 3-1.

All the information and data in Table 3-1 pertains to a seasonally or annually based planning approach, i.e., capacities, supplies and demands as well as other system characteristics are given for each of the four seasons of the year, and for the year. The index k is used to denote time periods (seasons, k = 1,2,3,4), and flows are given in acre-feet (AF) per season (AF/season) and acre-feet per year (AF/year) respectively. The data given and the symbolic representation of sector components illustrate the process of data reduction, from that shown in Appendix A, to a form appropriate for storage as a variable in a digital computer.



DESTINATIONS / ORIGINS			ORIGINAL SOURCES				WATER TREATMENT PLANTS						SEWAGE TREATMENT PLANTS					REUSE PLANTS		USE SECTORS					EXITS			TOTAL
			Poudre 1	Poudre 2	Aquifer 1	Aquifer 2	FT_1	FT_2	FT_3	FT_4	GT_1	GT_2	FS_1	FS_2	GS_1	GS_2	FGS	FST	GST	Irrigation$_1$	Irrigation$_2$	Ft Collins	Greeley	Storage	Export	Atmosphere	Outflow	
ORIGINS			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
ORIGINAL SOURCES	Poudre 1	1		1			2		5		3									4								
	Poudre 2	2																			6						2	
	Aquifer 1	3	3	4																7	8	9						
	Aquifer 2	4		5																	10	11	12				6	
	CBT import	5						13				14									15							
	New import	6								1										20	21							
WATER TREATMENT PLANTS	FT_1	7																				2						
	FT_2	8																				13						
	FT_3	9																				5						
	FT_4	10																				1						
	GT_1	11																					3					
	GT_2	12																					14					
SEWAGE TREATMENT PLANTS	FS_1	13		18																								
	FS_2	14		18																								
	GS_1	15																									21	
	GS_2	16																									19	
	FGS	17																									25	
REUSE PLANTS	FST	18																				16						
	GST	19																					17					
USE SECTORS	Irrigation$_1$	20	9	10	11																				E_1	12		
	Irrigation$_2$	21		13		14																			E_2 I_w	15	16	
	Ft Collins	22			17								18	18			22	16								19		
	Greeley	23				20									21	19	23		17							22		
	Storage	24																										
TOTALS		25																										

Figure 3-3. Cache La Poudre System Input-Output Matrix

Table 3-1. Information and Data

	Symbol	Unit	Time Periods 1-4				Year	Const.
			Oct-Dec	Jan-Mar	Apr-Jun	Jul-Sep		
Demands								
Irrigated area, total	A	acres						218,600
Agricultural demand, area 1	D^k_{A1}	AF/season	-	-	54,810	101,790	156,600	
Agricultural demand, area 2	D^k_{A2}	AF/season	-	-	36,540	67,860	104,400	
Ft. Collins demand, year 2000	D^k_F	AF/season	3,090	2,500	6,180	7,530	19,300	
Ft. Collins demand, year 2020			4,800	3,900	9,600	11,700	30,000	
Greeley demand, year 2000	D^k_G	AF/season	2,430	1,980	4,860	5,930	15,200	
Greeley demand, year 2020			3,710	3,020	7,420	9,050	23,200	
Urban use distribution factor	F^k_u	-	0.16	0.13	0.32	0.39	1.00	
Urban use peak factor	P_u	-	1.5	1.5	1.8	1.5	2.3	
Urban effluent peak factor	p^k_{ue}	-	1.5	1.5	1.8	1.5	1.8	
Minimum outflow	Q^k_o	AF/season	4,500	4,500	3,000	3,000	15,000	
Minimum river flow	Q_{min}	AF/season	2,500	2,500	2,500	2,500	10,000	
Export, from area 1	E_1	AF/season	-	-	17,500	32,500	50,000	
Export, from area 2	E_2	AF/season	-	-	7,000	13,000	20,000	
Supply								
Poudre flow, average	Q^k_i	AF/season	8,600	5,700	168,700	90,000	273,000	
Poudre flow, 4-year drought			7,600	5,000	122,200	61,700	196,500	
CBT import (maximum	I_{CBT}	AF/season	-	-	15,000	60,000	75,000	
BT import	I_{BT}	AF/season	-	-	11,000	20,300	31,300	
System Capacities								
Water treatment plants: FT_1	C_{FT1}	AF/season	3,730	3,730	3,110	3,730	9,620	
FT_2	C_{FT2}	AF/season	3,000	3,000	2,500	3,000	7,730	
GT_1	C_{GT1}	AF/season	3,360	3,360	2,800	3,360	8,650	
GT_2	C_{GT2}	AF/season	5,600	5,600	4,670	5,600	14,420	
Sewage treatment plants: FS_1	C_{FS1}	AF/season	3,930	3,930	3,280	3,930	13,111	
GS_1	C_{GS1}	AF/season	1,680	1,680	1,400	1,680	5,600	
Maximum storage capacity	S_m	AF						250,000
Hydrology								
Return flow/net recharge	f^k	-	-	-	1.0	1.0	1.0	
Return flow within the system	R_{r_A}	-						0.80
Winter return flow	R_w	AF/season/mi	400	400	-	-	800	
Agricultural recharge near urban area	P_G	-	-	-	-	-		0.05
Present pumpage for irrigation	f_p							0.36
Storage seepage	ℓ_s	-						0.20
Storage evaporation	e_s	-						0.11
Irrigation efficiency, surface	$e_{a,s}$	-						0.45
Irrigation efficiency, well	$e_{a,g}$	-						0.60
Irrigation percolation, surface	$\ell_{a,s}$	-						0.52
Irrigation percolation, well	$\ell_{a,g}$	-						0.35
Surface return flow, surface	$s_{a,s}$	-						0.05
Surface return flow, well	$s_{a,g}$	-						0.05
Urban evapotranspiration	e^k_u	-	-	-	0.32	0.32	0.225	
Urban deep percolation	ℓ^k_u	-	0.10	0.10	0.15	0.15	0.135	
Urban effluent within the system	r_u	-						0.36

3.5.2 Cost Functions. In a planning situation one usually does not have adequate information to define cost functions for all treatments and transfers in the system. However, if costs can be estimated for one flow rate the economies of scale parameter, α_j, may be taken from the literature, where α_j is defined in Equation (3-1) below.

$$C(x_j) = A_j\ x_j^{\alpha j},\ A_j > 0,\ 0 < \alpha_j < 1 \qquad (3\text{-}1)$$

where $C(x_j)$ is the cost associated with treatment (at a prescribed level) or transport of the water quantity x_j, given as a flow rate, and A_j and α_j are constants. At the extremes, $\alpha_j = 0$ represents a situation in which total costs are independent of quantity, while $\alpha_j = 1$ reduces the cost relation to one of constant unit cost A_j, i.e., no economies of scale. This is a power type of cost function. It applies to capital as well as to operation and maintenance costs. Total costs--the sum of capital, operation and maintenance costs--are also given by this expression; the procedure for arriving at total costs is outlined in the user's manual (Jønch-Clausen and Morel-Seytoux, 1978).

When adequate information on the economies of scale characteristics of the costs in the system is not available, one might instead decide to use the simpler quadratic cost functions directly. Quadratic cost functions are fitted to a power function for optimization purposes anyway, and computer time can be saved by providing quadratic cost functions directly. The planner may even go so far as to neglect economies of scale altogether and work with constant unit costs, possibly revising his cost estimates in successive optimizations; this can be accomplished by simply ignoring the second order terms in the quadratic cost functions. The three types of cost functions, in order of sophistication and realism: linear--quadratic--power, are illustrated in Figure 3-3. In the case study here the more realistic power cost functions are used.

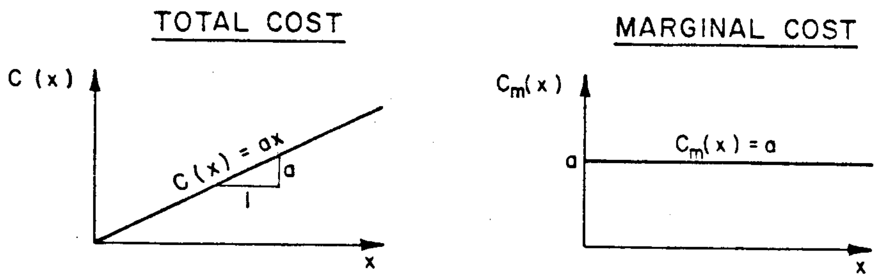
System cost information is displayed in Figures 3-4 and 3-5. Appropriate cost parameters are indicated in the matrix elements corresponding to the pertinent transfer or treatment processes. Figure 3-4 indicates the values of the parameters A_j in Equation (3-1), while Figure 3-5 indicates the values of the scale parameters α_j. The figures represent annual costs, adjusted to the same year, the annual cost of capital investments being based on an appropriate capital recovery factor (see Jonch-Clausen and Morel-Seytoux (1978) for details).

In the general cost function (3-1), x_j is a flow rate which is given in AF/year. However, when planning on a seasonal basis, having four seasons in a year, x_j denotes a flow rate in AF/(3 months).

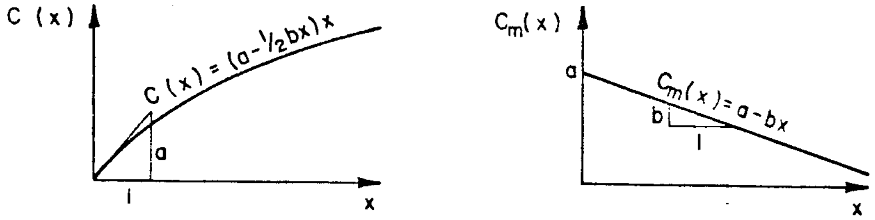
3.6 Quadratic Programming

As noted, the optimization problem to be solved is nonlinear in the objective. Neither expected costs nor cost variances in water resources systems behave linearly; due to economies of scale cost functions in water resources are often strictly concave, whereas cost variance functions are strictly convex.

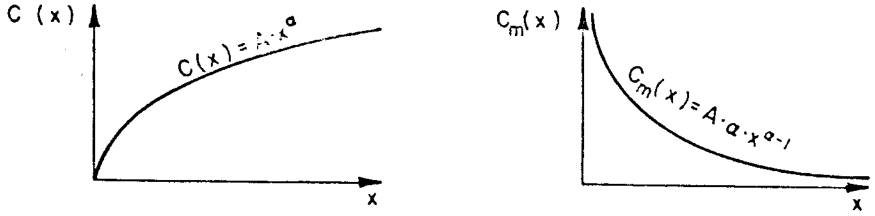
The optimization problem is one of minimizing a nonlinear (strictly concave or strictly convex) objective function, subject to linear constraints. The nonlinear objective may have various functional forms, depending on whether expected cost or cost variance is the objective to be minimized. Consequently, a rather versatile optimization approach is called for: not only must it be able to cope with different types of objective functions, it must also be capable of dealing with the quite tricky problem of minimizing a concave objective function.



LINEAR COST FUNCTION



QUADRATIC COST FUNCTION



POWER COST FUNCTION

Figure 3-4. Types of Cost Functions

ORIGINS \ DESTINATIONS			ORIGINAL SOURCES				WATER TREATMENT PLANTS						SEWAGE TREATMENT PLANTS					REUSE PLANTS		USE SECTORS					EXITS			
			Poudre 1	Poudre 2	Aquifer 1	Aquifer 2	FT_1	FT_2	FT_3	FT_4	GT_1	GT_2	FS_1	FS_2	GS_1	GS_2	FGS	FST	GST	Irrigation$_1$	Irrigation$_2$	Ft Collins	Greeley	Storage	Export	Atmosphere	Outflow	TOTAL
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
ORIGINAL SOURCES	Poudre 1	1		–			210		829		223									4								
	Poudre 2	2																			4						–	
	Aquifer 1	3	–	–																33	67	245						
	Aquifer 2	4		–																33	67		245				–	
	CBT import	5						206				206									8							
	New import	6								829										4	4							
WATER TREATMENT PLANTS	FT_1	7																				–						
	FT_2	8																				–						
	FT_3	9																				–						
	FT_4	10																				–						
	GT_1	11																					–					
	GT_2	12																					–					
SEWAGE TREATMENT PLANTS	FS_1	13		–																								
	FS_2	14		–																								
	GS_1	15																									–	
	GS_2	16																									–	
	FGS	17																									60C	
REUSE PLANTS	FST	18																				–						
	GST	19																					–					
USE SECTORS	Irrigation$_1$	20	–	–	–																				E_1	–		
	Irrigation$_2$	21		–		–																			$E_2 I_m$	–	–	
	Ft Collins	22			–								231	556			–	1620								–		
	Greeley	23				–									231	556	–		1620							–		
	Storage	24																										
TOTALS		25																										

DECISION VARIABLE

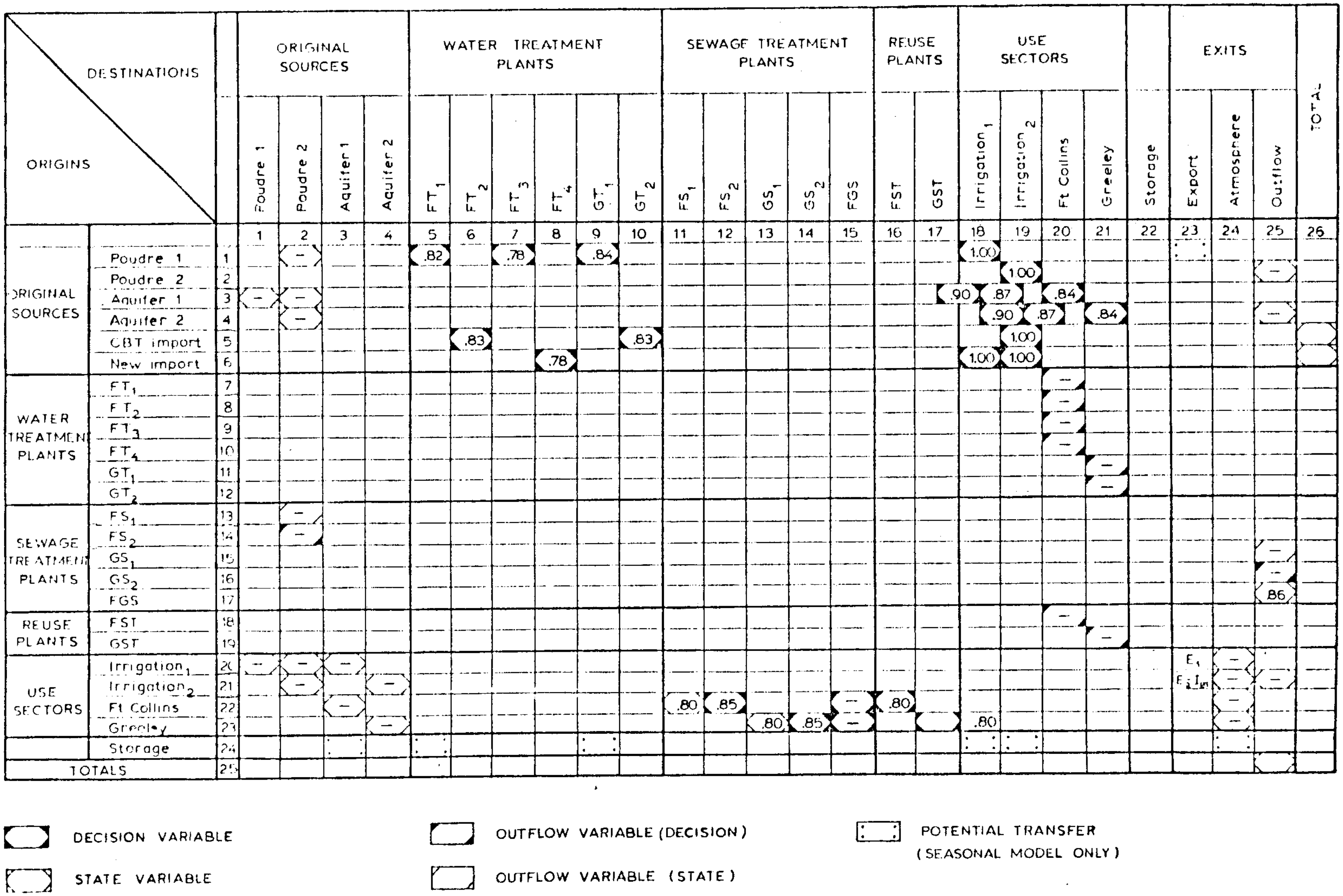
STATE VARIABLE

OUTFLOW VARIABLE (DECISION)

OUTFLOW VARIABLE (STATE)

POTENTIAL TRANSFER (SEASONAL MODEL ONLY)

Figure 3-5. Cost Coefficients A_j.



ORIGINS \ DESTINATIONS			ORIGINAL SOURCES				WATER TREATMENT PLANTS						SEWAGE TREATMENT PLANTS					REUSE PLANTS		USE SECTORS					EXITS			
			Poudre 1	Poudre 2	Aquifer 1	Aquifer 2	FT_1	FT_2	FT_3	FT_4	GT_1	GT_2	FS_1	FS_2	GS_1	GS_2	FGS	FST	GST	Irrigation_1	Irrigation_2	Ft Collins	Greeley	Storage	Export	Atmosphere	Outflow	TOTAL
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
ORIGINAL SOURCES	Poudre 1	1		–			.82		.78		.84									1.00					⁞			
	Poudre 2	2																			1.00						–	
	Aquifer 1	3	–	–																.90	.87	.84						
	Aquifer 2	4		–																	.90	.87	.84				–	
	CBT import	5						.83				.83									1.00							⬡
	New import	6								.78										1.00	1.00							⬡
WATER TREATMENT PLANTS	FT_1	7																				–						
	FT_2	8																				–						
	FT_3	9																				–						
	FT_4	10																				–						
	GT_1	11																					–					
	GT_2	12																					–					
SEWAGE TREATMENT PLANTS	FS_1	13		–																								
	FS_2	14		–																								
	GS_1	15																									–	
	GS_2	16																									–	
	FGS	17																									.86	
REUSE PLANTS	FST	18																				–						
	GST	19																					–					
USE SECTORS	Irrigation_1	20	–	–	–																				E_1	–		
	Irrigation_2	21		–		–																			$E_i I_m$	–	–	
	Ft Collins	22			–								.80	.85			–	.80								–		
	Greeley	23				–									.80	.85	–		⬡	.80						–		
	Storage	24			⁞		⁞				⁞									⁞	⁞					⁞		
TOTALS		25																									⬡	

DECISION VARIABLE

STATE VARIABLE

OUTFLOW VARIABLE (DECISION)

OUTFLOW VARIABLE (STATE)

⁞ POTENTIAL TRANSFER (SEASONAL MODEL ONLY)

Figure 3-6. Cost Coefficients α_j.

Several mathematical programming techniques are available which satisfy the first requirement, i.e., minimizing a general nonlinear objective, subject to linear constraints. They include: general nonlinear programming, separable programming (piecewise linear programming), approximation of the nonlinear objective with a simple second order function, using quadratic programming technique to minimize the resulting second order objective function, and mixed integer programming and branch and bound techniques.

Quadratic programming is chosen here. It is mathematically simple and does not require more variables than does a general nonlinear programming technique. A satisfactory search procedure is fairly easily added to the standard quadratic programming algorithm, giving it the capability of, if not guaranteeing a global expected cost minimum, then at least obtaining a minimum which in all probability is global. Based on these considerations the successive quadratic programming approach has been chosen here. Very few iterations have been required to approximate the nonlinear objective very closely, and the search procedure in the expected cost minimization has proven to be simple and effective.

The methodology developed here takes advantage of the convenient input-output formulation of water resources systems in reducing the size of the ultimate quadratic programming problem. This is done by distinguishing between "primary" planning variables (decision variables) which necessarily must appear as variables in the optimization problem; and "secondary" variables (state variables) which can be expressed in terms of the primary variables, and thus be eliminated a priori from the quadratic programming formulation. Using this technique, out of the 60 variables that appear in the input-output formulation of the case study in Figure 3-1 only 23 are required in the quadratic programming formulation. Further, 25 linear equations have been required to express the "secondary" variables in terms of "primary" and "secondary" variables. In a direct formulation based on all the variables in the input-output formulation of the problem most of these equations would have to be included as additional constraints; with the approach taken here only 13 constraints are needed in the final quadratic programming formulation.

The mechanics of operation of the quadratic programming routine and the logic behind it is given by Jønch-Clausen and Morel-Seytoux (1977). Its application is described more completely in the User's Manual by Jønch-Clausen and Morel-Seytoux (1978). Appendix B summarizes some of the key ideas of quadratic programming; it is included for reference.

3.7 Formulation of the Annual Model

The first decision to be made when applying the optimization methodology is the selection of a time frame. Planning on an annual basis requires moderate data and information about the system, and the computational burden is considerably easier than in the case of seasonal planning. However, the simplicity of the annual approach has its price in that results are less specific and reliable than those obtained in the seasonal approach. The best approach to planning with the methodology presented here is to explore a wide range of system assumptions and future scenarios with the relatively cheap and manageable annual model. On the basis of these results conditions warranting the more comprehensive seasonal modeling are selected for further study.

3.7.1. *Definition of Variables*

The input-output matrix describing the Cache La Poudre planning system is shown in Figure 3-2. Each of the transfers in this matrix is a planning variable whose value depends on the system configuration and operation. To each alternative plan corresponds a set of variables $\{t_{ij}\}$ where t_{ij} is the transfer from row i to column j. For most i-j combinations $t_{ij} = 0$, corresponding to an infeasible or very unlikely transfer.

Two basically different kinds of transfers can be identified: transfers controlled by man, and transfers controlled by natural hydrologic processes.

As noted, variables associated with these kinds of transfers are characterized decision and state variables, respectively. Decision variables, x_j, and state variables, y_i, are indicated in Figures 3-1 and 3-2. An example of a decision is the diversion for a water treatment plant, and an example of a state is the evapotranspiration from the urban sector which directly depend on the water use in the sector.

A particularly simple state-decision relationship results when flow continuity implies that one variable equals another as, for instance, when a treatment plant receives inflow from only one source and no losses occur in the plant. (Outflow equals inflow). In such cases the outflow variable is eliminated and replaced by the relevant inflow variable whenever it would have appeared. Replaced outflow variables are indicated in Figure 3-2, their indices corresponding to those of the respective inflow variables.

3.7.2 Upper Bounds and Constraints. Upper bounds serve two purposes in the allocation model. One purpose of upper bounds is to constrain decision variables, x_j, to their feasible ranges (exact upper bounds), the other is to provide intervals for the fitting of quadratic approximations to the objective function (approximate upper bounds).

The linear system constraints in this case study include the necessary demand, availability and capacity constraints. In addition a certain minimum streamflow is specified for environmental reasons, and a minimum outflow constraint is included to insure compliance with downstream water rights. A constraint is included to express that wells in the urban area should not be pumped at a rate exceeding the recharge to the aquifer underlying the urban area, a recharge which comes from the urban area itself, plus a fraction of the agricultural area. The last constraint expresses the planning requirement that the net recharge to the aquifer (deep percolation minus pumping), and consequently the return flow, must be positive, i.e., groundwater mining in the planning year is unacceptable. Any number of additional constraints could be imposed for environmental, legal, economic, social or other reasons.

3.8 Results from the Annual Model

3.8.1 Year 2000, Average Conditions. Figure 3-6 displays in matrix form the minimum expected cost solution for year 2000, assuming average flow conditions and intermediate, "realistic" urban water demand projections. Inspecting the solution in Figure 3-6 it is immediately obvious that the present supply sources of water are adequate for meeting intermediate demands under average hydrologic conditions in year 2000. The outflow constraint which requires a minimum outflow of 15,000 AF/yr is loose, the outflow in the optimal (minimum expected cost) solution being 84,500 AF/year. Also, the cheap supply sources, Cache La Poudre River water and Colorado Big Thompson (CBT) water are

DESTINATIONS / ORIGINS			ORIGINAL SOURCES				WATER TREATMENT PLANTS						SEWAGE TREATMENT PLANTS					REUSE PLANTS		USE SECTORS					EXITS			TOTAL
			Poudre 1	Poudre 2	Aquifer 1	Aquifer 2	FT_1	FT_2	FT_3	FT_4	GT_1	GT_2	FS_1	FS_2	GS_1	GS_2	FGS	FST	GST	Irrigation$_1$	Irrigation$_2$	Ft Collins	Greeley	Storage	Export	Atmosphere	Outflow	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
ORIGINAL SOURCES	Poudre 1	1		10.00			9.62		0		.78									315.26					⬚			
	Poudre 2	2																			139.82						10.00	
	Aquifer 1	3	54.25	54.25																70.90	0	1.95						
	Aquifer 2	4		59.02																	27.82	0	0				59.02	
	CBT import	5						7.73				14.42									52.86							75.00
	New import	6								0										0	0							0
WATER TREATMENT PLANTS	FT_1	7																				9.62						
	FT_2	8																				7.73						
	FT_3	9																				0						
	FT_4	10																				0						
	GT_1	11																					0.78					
	GT_2	12																					14.42					
SEWAGE TREATMENT PLANTS	FS_1	13		12.35																								
	FS_2	14		0																								
	GS_1	15																									5.60	
	GS_2	16																									4.13	
	FGS	17																									0	
REUSE PLANTS	FST	18																				0						
	GST	19																					0					
USE SECTORS	Irrigation$_1$	20	8.40	8.40	162.75																				E_1	156.60		
	Irrigation$_2$	21		5.80		115.80																			$E_2 I_w$	104.40	5.80	
	Ft Collins	22			2.61								12.35	0			0	0								4.34		
	Greeley	23				2.05									5.60	4.13	0	0	0							3.42		
	Storage	24			⬚		⬚				⬚									⬚	⬚					⬚		
TOTALS		25																									84.55	

(UNIT: 1000 AF)

DECISION VARIABLE

STATE VARIABLE

OUTFLOW VARIABLE (DECISION)

OUTFLOW VARIABLE (STATE)

⬚ POTENTIAL TRANSFER
(SEASONAL MODEL ONLY)

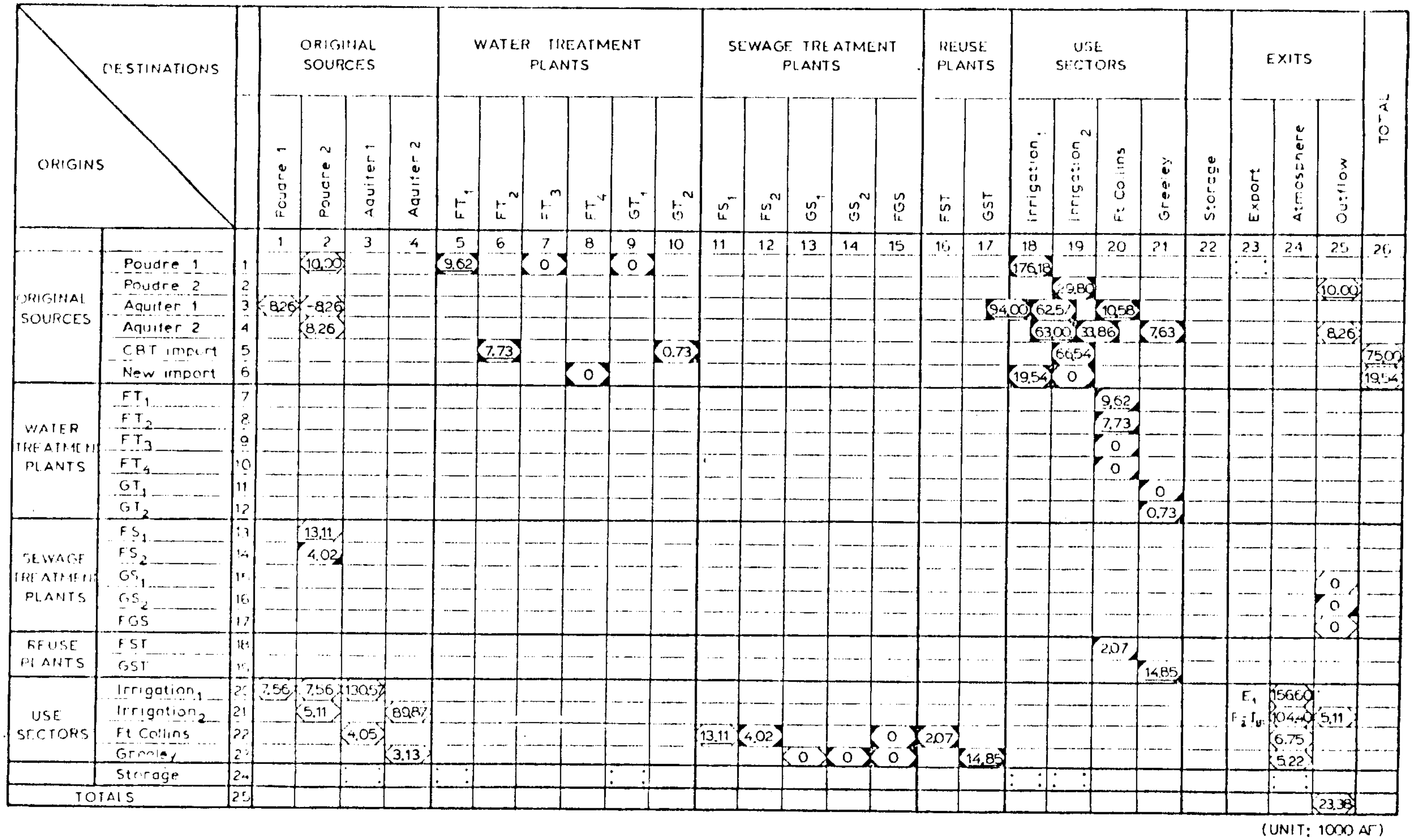
Figure 3-7. Minimum Expected Cost Solution, Year 2000. Average Water Yield, Intermediate Level of Water Demand fully utilized in the optimal solution. The minimum river flow constraints ($y_1 = y_2 = 10{,}000$ AF/year), and the CBT water availability constraint ($y_7 = x_{13} + x_{14} + x_{15} \leqq 75{,}000$ AF/year) are both tight. Groundwater is being moderately utilized at the optimum, close to 100,000 AF/year being pumped for irrigation, and some 2000 AF/year being pumped for municipal use. However, it must be emphasized that groundwater and surface water are inseparable resources. Every AF of water pumped from the (alluvial) aquifer is ultimately drawn from the river, and vice versa. Thus, groundwater is not a supply source per se, rather the aquifer is a vehicle for maximizing the beneficial use of available system water. Only by reclaiming water "lost" to seepage from canals and reservoirs and deep percolation below the root zone by pumping from the aquifer can water resources in the system be fully utilized, and the need for expensive new interbasin water transfers postponed. The cost associated with groundwater utilization being much higher than that associated with purchase and conveyance of CBT water, it is economical to import the maximum CBT allowance before drawing on the groundwater resource.

Variables--states or decisions--which in the optimal solution reach their upper bounds are underlined in Figure 3-7. The case of tight constraints for river flow and CBT imports is already discussed; the other case in which variables reach their upper bounds is when facilities are utilized to capacity. In the optimal solution Fort Collins utilizes both of its existing water treatment plants FT_1 and FT_2 to capacity, satisfying the remaining demand with groundwater. Greeley utilizes its CBT water treatment facilities GT_2 fully, but has excess capacity in its water treatment plant at the river (GT_1). Fort Collins has sufficient sewage treatment capacity in its existing plants (FS_1), while Greeley must expand its secondary sewage treatment capacity by 4100 AF/year (GS_2).

Neither municipal water reuse, nor treatment of wastewater in a regional sewage treatment facility is indicated in the minimum expected cost solution for the year 2000.

3.8.2 Year 2020, Drought Conditions. Figure 3-7 displays the minimum cost solution for year 2020, assuming low flow conditions and high urban water demand projections. Comparing this solution to the previously described solution for year 2000 the following should be noted. Present sources of supply are no longer adequate for meeting demands, and an additional 19,500 AF of water must be made available from exterior sources. The high cost associated with such new interbasin transfers ($500 per AF) ensures that the demand for these transfers is minimized: (1) groundwater is being utilized to the maximum possible extent, the total net recharge being zero (net recharge constraint $y_{24} \geqq 0$ tight); (2) urban effluent from Greeley which otherwise would contribute to system outflow is conserved by reusing the entire amount of effluent from that city in a new tertiary water treatment facility; (3) Cache La Poudre River water is fully committed, minimum flow constraints being tight ($y_1 = y_2 = 10{,}000$ AF/year); and (4) the maximum possible amount of CBT water (75,000 AF/year) is utilized.

In the utilization of the groundwater resource it should be noted that: (1) a net withdrawal of 16,500 AF/year from the aquifer underlying area 1 is compensated for by a net recharge of the same amount in area 2; (2) existing pumps are utilized to capacity (variables x_7 and x_{10} are at their upper limits), and 96,300 AF/year of pumpage from new wells is



DESTINATIONS / ORIGINS			ORIGINAL SOURCES				WATER TREATMENT PLANTS						SEWAGE TREATMENT PLANTS					REUSE PLANTS		USE SECTORS					EXITS			
ORIGINS			Poudre 1	Poudre 2	Aquifer 1	Aquifer 2	FT_1	FT_2	FT_3	FT_4	GT_1	GT_2	FS_1	FS_2	GS_1	GS_2	FGS	FST	GST	Irrigation$_1$	Irrigation$_2$	Ft Collins	Greeley	Storage	Export	Atmosphere	Outflow	TOTAL
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
ORIGINAL SOURCES	Poudre 1	1		10.00			9.62		0		0									176.18					⁞			
	Poudre 2	2																			29.80						10.00	
	Aquifer 1	3	8.26	-8.26																94.00	62.57	10.58						
	Aquifer 2	4		8.26																63.00	33.86		7.63				8.26	
	CBT import	5						7.73				0.73									66.54							75.00
	New import	6								0										19.54	0							19.54
WATER TREATMENT PLANTS	FT_1	7																				9.62						
	FT_2	8																				7.73						
	FT_3	9																				0						
	FT_4	10																				0						
	GT_1	11																					0					
	GT_2	12																					0.73					
SEWAGE TREATMENT PLANTS	FS_1	13		13.11																								
	FS_2	14		4.02																								
	GS_1	15																									0	
	GS_2	16																									0	
	FGS	17																									0	
REUSE PLANTS	FST	18																				2.07						
	GST	19																					14.85					
USE SECTORS	Irrigation$_1$	20	7.56	7.56	130.57																				E_1	156.60		
	Irrigation$_2$	21		5.11		89.87																			[illegible]	104.40	5.11	
	Ft Collins	22			4.05								13.11	4.02			0	2.07								6.75		
	Greeley	23				3.13									0	0	0		14.85							5.22		
	Storage	24			⁞		⁞				⁞									⁞	⁞					⁞		
TOTALS		25																									23.38	

(UNIT: 1000 AF)

DECISION VARIABLE

STATE VARIABLE

OUTFLOW VARIABLE (DECISION)

OUTFLOW VARIABLE (STATE)

⁞ POTENTIAL TRANSFER (SEASONAL MODEL ONLY)

Figure 3-8. Minimum Expected Cost Solution, Year 2020 (1) indicated; and (3) groundwater is used to supply Fort Collins to the maximum possible extent (x_9 is at its upper limit).

While groundwater accounted for only 16 percent of total supplies in the previous solution for year 2000, 47 percent of supplies in this solution are pumped from the aquifer.

In the minimum expected cost solution for year 2020 Fort Collins utilizes both of its existing water treatment plants (FT_1 and FT_2) as well as the aquifer underlying the city to capacity, relying on water reuse for the remainder of its supply. As already mentioned Greeley reuses its entire effluent, letting groundwater and river water through its existing water treatment plant GT_1 supply the required additional amount. In reality, of course, reuse of the entire effluent for municipal water supply is hardly feasible, and a constraint should be imposed to limit municipal reuse to some fraction of the effluent. In the model this simply requires reduction of the upper bounds on the reuse decision variables (x_{16} and x_{17}), and it is only for purposes of illustration of the role of municipal water reuse that full utilization of the reuse alternative is permitted here. With the high demand characterizing the scenario for year 2020, Fort Collins must expand its secondary treatment capacity whereas Greeley does not even utilize its existing sewage treatment plant because of the extensive reuse. The system reuse factor for the year 2020 minimum expected cost solution is $F_R = 2.10$. Compared to the value $F_R = 1.81$ for the year 2000 solution it is obvious that the poorer supply-demand ratio for year 2020 results in increased efficiency in water use.

Table 3-2 compares solutions in tabular format for the above two assumed cases and two others as well for the year 2020. In addition, results from the minimum cost variance model are shown as well.

Table 3-2. Comparison of Annual Solutions.

Objective Scale Factor, Regional Stp Minimum Outflow (AF) Hydrologic Conditions		Cost 0.86 15,000 Average	Variance 0.86 15,000 Average	Cost 0.86 15,000 Drought	Cost 0.86 70,000 Drought	Cost 0.70 70,000 Drought	Variance 0.86 15,000 Drought
Variable	Transfer (from-to)	Year 2000		Year 2020			
x_1	Import-FT_4	0	242	0	863	868	246
x_2	River-FT_1	9,620*	9,620*	9,620*	9,620*	9,620*	9,620*
x_3	River-GT_1	780	780	0	287	453	0
x_4	River-Irrigation 1	315,260	315,510	176,180	220,150	219,820	180,360
x_5	River-FT_3	0	0	0	0	0	0
x_6	River-Irrigation 2	139,820	140,370	29,799	107,910	95,569	30,160
x_7	Ground-Irrigation 1 (ex)	70,901	70,715	94,000*	92,254	92,495	94,000*
x_8	-do- (new)	0	0	62,568	0	0	56,486
x_9	Ground-Ft. Collins	1,950	1,691	10,579*	11,786*	11,782*	10,693*
x_{10}	Ground-Irrigation 2 (ex)	27,823	27,379	63,000*	50,687	59,534	63,000*
x_{11}	-do- (new)	0	0	33,856	0	0	39,938
x_{12}	Ground-Greeley	0	0	7,626	8,493	8,327	7,212
x_{13}	CBT-FT_2	7,730*	7,730*	7,730*	7,730*	7,730*	7,730*
x_{14}	CBT-GT_2	14,420*	14,352	726	14,420*	14,420*	9,574
x_{15}	CBT-Irrigation 2	52,850	52,918	66,544	52,850	59,534	57,696
x_{16}	Ft. Collins reuse (FST)	0	17	2,071	0	0	1,710
x_{17}	Greeley reuse (GST)	0	68	14,848*	0	0	6,114
x_{18}	Ft. Collins-FS_2	0	0	4,018	6,089	0	4,379
x_{19}	Greeley-GS_2	4,128	3,168	0	9,248	0	1,581
x_{20}	Import-Irrigation 1	0	0	19,543	65,305	65,300	23,844
x_{21}	Import-Irrigation 2	0	0	0	0	0	0
x_{22}	Ft. Collins-FGS	0	0	0	0	6,089	0
x_{23}	Greeley-FGS	0	892	0	0	14,848	1,552
y_1	River flow, reach 1-2	10,000*	10,000*	10,000*	10,000*	10,000*	10,000*
y_2	River flow, reach 2-out	10,000*	10,000*	10,000*	10,000*	10,000*	10,000*
y_7	CBT import	75,000*	75,000*	75,000*	75,000*	75,000*	75,000*
y_8	New import	0	242	19,543	66,168	66,168	24,091
y_{18}	Ft. Collins-FS_1	12,352	12,335	13,111*	13,111*	13,111*	13,111*
y_{21}	Greeley-GS_1	5,600*	5,600*	0	5,600*	0	5,600*
y_{23}	System outflow	84,538	84,780	23,375	70,000*	70,000*	27,922
y_{24}	Net recharge	226,530	227,660	0*	149,900	137,570	0*
Total expected Cost (mill. $ per year)		6.18	6.48	21.63	42.16	40.39	23.31
Cost Standard Deviation (mill $ per year; % of expected cost		0.22 (3.6%)	0.21 (3.2%)	1.09 (5.0%)	-	-	0.61 (2.6%)

*indicates a tight constraint All flows in AF/year

3.9 Seasonal Model

While the single-period (annual) allocation model is rather general in scope and applicability the seasonal modeling approach is more problem specific. For different planning systems, and even for the same planning system under different conditions, inter-seasonal linkages vary from case to case, and consequently, so does the appropriate allocation model structure. The approach taken here for dealing with multiple seasons is one of decomposition--or multilevel optimization--in which the controlling variables are determined by the actual linkages between the seasons.

3.9.1 Case Conditions. The previously studied scenario for year 2000 (intermediate, "realistic" water demand projections, and average flow conditions) is selected as a case study for the seasonally based modeling approach. In order to determine the appropriate multilevel structure of the model to be applied, the problem solution is carried as far as possible by common sense and judgement. The following preliminary observations are immediately apparent from the supply, demand, and cost information.

1. Practically all the diversions for irrigation purposes in the Cache La Poudre River basin take place in the period April through September. Thus, the water year (October-September) can conveniently be divided into two winter periods (Period 1: October-December, and Period 2: January-March) in which no irrigation takes place, and two summer periods (Period 3: April-June, and Period 4: July-September) in which water is being applied to fields and lawns.

2. The three major potential inter-season linkages to be considered are: (1) carry-over storage from one season to another; (2) availability of Colorado-Big Thompson project water (there is only a certain amount

available for the year); and (3) availability of groundwater, considering a safe yield policy for the year.

Natural surface water supplies are more than adequate for satisfying demands in the winter periods, which implies that the more expensive CBT and groundwater sources are not required for meeting these demands. Diversion to storage in the winter periods is negligible compared to the total diversion in a year. (The winter inflow to the area represents 5 percent of the total annual inflow, and only a small fraction of it can be diverted into storage.) Consequently, the winter periods can be optimized separately, without consideration of any linkage to the summer periods.

3. Streamflows are very high in the early summer, while demands are at their maximum levels in the late summer, and consequently water is diverted into storage in period 3 (April-June) for subsequent use in period 4 (July-September). Thus carry-over storage between these periods is a linkage which must be considered.

4. A simple supply-demand consideration for the summer periods shows that new inter-basin transfers will be needed in order to satisfy consumptive use requirements. Thus it is obvious that the cheaper CBT project water supply will be fully utilized, and also that it makes no difference how the CBT water use is distributed over time, as long as the total amount available is being used. If this condition is satisfied the CBT water availability constraint does not necessitate an additional linkage between the two summer periods.

From the above considerations, the following rules are formulated:

(1) The periods 1 and 2 can be optimized separately and independently.

(2) Carry-over storage links the periods 3 and 4.

(3) Availability of CBT water does not represent a linkage between periods 3 and 4 as long as the CBT water availability constraints remain tight

(4) Availability of groundwater does not represent a linkage between periods 3 and 4 as long as the net recharge constraints remain loose.

(5) Initially the affirmative is assumed for both of the conditions (3) and (4) above--and this assumption proves to be valid in this case study.

The resulting dual-period allocation model is described in section *3.9.2*.

3.9.2 Formulation of the Dual-Period Model. The formulation of the dual-period allocation model falls in two parts: (1) formulation of the subproblems; and (2) formulation of the master problem. Only cost minimization is considered in the demonstration of the seasonal approach. The consideration of cost uncertainties is best done by comparing minimum expected cost and minimum cost variance solutions on an annual basis.

The subproblem formulation follows closely the already described formulation of the annual model, the only difference being the inclusion of the storage sector in the formulation. Diversion to and losses from storage are additional variables to be considered in period 3, while withdrawals from storage become additional variables in period 4.

The master program adjusts storage iteratively until any feasible change--increase or decrease--of the diversion to storage in period 3 results in increasing overall expected costs; at that point the optimal storage has been identified, as well as the corresponding optimal solutions for periods 3 and 4. Computational experience has shown that the overall expected cost (combined cost of periods 3 and 4) is a unimodal function of the storage use. This means that no matter what initial diversion to storage is chosen in period 3, the optimal storage will come out the same. However, the overall expected cost may be rather insensitive to storage over a wide range.

The input to the master program is an initial value of the diversion to storage in period 3, the maximum storage capacity, seepage and evaporation loss factors, and parameters specifying the storage increment in the iteration procedure as well as the termination accuracy (See Jønch-Clausen and Morel-Seytoux, 1978, for details).

3.9.3 Results from the Seasonal Model. The minimum expected cost solutions for periods 3 and 4 show that the optimal storage policy is to divert 63,000 AF to storage in the early summer, withdrawing the amount available for late summer irrigation in the upper area.

The optimal allocation patterns in both of the periods 3 and 4 are similar to that of the minimum expected cost solution obtained on an annual basis. Urban water demands are satisfied through existing water treatment facilities, supplemented by moderate groundwater use; existing sewage treatment facilities are utilized to capacity, and Greeley expands its secondary treatment capacity; agricultural demands are satisfied through maximum possible reliance on river- and groundwater, keeping new imports from other basins at a minimum (25 AF in period 3; 55,687 AF in period 4). As in the annual solution river flow and CBT water importation constraints are tight in periods 3 and 4. Further, in contrast to the annual solution, the system outflows are at their minimum levels in the two summer periods.

The significance of storage in reducing imports--and thus costs to the system--are described also. The total expected cost (sum of equivalent seasonal expected costs) associated with the optimal 63,000 AF storage use is 32 mill $/yr, compared to 50 mill $/yr at 10,000 AF and 39 mill $/yr at 150,000 AF storage use. It is obvious from Figure 3-7 that the minimum total cost coincides with minimum import from outside; in fact, the maximum diversion to storage in period 3 for which no new import from other basins is required is the desired optimum in this case. Thus, wise use of storage is a vehicle for the efficient and economic use of the available water resources in the system, and with proper operation of storage facilities millions of dollars can be saved annually, given the high cost of transbasin water transfers assumed here. Also it appears that total costs are not very sensitive to storage, once 63,000 AF or more is diverted in period 3. Thus, the optimal value of the diversion to storage is not very critical, and an indication within 5-10,000 AF is adequate. The U.S. Bureau of Reclamation (1966) found the average annual yield from storage in the Cache La Poudre River basin in the period 1947-60 was 60,000 AF, a result which confirms that the Cache La Poudre system in fact operates very efficiently. (Conversely, the result may be interpreted as an indication of the validity of the modeling assumptions made in this case study.)

An important aspect of the multi-seasonal approach should be mentioned here. In applying the multi-level optimization scheme in which individual time periods are optimized separately and coupled via a master program (controller), problems of compatibility between the optimal solutions for different seasons may arise. As an example, urban water reuse resulting in no need for expansions of secondary treatment capacity may be indicated in one season, while the optimal solution for another season calls for a new secondary sewage treatment plant and no urban water reuse. Combining these solutions would indicate that a secondary as well as a tertiary treatment facility, both of moderate capacity, should be built, instead of basing the future strategy on just one of those alternatives. Should such compatibility problems arise, the analysis must be repeated: first assuming that the tertiary treatment facility actually exists, and thus need to be considered only with operation and maintenance costs; and secondly, assuming that it is the secondary treatment plant that actually exists. Capital costs generally being significantly higher than the operation and maintenance costs, this procedure should ensure that the optimal solutions for both seasons rely on the "existing" rather than the new facility. The best of the two solutions should then be considered optimal.

The results of the seasonal optimization study are given in Table 3-3. The corresponding results from the annual model are shown for comparison. The most significant difference between the two solutions is that while no new imports from other basins are required in the annual solution, 55,700 AF must be supplied from new interbasin water transfer schemes in the seasonal solution. This demand for additional supplies in the seasonal approach is due to: (1) higher system outflow; and (2) evaporation from storage. The higher system outflow in the seasonal solution is caused by excess lower reach river flow during the winter, as explained above. By ignoring these additional losses supplies are over-estimated in the annual modeling approach. Also, by using annually based peak flow factors actual treatment plant capacities

Table 3-3. Seasonal and Annual Solutions

Variable	Transfer Sectors (from - to)	Water Transfers (acre feet)				
		Seasonal Model				Annual Model
		Winter	Period 3	Period 4	Year	
x_1	Import - FT_4	0	0	0	0	0
x_2	River - FT_1	5,590	3,110*	3,730*	12,430	9,620*
x_3	River - GT_1	4,410	0	0	4,410	780
x_4	River - Irrigation 1	0	140,850	132,740	317,060	315,260
x_5	River - FT_3	0	0	0	0	0
x_6	River - Irrigation 2	0	64,057	97,314	161,371	139,820
x_7	Ground - Irrigation 1 (ex.)	0	2,929	26,752	29,681	70,901
x_8	-do- (new)	0	0	0	0	0
x_9	Ground - Ft. Collins	0	570	800	1,370	1,950
x_{10}	Ground - Irrigation 2 (ex.)	0	6,464	1,290	7,754	27,823
x_{11}	-do- (new)	0	0	0	0	0
x_{12}	Ground - Greeley	0	260	330	590	0
x_{13}	CBT - FT_2	0	2,500*	3,000*	5,500	7,730*
x_{14}	CBT - GT_2	0	4,600*	5,600*	10,200	14,420*
x_{15}	CBT - Irrigation 2	0	7,900	51,400	59,300	53,850
x_{16}	Ft. Collins - FST	0	0	0	0	0
x_{17}	Greeley - GST	0	0	0	0	0
x_{18}	Ft. Collins - FS_2	0	0	0	0	0
x_{19}	Greeley - GS_2	609	1,176	1,463	3,248	4,128
x_{20}	Import - Irrigation 1	0	25	55,687	55,712	0
x_{21}	Import - Irrigation 2	0	0	0	0	0
x_{22}	Ft. Collins - FGS	0	0	0	0	0
x_{23}	Greeley - FGS	0	0	0	0	0
-	River - Storage	0	63,000	0	63,000	-
-	Storage - Irrigation 1	0	0	43,470	43,470	-
y_1	River flow, reach 1-2	≈5,000	2,500*	2,500*	≈10,000*	10,000*
y_2	River flow, reach 2-out	54,111	2,500*	2,500*	59,111	10,000*
y_7	CBT import	0	15,000*	60,000*	75,000*	75,000*
y_8	New import	0	25(≈0)	55,687	55,712	0
y_{18}	Ft. Collins - FS_1	5,031	3,275	3,991*	12,297	12,352
y_{21}	Greeley - GS_1	3,360*	1,400*	1,680*	6,440*	5,600*
y_{23}	System outflow	58,300	25,000*	50,000*	133,300	84,538

*indicates a tight constraint.
All flows are in AF.
(Rounding errors cause minor discrepancies between solutions).

are underestimated in the annual model. The seasonal peak factors reflect the ratio between the actual peak flow and average flow in each season, and in the computation of effluent peak factors the seasonal variation of municipal losses (evapotranspiration and seepage) is considered. The annual peak flow factors exaggerate the actual flow variation by ignoring the fact that the annual peak occurs in the summer when the average flow is high.

In conclusion, the advantages of the seasonally based approach over the simpler annual model can be stated as follows:

(1) Only in the seasonal approach are storage operation criteria obtained.

(2) Only the seasonal approach considers the discrepancy between the occurrence of supply and demand in time.

(3) Seasonal peak flow factors are more realistic than annual peak flow factors, the latter being too conservative.

(4) Only the seasonal approach considers the fact that the most economic mix of treatment facility utilization may vary over the year.

(5) Seasonally based low flow criteria have more meaning than an annual minimum flow rate.

Although the seasonally based approach yields better and more complete results than does the annually based one, it also requires a lot more computer time and efforts from the planner. Consequently, the two approaches should not be considered mutually exclusive, but rather highly complementary. Valuable insight into the weaknesses and pitfalls in annually based modelling can be gained from the seasonal approach, and lead to improvements in the cheaper and easier annual approach.

Further, within the planners time and money constraints, a host of different conditions and assumptions about the system may be explored through annually based modeling before arriving at the final formulation of a seasonal model.

IV. CONCLUSIONS

Two system water planning tools: the input-output water balance model, and a quadratic programming optimization model have been developed from this research. Further, both have been demonstrated for water planning in the South Platte River basin and in the Cache La Poudre River basin, respectively. Both models delineate the role of water reuse in regional water planning.

The input-output model is a descriptive model of a whole system. Its strength lies in its display of system water transactions. Thus it permits one to inject subjective knowledge about aspects of the system, facilitating choices based upon normative value positions (e.g., those which are politically oriented).

The quadratic programming optimization model facilitates evaluation of alternative water system configurations through the computer searching process for some optimum as prescribed by an objective function, e.g., least cost. The model accommodates nonlinear cost functions, thus permitting a more realistic optimum.

The models illustrate the idea that water reuse has a system context. In 1970 the South Platte River basin reuse factor (the ratio of diversions for beneficial use to the native water supply plus imports) was 2.03. It could increase to 2.48 by 2020 under average water conditions and 3.52 under drought conditions. (Note: the significant figures used do not imply accuracy; they are used to facilitate tracing calculations.) Planned water reuse will increase either by policy decision, in the case of a tight water rights situation such as Denver, or by economic considerations. Using the latter criteria, planned water reuse will be implemented only if it is included in the cheapest system configuration.

This turns out to be the case by 2020 for the Cache La Poudre system for the drought assumption.

Thus with the models provided, water reuse can be evaluated in its systems context. The models can be used either independently or in a complimentary fashion.

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APPENDICES

APPENDIX A

CASE STUDY--THE SOUTH PLATTE BASIN

The models described herein--the input-output water balance model and the quadratic programming optimization model--were developed from the empirical context of the South Platte River basin and the Cache La Poudre River basin. Input-output models were constructed for the South Platte River basin for 1970, 1980, 2000, and 2020, and for the Cache La Poudre River basin for 1970. The optimization model was constructed about conditions in the Cache La Poudre River basin. This chapter summarizes the water context of the South Platte River basin. The Cache La Poudre River basin is a major drainage within the latter, and is discussed only briefly.

A.1 Water Resources Development

Water resources development in the South Platte River basin has proceeded since the first irrigation diversion in 1856 in an incremental fashion, project by project. Today the water transfers within the basin number in the thousands, forming a complex interdependent network of water use activities. Development of new supplies within the basin is at or near the hydrologic limit, while proposed projects to import more water from the Colorado basin are shrouded in controversy, suggesting that perhaps there is an upper political limit on such projects. At the same time, the population of the South Platte basin, principally the Front Range urban corridor, is increasing at a high rate, with commensurate demands for water.

A.2 Water Supply Alternatives

The stresses of the highly competitive water situation are bringing about new social, economic, ecological, and hydrologic equilibriums, as adjustments are made to accommodate the increasing demands for water from different sectors of water use. These adjustments may range from yields to environmental pressures with respect to certain projects, to changes in farm market structures due to purchases of agricultural water rights by urban interests. However, many water supply alternatives are possible to accommodate future demands by the various use sectors. These alternatives may be grouped into the broad categories of: 1) increasing supplies; 2) decreasing demands; and 3) reallocation of existing supplies. Table A-1 expands on these categories showing some of the types of alternatives and examples. As noted, water reuse is one of the alternatives for increasing supply. The main point is that it must be considered as one alternative.

Table A-1. Water Supply Alternatives, South Platte Basin

Category	Alternative	Examples
Increase Supply	Develop new projects within South Platte basin	Narrows Two Forks
	Develop new projects to import water from Colorado River basin	Windy Gap Eagle-Piney Eagle-Colorado
	Cloud seeding	1977 Colorado Program
	Water reuse	Denver's successive use program Exchanges between agriculture and urban uses
Decrease Demands	Domestic water conservation programs	Metering, pricing, water saving plumbing
	Industrial water conservation	Process modifications Internal reuse

Table A-1. Continued

Category	Alternative	Examples
Decrease demands	Agricultural water conservation practices	Scientific irrigation Center pivot sprinkler technology Trickle irrigation technology Conversion of direct flow rights to storage rights
Reallocation	Transfers from agriculture to urban Transfer from agriculture to energy Symbiosis between agriculture and other use sectors	Continue free market purchases

A.3 Geography

A.3.1 *Area*--The South Platte River basin has an area of 24,030 square miles; 19,020 square miles are contained in Colorado, about 2,000 square miles are in Wyoming, and about 3,010 square miles are in Nebraska.

A.3.2 *Relation to Missouri Basin*--Figure A-1 shows the South Platte River basin in relation to its proximity to the Missouri River basin. The South Platte basin has 4.6 percent of the land area but it contributes only 0.61 percent of the flow to the larger system.

A.3.3 *Physiography*--The basin is dominated by the Front Range mountains which are a part of the Colorado Rockies. One of the 19,022 square miles of the basin in Colorado, 23 percent is above 8,700 feet in elevation; 54 percent is above 6,000 feet. Several peaks rise to 14,000 feet. Figure A-2 is a satellite photograph showing the land

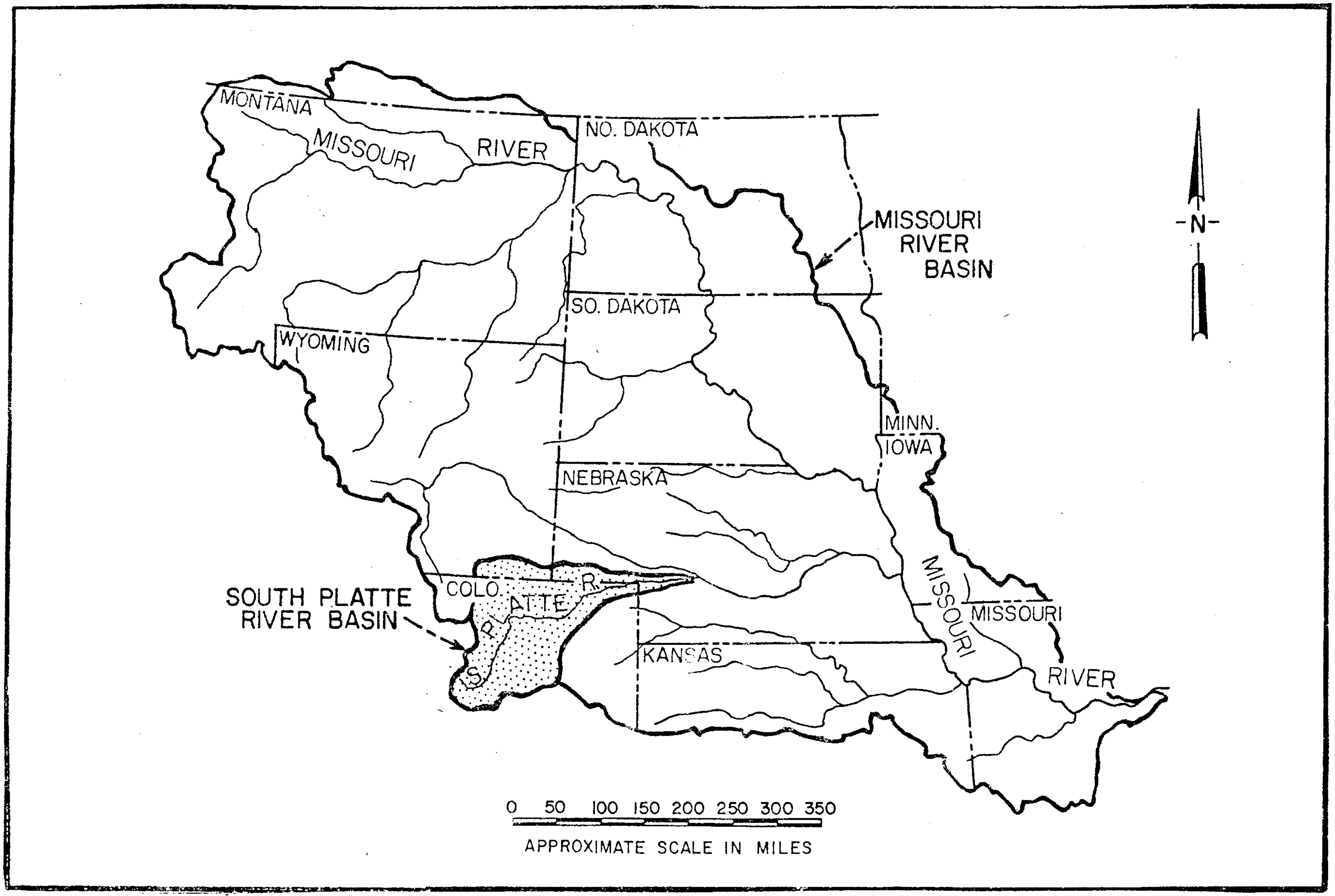


Figure A-1. South Platte River Basin Location Map (Bureau of Reclamation, 1959).

Figure A-2. Satellite Photo of Portion of South Platte Basin Showing Front Range Mountains, Lakes and Reservoirs, Drainage Patterns, Irrigated Land, and Major Cities (NASA Satellite Photo) features of the Front Range vicinity of the basin. The high snow covered peaks are evident. Also visible are many lakes, the major cities, irrigated lands, and drainage patterns. The eastern portion of the basin is a part of the great plains.

The South Platte River system has been likened to a giant fan. Figure A-3 shows the river system, and the major cities. Each tributary is identified also. The plains tributaries are mostly intermittent streams carrying little flow except that of occasional cloudbursts. Figure A-4 shows the major hydrologic sub-basins of the South Platte basin.

For convenience in aggragating, the basin is divided into three physiographic-consumptive use zones: mountains, transition and plains. Figure A-5 shows these divisions.

A.3.4 *Administrative Units*--The administrative units in the South Platte River basin inlcude: state, county, Water Commissioner's districts, city, Northern Colorado Water Conservancy District, municipal water districts, sanitation districts, river basin, regional councils of governments, a national park, national forests, and possibly others.

A.3.5 *Land Classification*--The categories of land use are listed in Table 2-2 as irrigated cropland, non-irrigated cropland, rangeland, woodland, urban areas, sub-divisions under development, and water areas. Quantitative data by county are given in Table A-2, where available. The county lines are shown in Figure A-6.

The amount of irrigated land within the basin is of particular interest. Table A-3 shows the breakdown of irrigated land within the Colorado portion of the basin by county. These data were measured

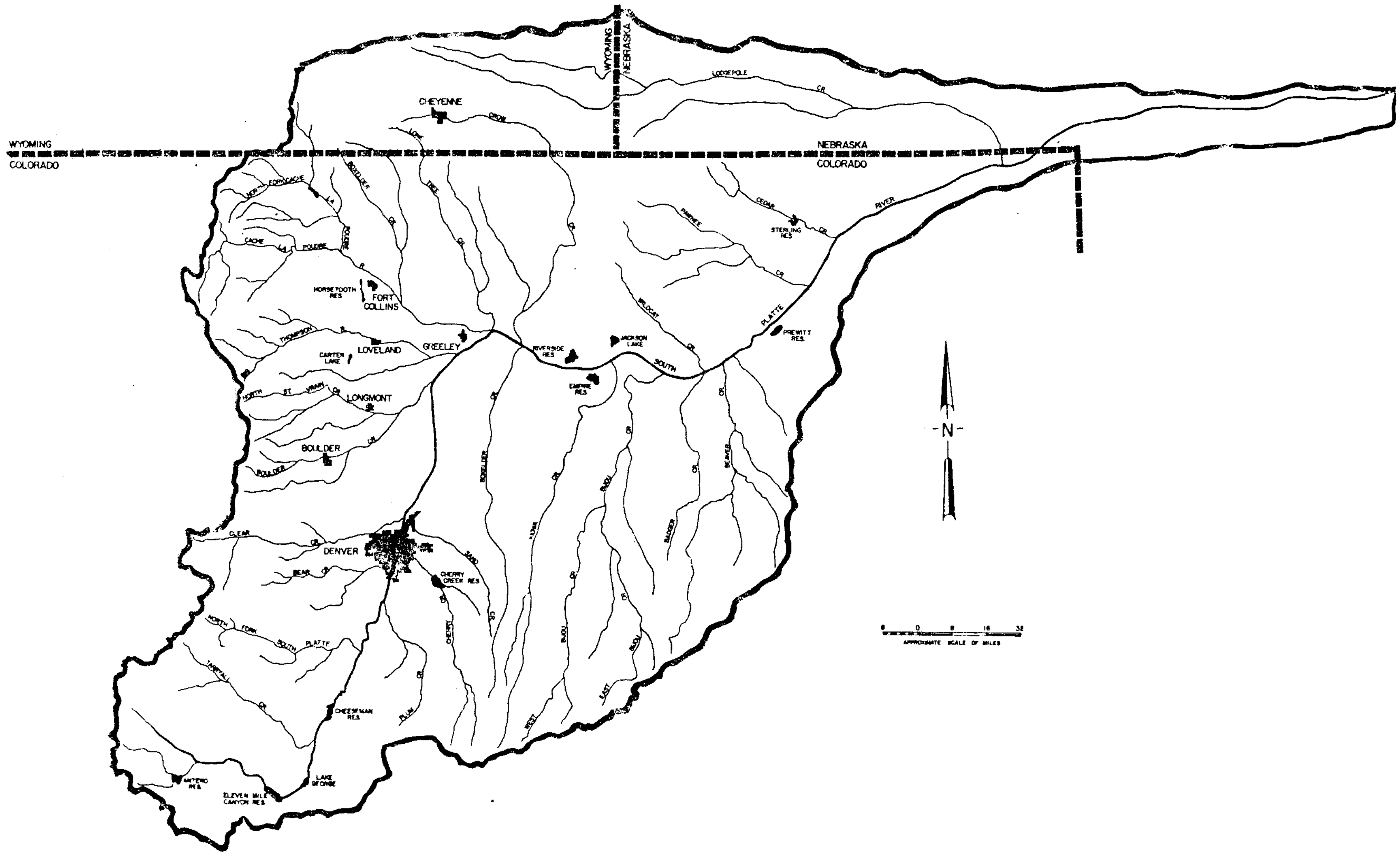


Figure A-3. The South Platte River and its Tributaries

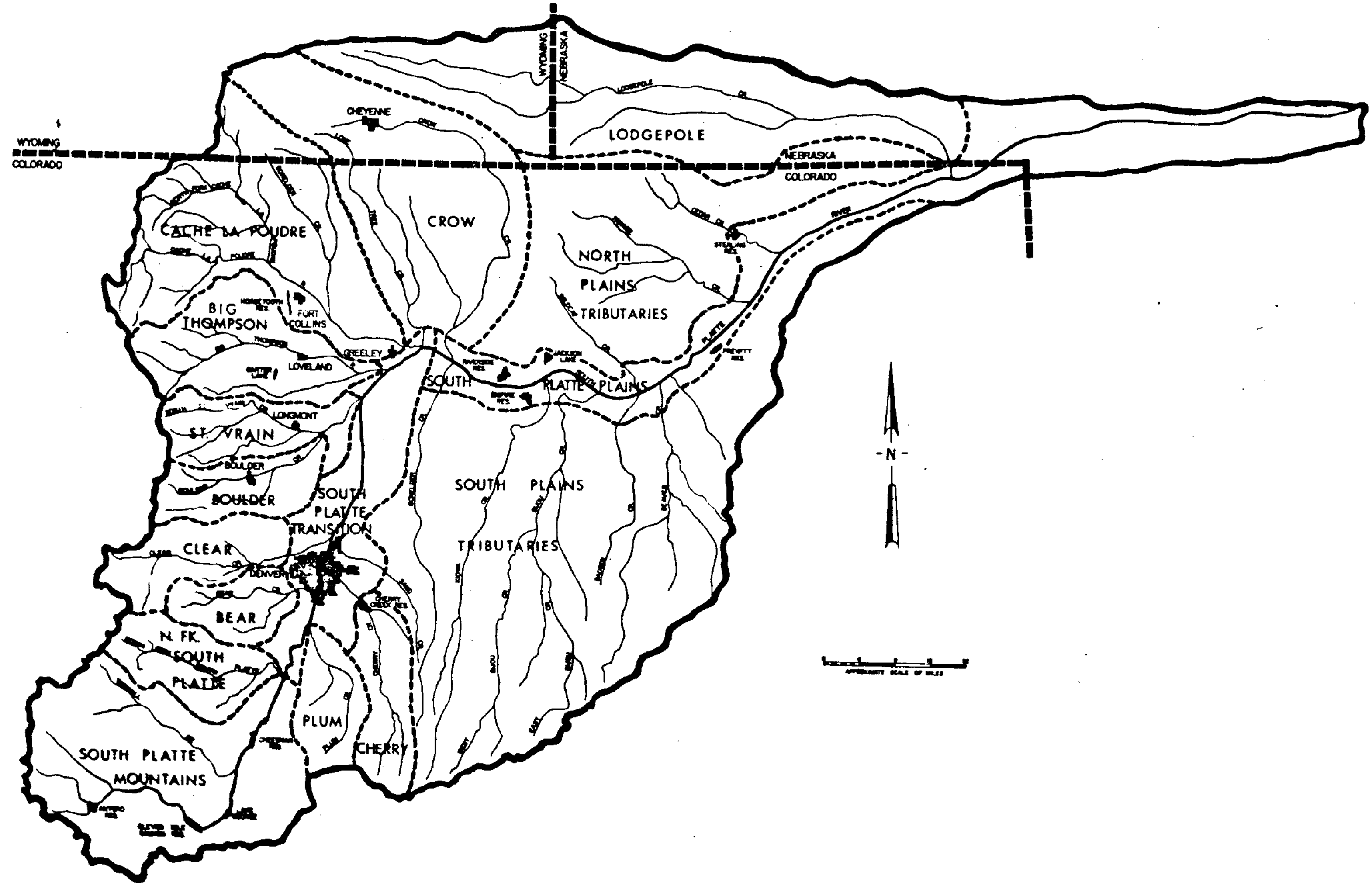


Figure A-4. Sub-Basins of the South Platte River Basin

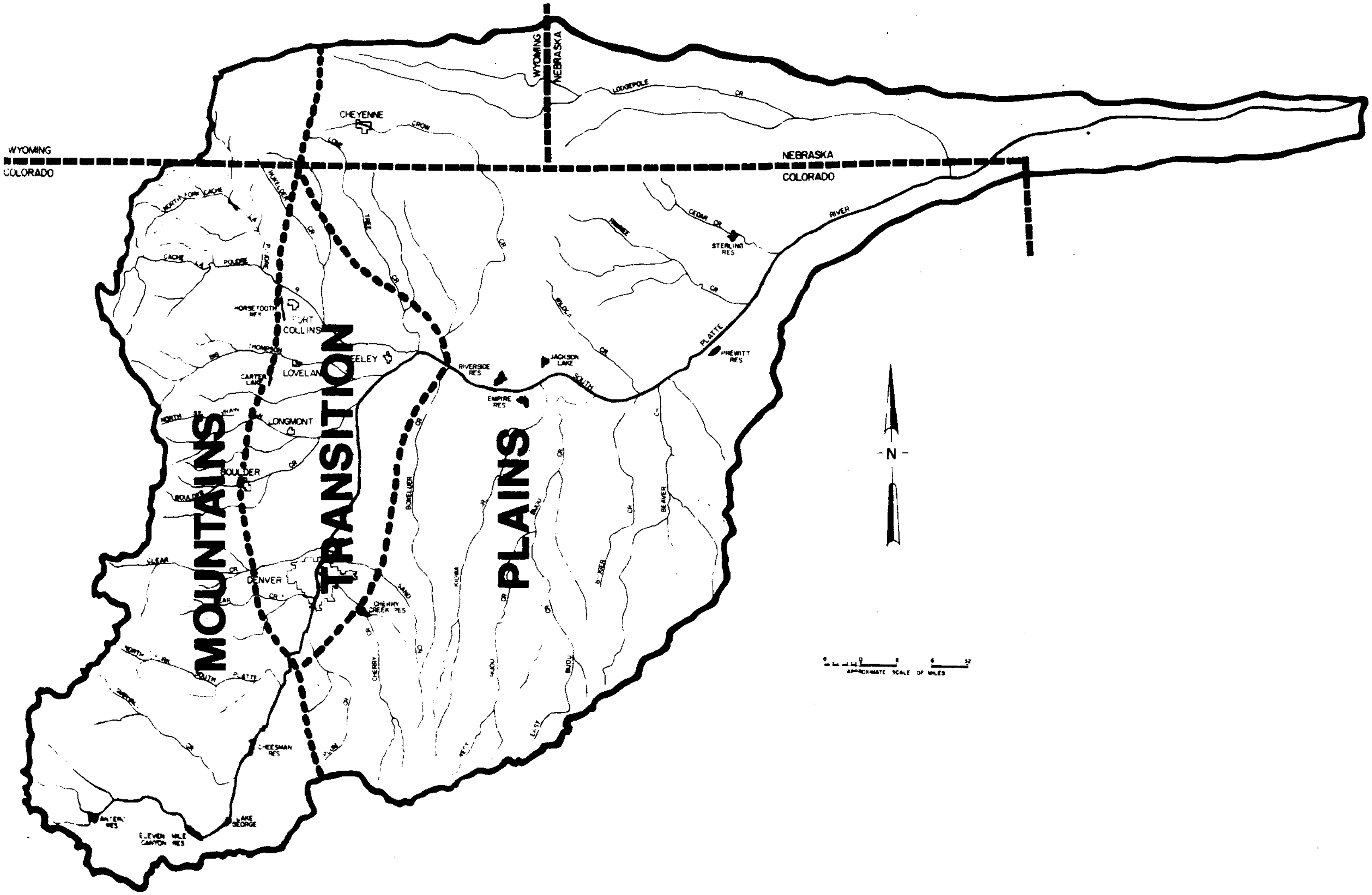


Figure A-5. Three Physiographic Zones of the South Platte River Basin

Table A-2. Land Use in South Platte Basin by County by Square Miles (Abstracted from Toups-ECI, 1974, Table 5-4, Using Data from Colorado State Land Use Commission and Soil Conservation Service)

Zone	County	Irrig. Cropland	Non Irr. Cropland	Range Land	Wood Land	Urban Areas	Sub-Div. Under Dev.	Water Areas	Other	Total
Mountain	Boulder	152.22[1]								758.00
	Clear Creek	-0[1]		68.65	303.90	4.50	10.00	3.65		394.70
	Gilpin	-0[1]		15.53	111.22	1.76	10.52	0.12	8.85	148.00
	Larimer	231.00	83.00	596.00	1332.40	23.90	29.70	24.70		2320.00
	Park	32.30		323.70	1499.20	1.60	25.10	18.30		1900.20
	Teller	-0[1]	8.40	46.60	179.10	6.20	0.70			555.00
Front Range	Adams	107.01[1]								1251.00
	Arapahoe	7.22[1]								820.00
	Denver	-0[1]								67.00
	Douglas	6.90	58.50	335.00	309.35	8.05	118.35	6.55		843.00
	El Paso	-0[1]		80.77	44.95		5.00			130.72
	Jefferson	17.27[1]								791.00
	Weld	640.00	780.00	2464.00	16.20	29.20	14.80	30.00	26.80	4002.00
Plains	Elbert	4.05	184.30	928.30	23.30	0.45	16.55			1156.95
	Logan	191.50	359.50	886.50		17.20		10.10		1473.00
	Morgan	243.80	196.40	788.80	16.30	8.80		16.30	7.30	1278.00
	Perkins									
	Sedgwich	45.40	43.10	156.60		2.00		10.90		258.00
	Washington	20.60	312.30	621.40		0.20		5.30		959.80
Nebraska	Cheyenne									1186.00
	Deuel									435.00
	Kieth									1072.00
	Kimball									953.00
	Lincoln									
Wyoming	Laramie									2703.00
	Albany									44.00
	TOTALS									2,4030.00[2]

[1] Measured from SCS maps.

[2] South Platte basin land area.

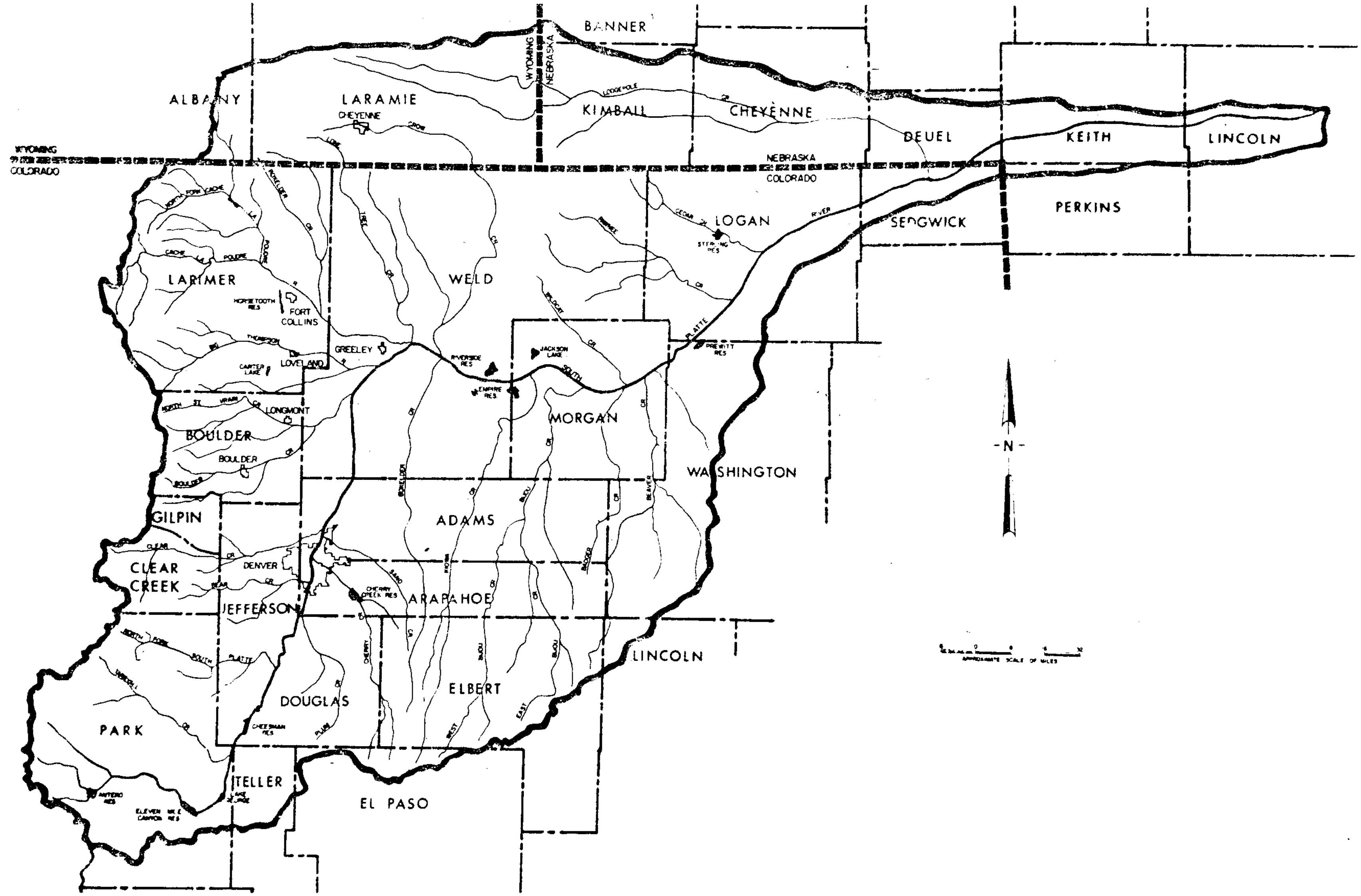


Figure A-6. Counties of the South Platte River Basin from maps of the Colorado Land Use Commission and the Soil Conservation Service; they are believed to be accurate. Table A-3 gives a total of 1,273,954 acres (which in round figures will be called 1,300,000 acres). Crops grown in the basin include hay, winter wheat, corn, barley, sorghum, dry beans, sugar beets, oats, alfalfa hay, potatoes, and spring wheat.

Table A-3. Irrigated Acreage by Counties within the South Platte River Basin in Colorado (Areas were Measured from Land Use Maps of the Colorado Land Use Commission and the U.S. Soil Conservation Service)

County	Date of Map	Area of Irrigated Land (Acres)
Adams	8/73	68,488
Arapahoe	7/73	4,621
Boulder	7/73	97,420
Clear Creek	8/73	0
Denver	--	N/A
Douglas	8/73	4,580
Elbert	8/72	2,280[1/]
El Paso	11/73	0[1/]
Gilpin	7/73	0
Jefferson	8/73	11,054
Larimer	11/73	171,061[1/]
Lincoln	9/72	0[1/]
Logan	8/72	117,920[1/]
Morgan	9/72	171,280
Park	8/73	72,520[1/]
Sedgwick	9/72	25,980[1/]
Teller	8/73	0[1/]
Washington	9/72	12,320[1/]
Weld	9/73	513,430
Counties Total		
Basin Total		1,273,954

[1/] County not entirely within the basin, value represents county's irrigated acreage within the basin.

A.3.6 *Activities*--The land categorization is also indicative of the variety of economic and leisure activities within the basin. The irrigated agriculture dates from the gold rush days and constitutes an important aspect of Colorado's economy. Ranching within the basin, utilizing rangeland, is historic. Non-irrigated farmland is extensive also. In the mountains, mining and recreation are particularly important. Colorado is noted for its scenic mountains, which is a strong attraction not only for tourists but for new residents.

Most of the urban growth is occurring along the Front Range urban corridor. While heavy industry is not extensive, some major companies have located in the area for manufacturing while others have located major headquarters within the area.

A.3.7 *Climate*--The average October-April precipitation in the basin varies from 3.5 inches in the lower plains to 22.5 inches in the mountains; the latter is mostly snowfall. The average May-September precipitation varies from 6.5 inches in the lower plains to 15.0 inches in the mountains. Because of the dry low relative humidity climate, much of the precipitation evaporates with little effect on root zone soil moisture levels. Average annual precipitation for the basin excluding that portion in Nebraska was measured from published isohyetal maps to be 16,978,300 acre-feet, while 14,912,500 acre-feet was lost back to the atmosphere by evaporation.

A.3.8 *Hydrology*--The natural streamflow in the basin is mostly snowmelt from the mountain watershed. About 70 to 80 percent of the total annual stream runoff occurs seasonally, during the period April-July. In its pre-development state, the South Platte system would carry most of the flow in the spring flood to the Missouri River. Also, the plains South Platte River was an ephemeral stream. The late summer-fall-winter low flows from the tributaries would sink into the sands of the main stem.

Most of the tributaries retain their natural hdyrologic character in their mountain reaches. However, as these tributaries emerge onto the plains, i.e., in the transition zone, numerous diversions begin. These diversions continue to the main stem and along the main stem to Nebraska. Continuous return flows and point source wastewater discharges also characterize the transition and plains zones of these streams. In fact, the continued diversions are sustained by the return flows. This system of water development and use emerged largely during the period 1870 to about 1924 with continued development to the present. The system thus includes numerous diversions, storage reservoirs and return flows. The plains South Platte is no longer an ephemeral stream due to these changes. The groundwater levels of the plains South Platte have been built up to such levels that it is now an "effluent stream" (i.e., it gains water from seepage into the stream). The stream and the adjacent aquifer are actually considered as one entity. Several thousand wells in the adjacent aquifer complicate the administration of water rights for the system.

Figure A-7 shows the monthly distribution of flows at the South Platte gaging station on the mainstem in the South Platte canyon. These annual hydrographs show: 1) the seasonal variation in discharge; and 2) the large range in annual runoff. Figure A-8 shows the variation in average annual discharge along the main stem of the transition and plains South Platte. The seasonal effects of tributary

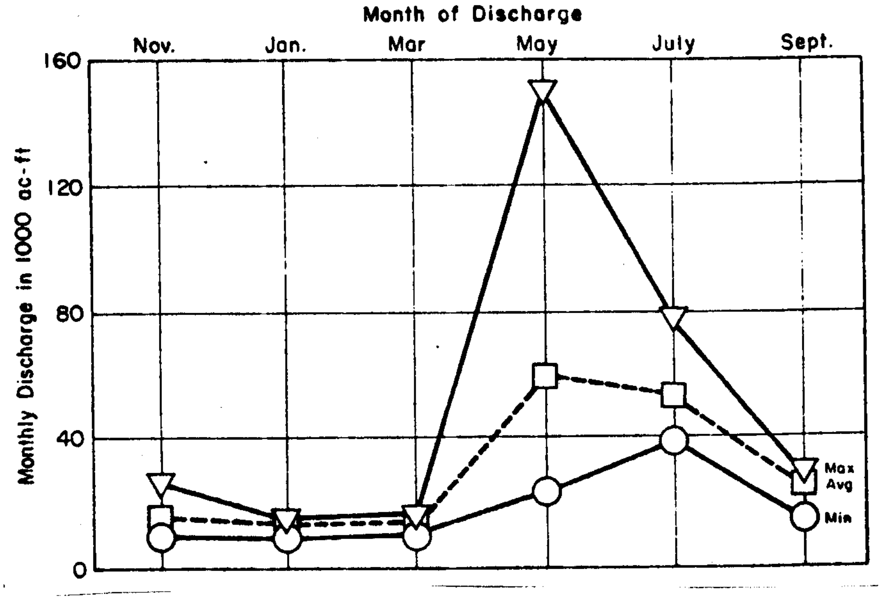


Figure A-7. Distribution of average discharges for period 1968-72, South Platte River at the South Platte Gaging Station (RK563.5). The figure also shows the range of the monthly discharges during the same period (Data from U.S.G.S., Surface Water Records).

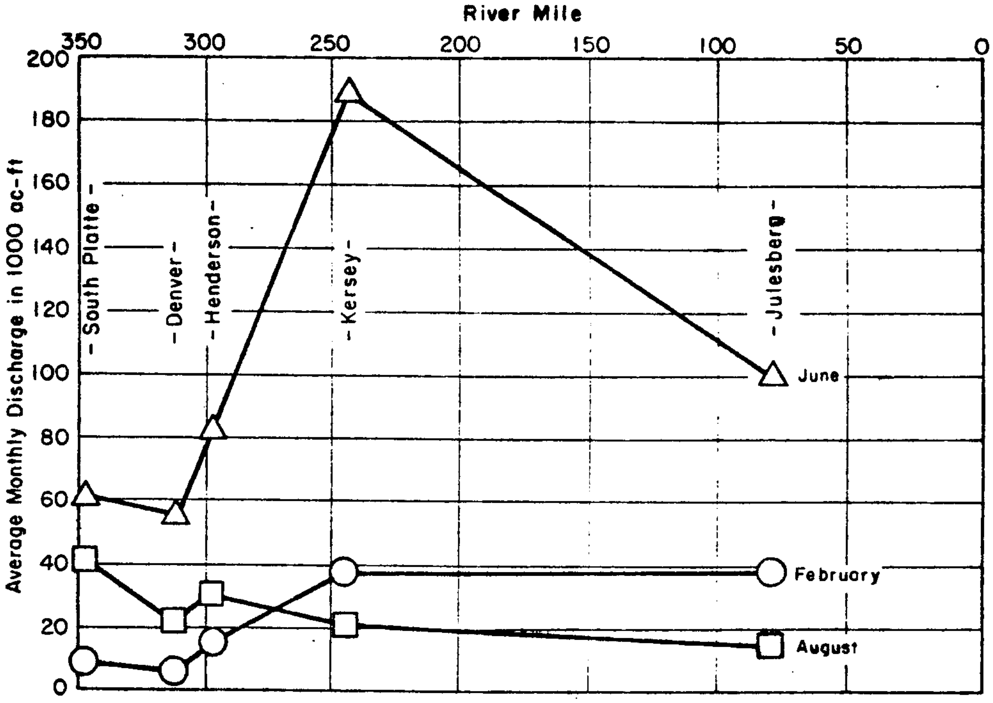


Figure A-8. Average annual discharge for South Platte River Stations, 1968-72 (U.S.G.S., Water Supply Papers for Colorado).

inflows, diversions and return flows are reflected in the discharge profiles for the different months.

A.3.9 *Population*--Most of the population of the South Platte basin is, and always has been, concentrated along the Front Range urban corridor from Denver to Cheyenne; over two-thirds of this population is concentrated in the Denver metropolitan area.

Population data for counties wholly and partly within the South Platte basin are given in Table A-4. As noted, some of the counties for which population data are given have a portion of their land areas outside the basin. Since most of these counties have low population, the error introduced by including them in the count is not felt to be substantial. The high growth rate within the basin and particularly in Denver and other Front Range cities is particularly noticeable. This high rate of growth has been the rule since the 1858 gold rush. The population trend for the basin for the period 1890-1950 is seen in the following tabulation:

Date	Population
1890	234,719
1900	275,696
1910	427,978
1920	521,752
1930	604,571
1940	657,207
1950	847,905

A.3.10 *Projected Population*--Population projections used in this study were furnished by the Corps of Engineers, Omaha, who utilized a report, "Colorado Population Projections 1970-2000," Colorado State Division of Planning, April 1976. The report developed high series and low series projections to the year 2000.

Table A-4. Population Data for Counties of the South Platte Basin 1950 to 1970 (Source: U.S. Department of Commerce, Bureau of Census)

County	1950 Population	1960 Population	1970 Population	Change (%) 1960-1970	Avg. Annual Growth Rate	Major City	1970 Population
COLORADO							
Adams	40,234	120,300	185,800	54.4	4.4	Aurora (part)	27,200
						Northglenn	27,900
Araphaoe	52,125	113,400	162,100	42.9	4.6	Aurora (part)	47,800
Boulder	48,296	74,300	131,900	77.5	5.9	Boulder	66,900
Clear Creek	3,289	2,800	4,800	71.4	5.5	Idaho Springs	2,000
Denver	415,786	493,900	514,700	4.2	3.5	Denver	514,700
Douglas	3,507	4,800	8,400	75.0	5.7	Castle Rock	1,500
Elbert	4,477	3,700	3,900	5.4	4.4	Elizabeth	500
Gilpin	850	700	1,300	85.7	6.3	Central City	200
						Black Hawk	200
Jefferson	55,687	127,500	233,000	82.7	6.2	Lakewood	92,800
Larimer	43,555	52,300	89,900	68.7	5.3	Fort Collins	43,300
Logan	17,187	20,300	18,900	-6.9	-0.7	Sterling	10,600
Morgan	18,074	21,200	20,100	-5.2	-0.5	Fort Morgan	7,600
Park	1,870	1,800	2,200	22.2	2.0	Fairplay	400
Sedgwick	5,095	4,200	3,400	-19.0	-2.0	Julesburg	1,600
Weld	67,504	72,300	89,300	23.5	2.1	Greeley	38,900
Washington	7,520	6,600	5,600	-15.2	-1.6	Akron	1,800
NEBRASKA							
Cheyenne	12,081	14,828	10,778	-27.3	-3.1	Sidney	6,411
Deuel	3,300	3,125	2,717	-13.0	-1.4		
Kimball	4,283	7,975	6,223	-21.9	-2.4	Kimball	3,484
Kieth	7,449						
WYOMING							
Laramie	47,662	60,100	56,400	-6.1	-0.6	Cheyenne	40,900
Albany	19,055						
TOTAL	859,861	1,207,128	1,551,418	28.5	2.5		

Figure A-9 shows the 1950-1970 historical trend in basin population. The population trend of the Denver metropolitan area is shown for comparison. The high and low series projections for the basin are the main interest, they're seen as continuations from 1970. The high series projection shows a basin population of nearly 4 million by 2020.

A.4 Legal-Administrative Framework

The legal framework governing water allocation and use within the South Platte River basin and the aggregate amount of water available for use consists of Colorado water law and several interstate agreements. This system is administered by a variety of water agencies.

A.4.1 *Water Rights*--Colorado water law is founded on the appropriation doctrine. Some key points relevant to the present study are: 1) a water right can be sold separate from the land, 2) an appropriator can change the place of use of water providing there is no damage to other users, 3) a city may not capture its own wastewater for further use except by another appropriation, 4) the right of reuse is attached to foreign water from the Colorado River (except for water from the Colorado Big Thompson Project), 5) an appropriator can divert water from one watershed to another for beneficial use.

A.4.2 *Water Administration*--The water rights system is administered by the Office of the State Engineer. Within the South Platte River basin about 6,200 absolute and conditional decrees exist. The aggregate water requirement if all these rights were filled to the upper limit would be about 30 million acre-feet annually. There are about 175 mutual irrigation companies, 7 or 8 irrigation districts, 5 water conservancy districts, and numerous municipal water districts

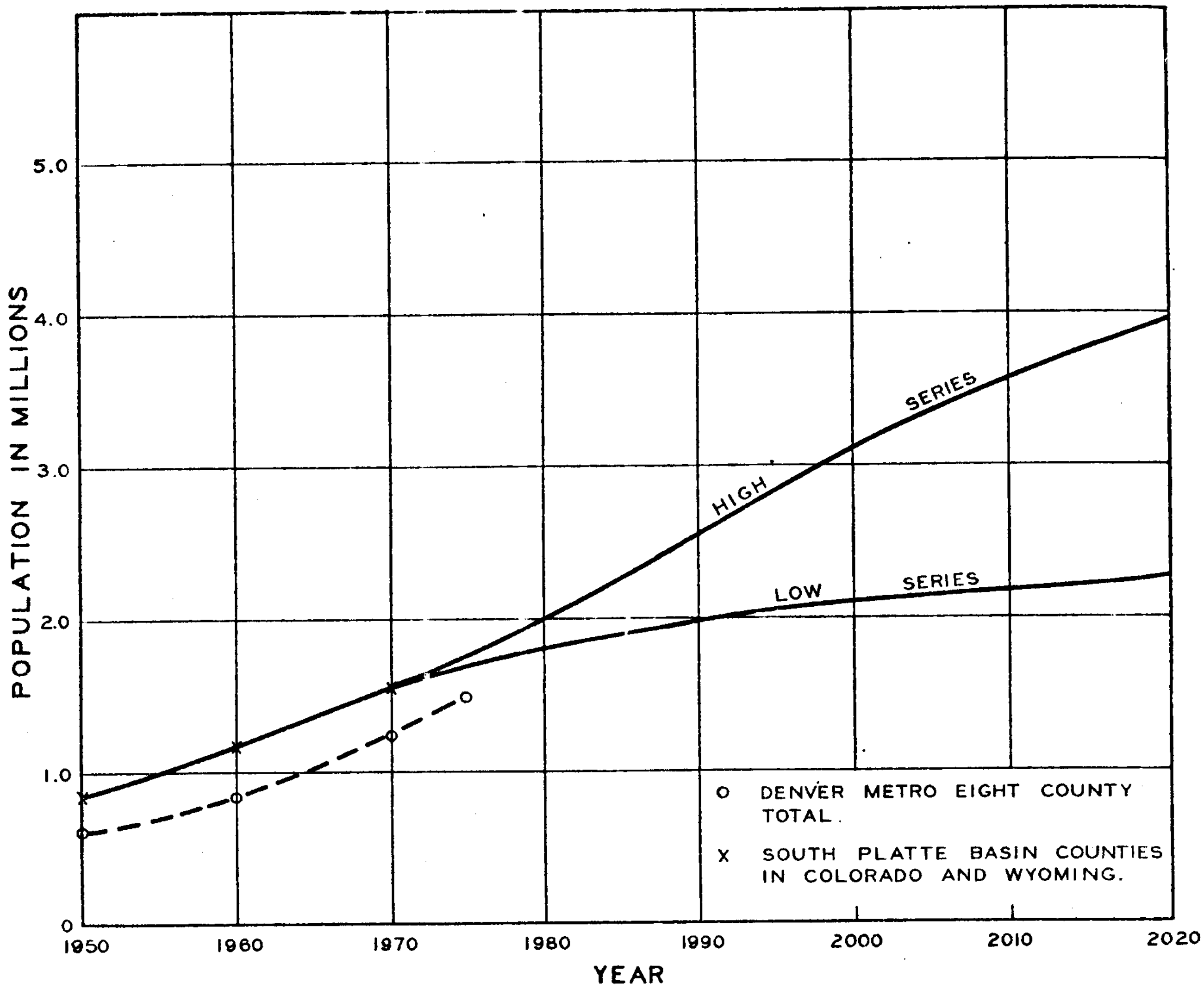


Figure A-9. Population Growth, South Platte Basin Counties to 1970 with Projections to 2020 (1950-1970, U.S. Bureau of Census; Colorado Population Projections, 1970-2020, Colorado State Division of Planning, April 1976) and sanitation districts. Around Denver alone there are 209 water organizations of various sorts.

A.4.3 *Interstate Compacts*--The first interstate water compact was the 1922 Colorado River Compact. It came about as a result of the contemplated acquisition of Colorado River water by Southern California cities and irrigation districts. Upper basin states feared that if the doctrine of prior appropriation applied, the fast developing Southern California region would preempt the rights of the upper basin states to Colorado River water (i.e., when their development was sufficient to require the water, it would not be available). The Colorado River Compact was hammered out then in exchange for the political support of the basin states for the Boulder Canyon Project Act, which passed Congress in 1928. This compact and the 1948 Upper Colorado River Compact, and the 1944 Mexican Treaty, has permitted the upper basin states to develop at their own pace, with the certainty that the allotted amount of water can be used. In addition, their obligations to other users are stated. The Colorado River compacts and treaties are the basis for whole river basin programs (i.e., the 1928 Boulder Canyon Project Act, the 1958 Upper Colorado River Basin Project Act, the 1968 Central Arizona Project Act, etc.). Glen Canyon Dam for example, was built to permit the upper basin states to fulfill their compact obligation to deliver 75 million acre-feet of flow past Lee Ferry, Arizona, in any ten-year period.

The South Platte River Compact between Colorado and Nebraska was signed in 1923. It provides that between April 1 and October 15 of each year, Colorado will not permit any diversions from the Lower Section of the river, except those having priority dates prior to 14 June 1897, to an extent that will diminish the flow of the river at the Interstate Station, below a mean flow of 120 cfs. This flow amounts to 47,127 acre-feet per year.

A.4.4 *Litigations*--Litigations are another form of interstate document. The Laramie River Decree of 1957 and the 1945 North Platte Decree deal specifically with the question of transbasin diversions to the South Platte. Article II(a) of the former limits export from the Laramie River Basin to points in Colorado to 19,875 acre-feet of water in any calendar year. The North Platte Decree (Nebraska vs. Wyoming) limits the export of water from Jackson County to 60,000 acre-feet in any ten-year period.

A.5 Water Supplies

The additional water supplies available to users in the South Platte River basin must be ascertained in terms of an understanding of the systems involved, and a variety of influencing factors. First, the water supplies of users in the South Platte River basin are derived from several sources. These include the South Platte River basin, the Colorado River basin, and the North Platte River basin. Second, the amount of water available to the State of Colorado from each of these basins is stipulated by interstate compacts and litigation. Third, the allocation of this water to each of the many users in Colorado depends upon the priority date of the water right. This is established by the activities in developing the right; but it is legally confirmed only after adjudication. Fourth, political factors are becoming increasingly important in determining if and when new projects are built. This is especially true if there is any degree of federal involvement. Fifth, one must understand the hydrology of the mountain streams which supply most of the water. About seventy percent of the annual flow occurs during the April-July period. The amount of new water available depends upon the recurrence interval of any unappropriated excess floodwaters. At the present state of development this recurrence interval is likely to be a matter of several years for most tributaries of the South Platte River. Thus a study of both the hydrology and the existing exercise of water rights entitlements is necessary to determine the availability of new water. And finally, planned reuse by a city is possible only to the extent that the city has foreign water to which is attached the right of reuse.

Therefore, an appraisal of the potentials for the development of additional water supplies for users in the South Platte River basin is more involved than simply a presentation of numerical data. This section summarizes some of the important data and information relative to the availability of "new" water supplies for the basin. While this is done in a more simplistic manner than is actually the case, it serves to provide a "picture".

A.5.1 *Native Water Supplies*--Table 2-5 gives an overview of these three concerns--supply, use, and availability--by sub-basin in the South Platte River basin. It will be referred to throughout subsequent discussions on these topics.

Surface Water Runoff. The annual amount of native surface water supply is highly variable. The surface water runoff data in Table A-5 are an index of this variability. While the average annual runoff was 1,204,550 acre-feet for the period examined, the amount was

Table A-5. Water Supply Data for Sub-Basins of the South Platte River Basin

Subbasin	Drainage[1] Area (square miles)	Surface Water Runoff[1] (acre feet per year)			Total Number of Decreed Water Rights		Major Decreed Water Rights[2]					Major Storage Projects Proposed in Recent Years [3]				
							Direct Flow Rights			Storage Rights						
		Long Term[4] Average	Water Year[4] 1970	1953-56[4] Four Year Drought	Direct Flow	Storage	Number	Flow (cfs)	Volume Equivalent (acre feet/yr)	Number of Reservoirs	Decree Volume (acre feet/yr)	Project	Sponsor	Reservoir Size (acre feet)	Project Yield (acre feet)	Status
South Platte River-Mountains	2,142	208,500	402,200	119,250	625	40	93	6,850	4,959,400	44	393,000	Spinney Mountain	Aurora	48,000	1,410 to 3,723	Delayed due to funding problems
North Fork-South Platte River	479	112,400	198,680	64,290	240	45						Two Forks	USBR	975,000	20,000	Delayed due to political controversy
Plum Creek	302	22,780	31,440	7,140	190	55	77	403	291,772	13	16,800					
Cherry Creek	385	11,080	6,810	4,610												
Bear Creek	214	46,200	76,170	20,280	810	60	21	1,167	844,908	16	31,000					
Clear Creek	448	171,960	225,360	112,440	335	200	72	4,950	3,583,800	47	113,000					
Boulder Creek	439	118,800	162,900	85,870	320	155	90	5,500	3,982,000	31	49,300	Gross Res. Expansion Dark Reservoir Bradley Reservoir Coffin Top Geer Canyon	Denver Boulder Boulder Irrig. Dist. Irrig. Dist.	 84,000 90,000	N.A. N.A. N.A. 3,200-8,000 N.A.	Low priority Negotiations in process for land Negotiations in process for land Economically not feasible until later Studios are in process
Saint Vrain Creek	537	117,600	131,590	71,010	310	190	90	3,040	2,200,960	55	42,200					
Big Thompson River	828	148,100	176,900	100,290	265	80	75	2,730	1,976,520	14	101,000					
Cache La Poudre River	1,877	234,800	321,220	158,060	490	210	70	6,200	4,488,800	75	200,000	Idylwilde Livermore	USBR USBR	148,500 394,500	24,500	Investigations terminated in 1965 Investigations terminated in 1965
South Platte River-Transition	1,447	12,330	12,130	5,670	245	65	Included with South Platte-Mountains and North Fork									
Crow Creek	1,824	N.A.	57,230	26,020	644	170	Included with South Platte River-Plains									
North Plains Tributaries	2,400	N.A.	1,090	1,090			Included with South Platte River-Plains									
Lodge Pole Creek	1,946	N.A.	48,960	34,150			189	367	265,708	14	23,900					
South Plains Tributaries	4,276	N.A.	50,000	31,090			Included with South Platte River-Plains									
South Platte River Plains	1,956	0	0	0			436	10,668	7,723,632	48	335,411	Narrows	USBR	1,609,000	102,000	Delayed or cancelled in 1977
Basin Total	21,500	1,204,550	1,902,680	842,060	4,464	1,270	1,213	41,875	30,317,500	347	1,305,591				151,110 to 158,223	

1/Table 3-2, Gerlek (1977)
2/Table 3-3, Gerlek (1977)
3/Table 3-11, Gerlek (1977)

1,902,680 acre-feet for 1970, and 842,060 acre-feet for the 1953-56 four-year drought average. The importance of the flows from the mountain tributaries can be seen also in the data of Table A-5.

Surface Water Diversions. An important index of surface water diversions is seen in a summary of water rights. Table A-5 provides such a summary by sub-basin for both direct flow and storage rights. There are some 1,213 major direct flow rights, which have a collective entitlement (i.e., each right is exercised continuously for the whole year) of 30,317,500 acre-feet. These entitlements are not all satisfied, however, since many of them have priorities too low to yield much water. Many of the junior appropriators do get sufficient water, though, since the senior appropriators do not exercise their rights continuously, i.e., the "calls" average about 25 to 35 percent for the senior appropriators during May and June.

Table A-6 shows a total of 542 ditches making diversions of surface water in the South Platte River Basin. The total amount of surface water diverted in 1970 was 2,936,184 acre-feet (excluding 1,046,469 acre-feet put through turbines of hydro plants). The agricultural sector diverted 2,525,892 acre-feet of water, making agriculture the largest user. In 1973, about 48 major ditches diverted 1,005,600 acre-feet (Table 3-5, Gerlek, 1977).

Storage. There are some 370 reservoirs in the basin having storage capacities in excess of 500 acre-feet; these reservoirs have about 1,200 decreed water rights. The 150 largest reservoirs have collectively 2,129,742 acre-feet of storage capacity; this is about ninety percent of the basin total. Table 2-5 summarizes storage data in terms of water rights for in-basin storage. A

Table A-6. Total Surface Water Diversions in the South Platte River Basin During the 1970 Water Year (Table 3-6, Gerlek, 1977)

Sub-Basin	Number of Ditches Reporting Diversions 1/	Surface Water Diversions in Acre-Feet			
		Agricultural	Municipal	Industrial	Total
North Fork South Platte	0	0	0	0	0
South Platte River-Mountains		134,304	132,176	0	226,480
Plum Creek	226	4,949	0	0	4,949
Cherry Creek		8,795	0	0	8,795
South Platte River-Transition		511,931	86,578	63,057	661,566
Clear Creek	86	4,644	2,200	13,791	22,035
Bear Creek		1,054	2,100	0	3,154
Boulder Creek	62	108.493	17,894	1,437 1/	178,263
St. Vrain Creek	45	225,610	11,241	2,613 1/	139,464
Big Thompson River	37	229,054	9,792	1,007,715 1/	1,246,561
Cache La Poudre River	28	493,526	29,048	8,854	531,426
Crow Creek		60,005	8,811	0	68,816
Lodgepole Creek	58	43,023	0	0	43,023
North Plains Tributaries		1,090	0	0	1,090
South Plains Tributaries		50,000	0	0	50,000
South Platte River--Plains		749,414	0	7,615	757,029
Basin Total	542	2,525,892	299,840	110,452	2,936,184

1/ The amount of industrial water put through turbines in hydropower plants in 1970 amounted to 1,400 acre-feet for Clear Creek; 50,439 acre-feet for Boulder Creek; and 994,630 acre-feet for the Big Thompson River. These amounts are not included in the table.

considerable amount of basin storage is for foreign water. Horsetooth Reservoir and Carter Lake are in this category. Thus, the decreed storage volume of 1,305,591 acre-feet shown in Table A-5 is the approximate storage provided for native flows.

Groundwater Development. About 1,589,830 acre-feet of water was pumped from groundwater in 1970 (this is a rough estimate based upon records of electric energy consumption). About 1,471,940 acre-feet was used for agricultural use, 83,170 acre-feet was for municipal use, and 34,720 acre-feet was for industrial use. Most of this water was pumped from the South Platte alluvium, which extends along the river from all tributaries to the confluence of the main stem with the North Platte River in Nebraska. It is estimated that 25 million acre-feet is in storage in this alluvium.

The South Platte alluvium aquifer is recharged by irrigation. The buildup of the water table from irrigation has resulted in the plains South Platte River being an effluent stream, i.e., it gains water. Consequently many surface water appropriators have come to depend on this water, and indeed they have senior rights relative to the groundwater appropriators. The pumping of this aquifer has interfered with the exercise of these surface water rights, i.e., by lowering the water table. Presently, there is a moratorium on additional wells.

Potential for Development of New Water. As noted earlier, it is not easy to determine the availability of new water in the basin. Comprehensive hydrologic and water rights studies are required. A reasonable index of what is available is the proposed project over recent years. Again, Table A-5 has tabulated this information. Ten projects are listed which could yield collectively over 150,000 acre-feet of new water. The most prominent of these presently are Two Forks Reservoir and the Narrows Reservoir. Both are highly controversial and are being delayed for these reasons. Whether they will be built is uncertain. Two Forks yields only 20,000 acre-feet of water from native flows; however, its main function is to store increased diversions from west slope sources. The yield of the Narrows project is shown as 102,000 feet. The gross yield from this project is about 133,000 acre-feet since the project would acquire 31,000 acre-feet of water presently used on the lands to be inundated. Return flows which will accrue in the stream channel below the Narrows from the developed water will amount to 24,500 acre-feet accrual; this amount is not included in the above figures. The aggregate amount of water yielded from these projects is not large on a basin wide basis. The important point is that the South Platte system is presently over-appropriated and there are very few attractive projects.

Another view of potential supply is seen by comparing the average annual basin outflow across the Colorado-Nebraska state line with the amount stipulated by the 1926 South Platte Compact. The Compact stipulates that a flow of 120 cfs must be maintained across the state line between April 1 and October 15, and that only appropriators in the "compact control zone", i.e., that portion of the river between the Washington County line and the state line whose rights are junior to June 14, 1897, must yield to this requirement. The annual volume for this flow amounts to 47,116 acre-feet. In recent years, i.e., from 1947 to 1974, the average annual state line flow has been about 220,750 acre-feet.

A.5.2 *Foreign Water Supplies*--Water brought into a given basin from another is called "foreign water". The term is common in legal documents. Appropriators in the South Platte River basin presently import about 374,027 acre-feet of foreign water into the basin and there are conditional decrees for importation of a considerable amount of additional foreign water, i.e., from the Colorado River basin. However, there is controversy and uncertainty over whether these decrees can or should be exercised. Because of all of the variable factors involved, in the picture on how much additional water may be available from other basins is not clear. It must be tempered with knowledge of these contending factors.

Imports of Foreign Water. Table 2-7 summarizes also the exports of water to other river basins, including the South Platte. The current average annual exports to the South Platte amount to 374,027 acre-feet.

Potential for Further Imports of Foreign Water. The potential amount of additional water which may be diverted to the South Platte River basin from the North Platte and the Laramie River basins is not too difficult to project. However, the potential for additional water from the Colorado River basin is more difficult to determine.

North Platte River. The 1945 North Platte River Decree, amended in 1953, allocates the waters of the North Platte River between Colorado and Wyoming. The decree excluded the Laramie River. In specifying the terms of the allocation, the decree limits the amount of water which may be irrigated in Jackson County, Colorado, to 145,000 acres. It limits the amount of water which can be exported out of Jackson County to 60,000 acre-feet in any period of ten consecutive years. Present diversions to the South Platte River basin amount to

107 acre-feet annually from the Cameron Pass Ditch and 1,190 acre-feet from the Michigan Ditch. Therefore, an additional 4,703 acre-feet per year could be diverted to the South Platte River basin. The Joe Wright reservoir expansion project of Fort Collins will divert about 4,000 to 5,000 acre-feet per year of this toward this amount. The procurement of additional amounts toward the 6,000 acre-feet annual limit would require some purchase of senior water rights in Jackson County as well as improvements in collection structures. But it is legally possible to divert this additional amount of water with the procurement (i.e., purchase) of the needed water rights.

Laramie River. The 1957 Laramie River Decree placed a ceiling of 49,375 acre-feet per year on diversions of Laramie River water in Colorado. The decree also stipulates that Colorado's allottment of no more than 19,875 acre-feet per year may be exported from the watershed, i.e., to the South Platte River basin.

The present imports of Laramie River water, as seen in Table A-7, amount to 19,720 acre-feet. Thus, there is no additional water available for export to the South Platte River basin in Colorado. Diversions to the South Platte River basin in Colorado are subject only to Wyoming water laws.

Colorado River. According to Mr. Felix Sparks of the Colorado Water Conservation Board:

> "There has been a considerable amount of study together with a considerable amount of speculation, concerning the amount of water which is still available to the State of Colorado under the terms of the Colorado River Compact and the Upper Colorado River Basin Compact. The problem with any studies is that no one can actually define the precise amount of water to which Colorado is entitled under the terms of the compacts. At some future time it appears likely that these differences will be taken to the United States Supreme Court for resolution."

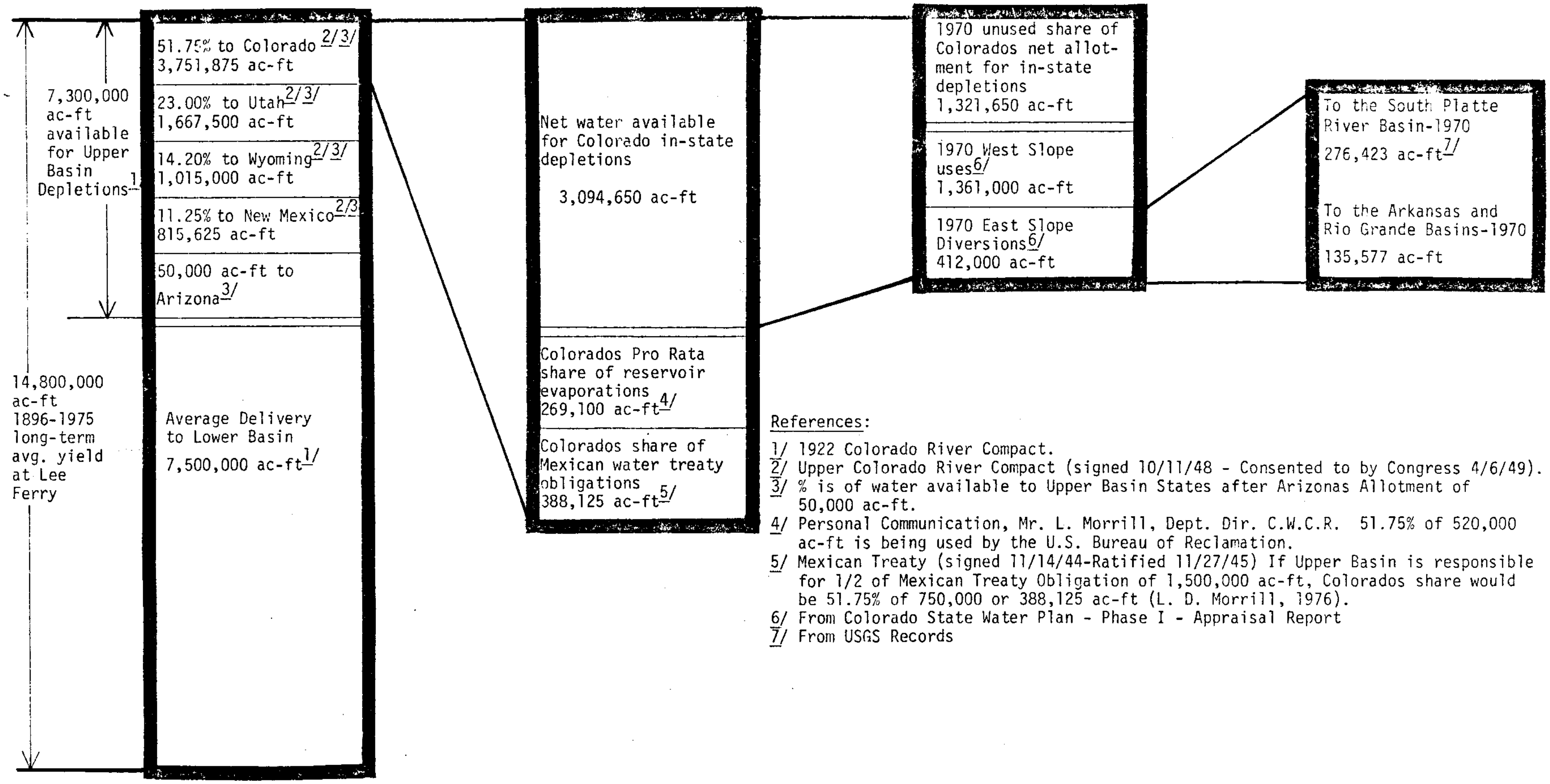
Table A-7. Native Surface Water Supplies of the Colorado and North Platte River Basins (at Gaging Stations below Points of Diversion to South Platte River Basin)

		Surface Water Runoff (acre-feet per year)			Average Annual Disposition of Surface Water (acre-feet per year)			
	Drainage Area (square miles)	Long-Term Average	Water Year 1970	1953-56 Four-Year Drought	Consumptive Uses	Exports to South Platte Basin	Exports to Other Basins	**Sub-Basin Outflow**
Colorado River--Mountains	540	378,474	384,800	237,600	31,850	249,219	0	97,405
Fraser River	285	159,144	173,600	143,500	12,620	55,394	0	91,130
Williams Fork River	184	109,909	125,500	70,600	8,640	4,540	0	96,729
Blue River	511	323,481	406,000	271,800	7,800	30,091	8,249	277,341
Piney River	86	55,131	64,800	38,800	520	0	0	54,616
Eagle River	944	445,432	529,400	347,800	22,100	6,450	28,818	388,064
Little Snake	285	173,478	218,500	121,000	2,600	7,316	0	163,562
Sub-Total	2,835	1,645,049	1,902,600	1,231,100	86,130	353,010	37,067	1,168,847
North Platte River--Mountains	1,431	487,326	555,000	282,800	169,000	1,297	0	317,209
Laramie River	294	145,878	171,000	93,800	6,032	19,720	0	120,126
Sub-Total	1,725	633,204	726,000	376,600	175,032	21,017	0	437,155
TOTAL		2,278,258	2,628,600	1,607,700	261,162	374,027		1,606,002

Acknowledging the problem noted by Sparks, that the terms of the compacts may be the subject of future litigation to clarify the apportionments, one still can read these documents and interpret them literally for a lower limit assessment of Colorado's allocation. This involves also making an assumption about the annual flow at Lee Ferry. This is done graphically in Figures A-10 and A-11, which trace through the water allocations based upon compact interpretations for the 1896-1975 average flow at Lee Ferry of 14,800,000 acre-feet and for the 1931-1964 average flow of 12,920,000 acre-feet respectively. The amount of water available to Colorado, from the two compacts and the Mexican Treaty, is seen to be 3,094,650 acre-feet for the former flow assumption, and 2,121,750 acre-feet for the latter flow assumption.

Once Colorado's allocation (and Wyoming's) is determined, the intrastate allocation procedures govern allocation. By present law, in both Colorado and Wyoming, the doctrine of prior appropriation determines the availability of water. Figures A-13 and A-14 based upon 1970 Colorado uses, show both east slope diversions and west slope uses as being fixed (i.e., not subject to change with low flows since these figures represent uses by senior appropriators). The amount of unused water for the high average flow of Figure A-10 is 1,321,650 acre-feet; however, it is only 348,750 acre-feet for the low average flow of Figure A-11.

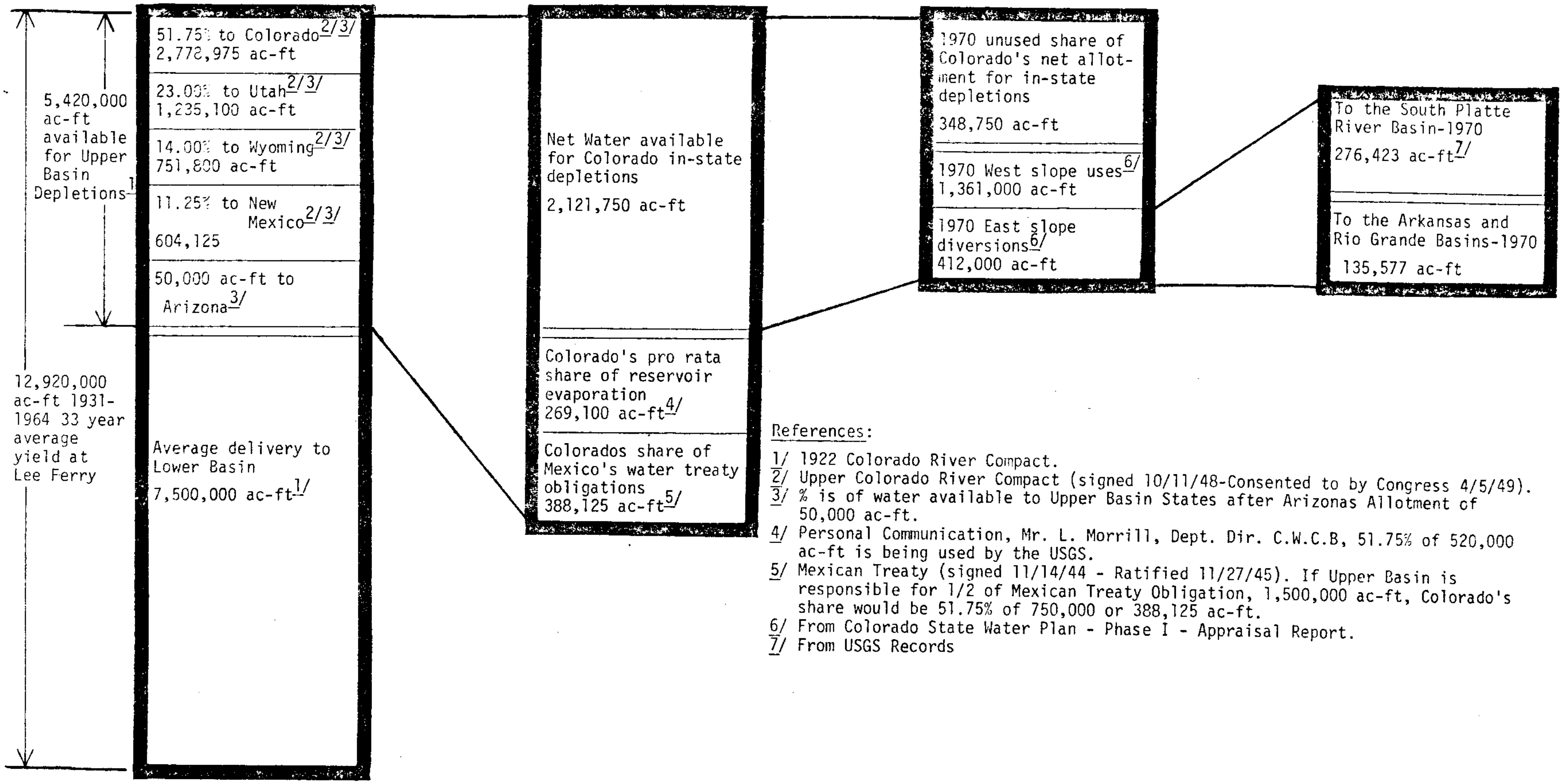
It should be kept in mind, however, that these "unused flows" are covered several times over by existing conditional decrees. While there is doubt as to Colorado's total share to begin with, it is nearly impossible to determine the future status of conditional decrees. In Colorado, water decrees are issued without regard to the availability of unappropriated water in the source. It is a certainty that many



References:

1/ 1922 Colorado River Compact.
2/ Upper Colorado River Compact (signed 10/11/48 - Consented to by Congress 4/6/49).
3/ % is of water available to Upper Basin States after Arizonas Allotment of 50,000 ac-ft.
4/ Personal Communication, Mr. L. Morrill, Dept. Dir. C.W.C.R. 51.75% of 520,000 ac-ft is being used by the U.S. Bureau of Reclamation.
5/ Mexican Treaty (signed 11/14/44-Ratified 11/27/45) If Upper Basin is responsible for 1/2 of Mexican Treaty Obligation of 1,500,000 ac-ft, Colorados share would be 51.75% of 750,000 or 388,125 ac-ft (L. D. Morrill, 1976).
6/ From Colorado State Water Plan - Phase I - Appraisal Report
7/ From USGS Records

Figure A-10. Calculation of Colorado's Annual Share of Colorado River Water if the Yield at Lee Ferry is 14.8 Million Acre-Feet (Based upon an Interview with Mr. L. Morrill, Colorado Water Conservation Board, 7/16/77; (Gerlek, 1977).



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6/ From Colorado State Water Plan - Phase I - Appraisal Report.
7/ From USGS Records

Figure A-11. Calculation of Colorado's Annual Share of Colorado River Water if the Yield at Lee Ferry is 12.9 Million Acre-Feet (Based upon an Interview with Mr. L. Morrill, Colorado Water Conservation Board, 7/16/78; (Gerlek, 1977).

such decrees will not develop into actual usage, but existing conditional decrees already far exceed anyone's guess of Colorado's unused share of the Colorado River. But it is from this "unused share" in Figures A-10 and A-11 from which any future diversions of water from the Colorado River basin to the South Platte River basin must come.

A picture of future diversions from the Colorado River basin to the South Platte River basin in Colorado is seen in Table A-8, based upon the analysis outlined in Gerlek (1977). The upper limit of future diversion is seen to be 707,729 acre-feet, or about twice the present amount. The Alva B. Adams Tunnel will carry about 54,000 acre-feet of additional water from the Windy Gap project which should be on line in the 1980's. The Moffat Tunnel will carry an additional 18,000 acre-feet by 1986 from expansion of the Williams Fork Collection System. The Harold D. Roberts Tunnel will carry an additional 259,000 acre-feet, if present plans come to fruition. A vital link in these plans is to provide adequate east slope storage for this water, which is a main role of Two Forks Reservoir. This water would come from Straight Creek (9,000 acre-feet), East Cove (70,000 acre-feet), Eagle River (100,000 acre-feet), and Eagle-Colorado (80,000 acre-feet). The Eagle-Piney project is politically controversial, however, and the Eagle-Colorado project could be a similar project. The result has been to make the Eagle-Piney project a very expensive one. The project can go ahead, however, as long as the legal obstacles are cleared relative to the new wilderness area created and as long as the conditional decress have high enough priority dates to yield the amount of water anticipated. The Denver Water Department

Table A-8. Future Diversions from the Colorado River Basin to the South Platte River Basin in Colorado (Gerlek, 1977).

Diversion Structure	Pre 1975 Historical Annual Average Diversion (acre-feet)	Future Annual Average Diversions (acre-feet)					
		1975	1980	1990	2000	2020	Date Uncertain
Grand River Ditch	17,523[1/]	21,523[2/]	21,523	21,523	21,523	21,523	?[3/]
Eureka Ditch	82	82	82	82	82	82	0
Alva B. Adams Tunnel	227,626[4/]	227,626	281,626[5/]	281,626	281,626	281,626	0
Moffat Tunnel	54,322[6/]	59,322[7/]	59,322	77,322[8/]	77,322	77,322	0
Berthoud Pass Ditch	615	615	615	615	615	615	0
Vidler Tunnel	48	48	48	48	48	48	365,000[9/]
Harold D. Roberts	28,654	28,654	28,654	28,654	28,654	287,654[10/]	0
Boreas Pass Ditch	103	103	103	103	103	103	0
Aurora-Homestake Pipeline	6,450	6,450	6,450	35,825[11/]	35,825	35,825	0
Four Counties	-	-	-	-	-	-	40,000[12/]
Total imports from the Colorado to the South Platte River Basin	335,423	344,423	398,423	445,798	445,798	704,798	405,000
% increase over the historical annual average	-	2.7	18.8	32.9	32.9	110.1	-

1/ Annual average diversion subsequent to the enlargement of the main intercepting canal in 1930 (Table B3-1).

2/ The 1975 increase in storage capacity of Long Draw Reservoir will provide an additional 4,000 acre-feet per year through the Grand River Ditch (U.S. Department of the Interior, 1973).

3/ Further enlargement of Long Draw Reservoir is possible and would allow increased average annual diversions through the Grand River Ditch without the acquisition of additional water rights. When this might be done and how much it would yield is uncertain.

4/ Annual average was taken between 1953 and 1974 excluding the first 6 years which were not representative of the systems potential (Table B3-3).

5/ Windy Gap Project to come on line in 1980 (NCWCD, 1975) and provide an additional 54,000 acre-feet per year (Engineering Consultants, Inc., 1974).

6/ Annual average was taken subsequent to the addition of the Jones Pass-Vasquez Tunnel infrastructure to the Moffat Collection System in 1959.

7/ Englewoods Development of their Ranch Creek Collection System in 1975 will provide an additional 5,000 acre-feet per year through the Moffat Tunnel (Denver Water Department, 1975).

8/ Expansion of the Williams Fork collection system will provide an additional 18,000 acre-feet per year through the Moffat Tunnel by 1986 at the latest (Robert Fischer, 1976).

9/ The Vidler Tunnel Corporation has filed with the courts to deliver 365,000 acre-feet per year to the South Platte River Basin (Roland Fischer, 1976). This project has not acquired any water rights or land and its feasibility has yet to be assessed. Therefore, the date of initial diversion is uncertain.

10/ The expansion of the Harold D. Roberts Collection system will at least be on line by 2020 with the proposed projects contributing the following amounts; (Robert Fischer, 1976), Straight Creek 9,000, East Gore 70,000, Eagle-Piney 100,000, Eagle-Colorado 80,000, Total 259,000.

11/ The Homestake Project Collection System expansion (including the Eagle-Arkanses Division) is to be on line by 1982 providing Aurora with an additional 20,515 acre-feet per year through the Aurora-Homestake Pipeline (Beck, 1974). Also includes presently unused share of existing yield, 8860 acre-feet.

12/ The Four Counties Water Association Project recently under the direction of a firm called Sproule, would deliver to the South Platte River Basin 40,000 acre-feet per year (Roland Fischer, 1976). When this project will start diversions and how they will get to the South Platte River Basin is uncertain at this time.

also has present absolute and conditional decrees for water from the Moffat and Harold D. Roberts systems (i.e., Blue River) as follows:

Moffat System (Williams Fork and Fraser River)

Average year yield of present water rights:	112,000 acre-feet
Present diversions:	54,200 acre-feet
Additional water which could be diverted:	57,800 acre-feet

Harold D. Roberts Tunnel System (Blue River Sub-Basin)

Average year yield of present water rights:	169,000 acre-feet
Present diversions:	29,941 acre-feet
Total:	139,059 acre-feet

These amounts are not included in Table A-8. The scenario assumption rule in the input-output models, utilized the additional water from the Fraser and Williams Fork Rivers and the Blue River in lieu of the Eagle-Piney, and Eagle-Colorado project water.

In Wyoming, present 1975 depletions of Colorado River Basin water are 323,000 acre-feet and main stem reservoir losses are 73,000 acre-feet. Based on the 6.3 million acre-feet available to the upper basin, and Wyoming's 14.00 percent allotment (875,000 acre-feet), it still has 479,000 acre-feet of unconsumed Colorado River water. However, Wyoming has a total of 292,000 acre-feet of this committed to the Cheyenne-Laramie, Lyman, Savery Pot Hook, Fontenelle M & I, and Seeskadee Projects. This leaves Wyoming with 187,000 acre-feet of Colorado River water for future development.

A.6 Water Demands

The individual water users within the South Platte basin are literally millions in number. To project water demands it is necessary to devise a taxonomy which aggregates these users into tractable groupings. Table A-9 shows the taxonomy devised for the South Platte River basin.

Table A-9. Taxonomy of Water Users for South Platte River Basin

Phylum	Water Users		
User Sector	Municipal	Industry	Agriculture
User Category	Denver, Boulder Longmont, Loveland, Fort Collins, Greeley, Cheyenne, Others-Mountains, Others-Transition, Others-Plains	Energy Resources, Power Generation, Mining, Sugar Beet Factories, Beer Brewery, Manufacturing	Transition Lands Plains Lands

All 1970 water use data for the basin have been aggregated by "use sector" and "user category", along the lines indicated in Table 2-9.

Water demand projections are made for these various use sectors and user categories for 1980, 1990, 2000, 2010 and 2020; 1970 data was used as the point of departure. The projections are developed to envelop ranges, or high and low limits.

The projection which actually materializes is a function of many factors. Some factors are exogenous to the basin (e.g., national population growth) and independent of each other, while others are endogenous and are mutually interdependent (e.g., agricultural water transfers and basin population growth). Thus, the demand for water by any given user or use sector depends upon the number of users which materializes, the intensity of the competitiveness for existing supplies (e.g., as gaged by price, political controversy, court rulings, etc.), and other factors. Present and projected demands by the major use sectors are summarized in the sections following. Complete documentation is found in Janonis (1977), Janonis and Gerlek (1977), Patterson (1977a), and Patterson (1977b).

Municipal Water Use. The "municipal sector" water usage includes all water diverted by cities, towns and municipal water districts. The groups of users are domestic, commercial and industrial.

This section summarizes the 1970 water use by the municipal sector and gives projections of municipal sector water demands to 2020. The volume by Janonis (1977) contains the following information for each major city:

1. A listing of water rights;
2. expected water yield of water rights holdings;
3. a listing of water service contracts;
4. a description of storage, conveyance, water treatment, and wastewater treatment facilities;
5. enumeration of 1970 and 1975 diversions from the various sources of water;
6. diagrams of water distribution and return flows, which balance with respect to inputs and outputs;
7. industrial users;
8. per capita use trends;
9. seasonal patterns of use.

The above listing of information is indicative of the complexity in describing and projecting water use for the municipal sector. Figure A-12 which shows the array of 1970 water transfers for the city of Denver is illustrative. Similar diagrams are given in Janonis (1977) for the other major cities as well.

A.6.2 *Per Capita Water Use*--The limits of projected municipal per capita water usage averaged for the whole South Platte basin are seen in Figure A-13. The upper limit curve is the present basin-wide average. It is difficult to conceive that an increasing trend could

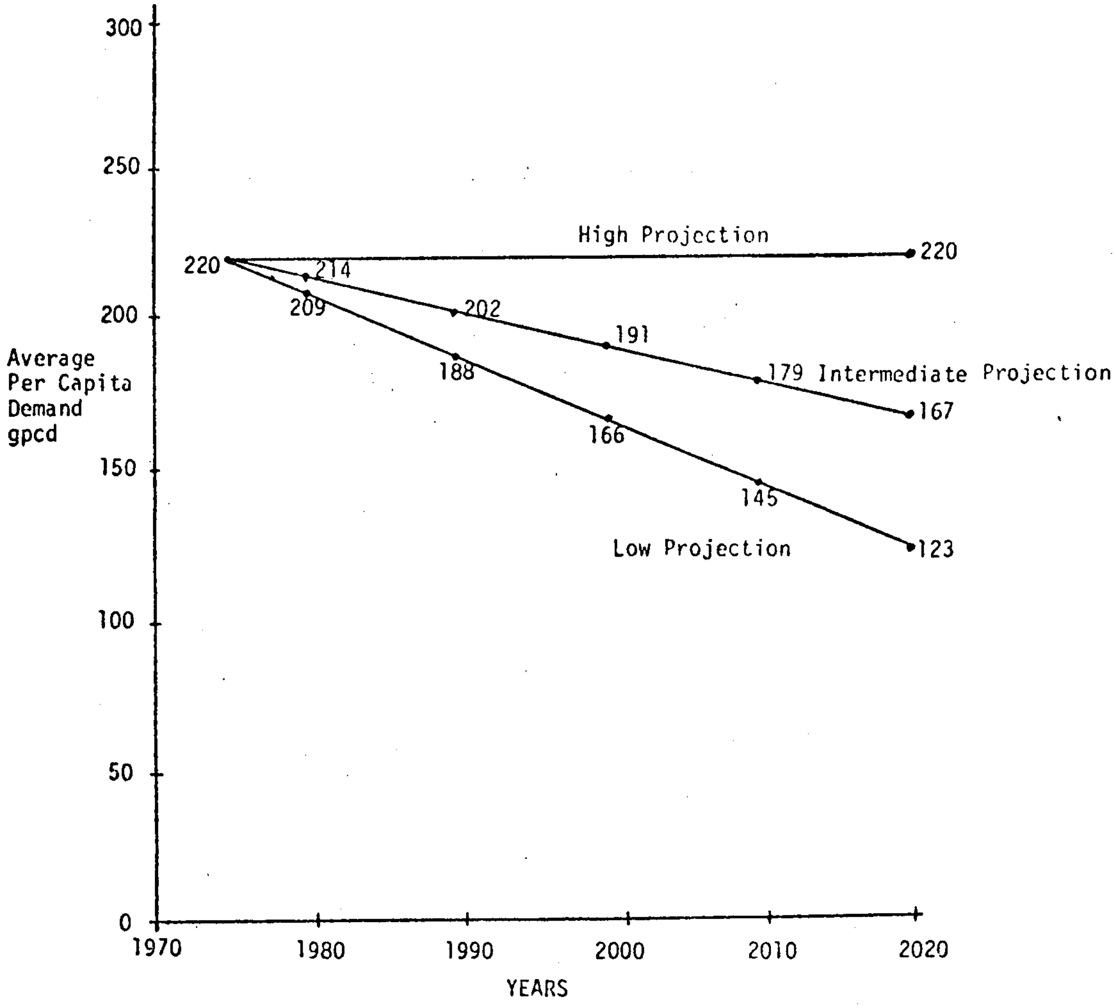


Figure A-13. Projected Municipal Sector Per Capita Water Demands for the South Platte River Basin (Janonis, 1977) develop given the present social mores about water use and the increasing stresses. The intermediate projection takes Boulder's present 167 gpcd as a reasonable basin-wide objective which could be reached gradually as a result of various cities adopting water metering. The loser limit projection would move similarly toward a lower limit of 123 gpcd, a figure based upon studies of what is possible with water saving plumbing fixtures.

Projected Water Demands. The combination of population and per capita water usage, giving projected water demands are infinite. Thus only limits are projected. Figure A-14 shows upper and lower limits of municipal water demand, and an intermediate level projection. The upper limit projection assumes a 220 gpcd water usage combined with the high series population projection; the lower limit projection assumes a lower limit trend in per capita water usage, as shown in Figure A-13, combined with the low series population projection; the intermediate level projection assumes the intermediate trend in per capita water usage as shown in Figure A-13, combined with the medium series population projection. The per capita water usages are shown on the respective curves.

Between the upper limit and the lower limit municipal water projections, a whole family of curves exists, with each curve in the family representing a particular combination of per capita water usage and population projection. It would be fallacious to propose one of these curves as a probable future. All one can say is that a particular population projection, combined with a particular set of per capita uses, will result in a given water demand projection. The "intermediate level projection" seems a reasonable one to pick for some of the studies with the input-output modeling.

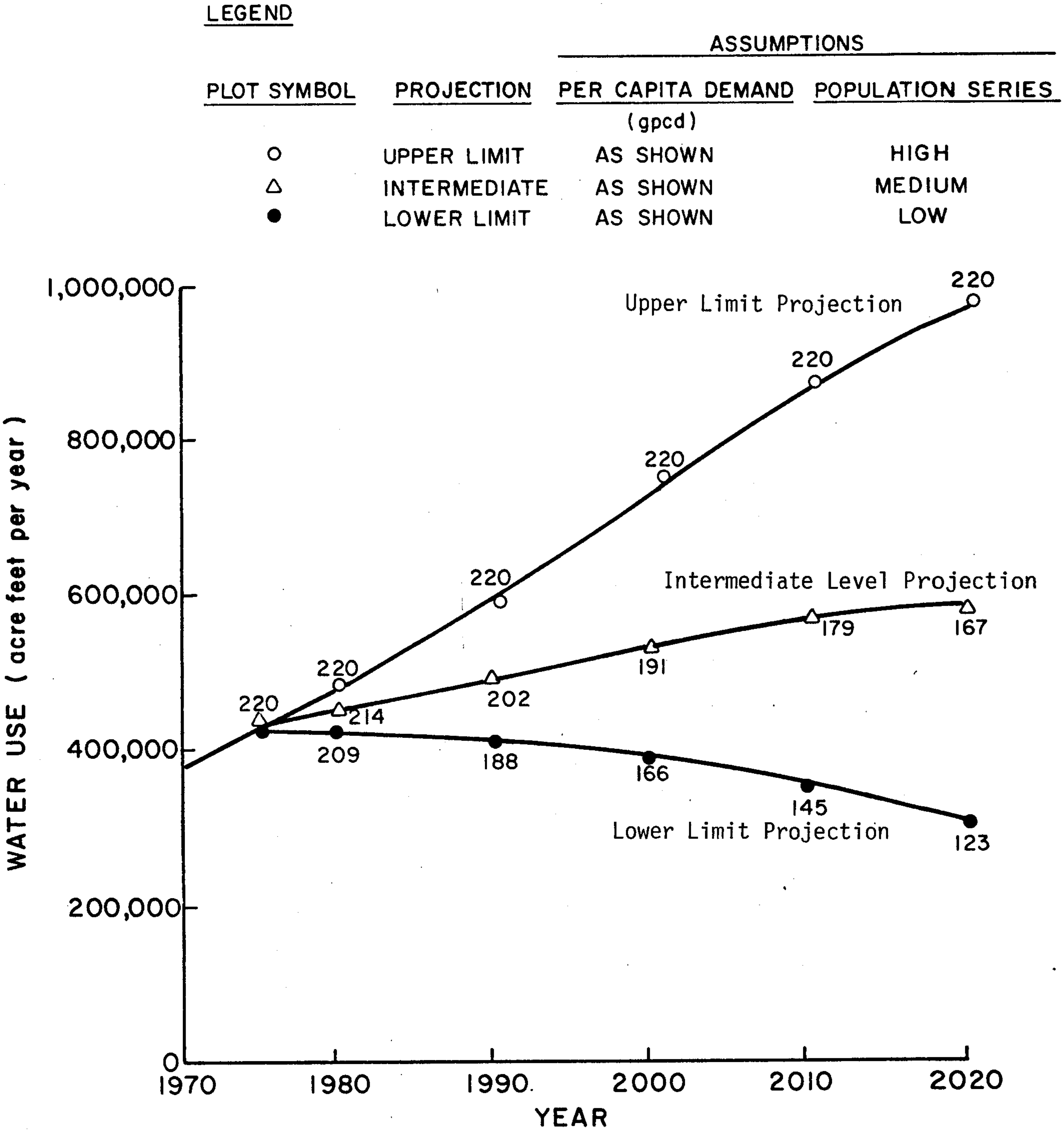


Figure A-14. Envelope of Projections of Municipal Water Demands, 1970-2020, South Platte Basin (Janonis, 1977).

Municipal Return Flows. The return flows from the municipal sector uses are variable; each city has different return flow characteristics. Janonis (1977) has detailed information on return flows for each municipality. The 1970 return flows ranged from 58.4 percent to 85.4 percent of the treated municipal water supplied. The basin average return flow was about 70 percent. The latter figure was used for the return flow projections to 2020.

A.6.2 *Industrial Water Use*--Industrial water users include all commercial water users who require water in their processes and operations. They include establishments in the following industries: thermal power generation, oil refining, mining, brewing, fish hatcheries, sugar beet processing, and manufacturing. They may obtain water either through their own water rights, or they may be supplied by municipal water districts or cities, or both. Also, they may have their own waste treatment facilities, or they may be hooked into a municipal system. They are categorized here as "major" and "minor". The "major" industrial establishments are defined here as those using water ar rates equal to or exceeding 1,000 af/yr; collectively they account for about ninety percent of the total water diversions by industrial sector water users.

Minor Industrial Users. The "minor" industrial establishments are those using water at rates less than 1,000 af/yr. They are absorbed into the municipal water sector for the purpose of depicting water transfers. The water supplied to both major and minor industries by municipalities for 1970 and 1975 (from Patterson, 1977) was:

Municipal Supplied Water	Thousands of acre-feet	
	1970	1975
Total of major and minor users	17.831	21.781
Total of minor users only	10.985	13.748

The basin-wide total of self supplied industrial water by the major industries was 152,262 acre-feet in 1970; in 1975 the total was 184,551 acre-feet. The overall consumptive use by the major industrial water users amounted to 22 percent for 1970 and 30 percent for 1975.

The oil refineries and thermal power generation industries are listed also in the discussion of water use by the "energy sector". This double listing is accounted for in summaries of total water usage by all sectors. They are categorized under the "major industry sector" in the input-output model.

Future Water Use by Industry. It is very difficult to project industrial water usage. However, based upon knowledge of the activities within the basin, three key assumptions seem reasonable. These are: 1) population growth in the basin probably is not tied to development of heavy industry; 2) the basin seems to be developing with further growth founded on the technological industries; and 3) such industries are likely to use municipal water. Thus, with such assumptions, the following assertions are made relative to future water demand by industry: 1) self-supplied industrial water usage remains constant at the 1975 level (except that water use is reduced by 1980 for plants which have been or will be closed between 1975 and 1980; and 2) the percent of industrial water use by industry for each city remains constant for all scenarios; 3) water use by the energy sector is expected to increase (since energy production is related to population).

It is felt that even if "surprises" occur (i.e., new unexpected industries come in) the effect on the basin water balance, depicted by the input-output model, will not be severe. In such cases, the amount of water demand by the industry probably would not be great relative to the total water picture. It should be noted also that the overall consumptive water use by industry is only about two percent.

A.6.3 *Energy Sector Water Requirements*--The "energy sector," as defined here, embraces all activities associated with the production of energy. Energy production has three phases: 1) mining of fuel; 2) manufacturing (e.g., oil refining); and 3) generation of electric power. Table A-10 identifies some of the common activities of each phase.

Table A-10. Phases of Energy Production and Associated Activities

Mining	Manufacturing	Electric Power Gen.
Petroleum recovery	Natural gas liquifaction	Geothermal
Coal mining	Slurry transport of coal	Thermal power production
Uranium mining	Bioconversion	Hydroelectric power production
Oil shale mining	Petroleum refining	

Present energy production activities in the South Platte basin include petroleum recovery, petroleum refining, thermal power production and hydroelectric power production. Future activities could include, in addition, coal mining, slurry transport of coal, natural gas liquification, bioconversion, and expanded thermal power production. In addition, the potential energy production activities in the Colorado River basin, and in the North Park area of the North Platte of Colorado, bear upon the political feasibility of new water diversions to the South Platte River basin. Energy production activities can provide the basis for formidable competition, both politically and in purchase of water rights, for available west slope water supplies--conditional decrees from Front Range interests notwithstanding. Because of these "negotiative types" of factors, it is not possible to determine with certainty the purposes to which Colorado's share of Colorado River basin water will be committed. However, one can construct some tentative scenarios, based upon existing factual knowledge of the basin (i.e., compact arrangements, hydrology, potential agricultural and energy developments, existing conditional decrees, political climate, etc.).

In 1970 and in 1975 also, the major activities in the energy sector were power generation by hydro and thermal plant facilities, oil refining, and oil recovery. The water requirements for the energy sector in 1970 and 1975 as determined by Patterson (1970b), were 47,630 and 91,406 acre-feet, respectively (excluding hydro power). It should be noted that the thermal power (which used 39,113 acre-feet in 1970 and 83,341 acre-feet in 1975) and oil refining categories (which used 3,517 acre-feet in 1970 and 4,385 acre-feet in 1975) were included also in the section on industrial water use. While this facilitates viewing these activities, the dual entry should be noted in order to avoid the possibility of double accounting. The 1970 electric energy generating capacity amounted to 3,338.85 megawatts. The distribution between thermal and hydro was 2,667 and 671.850 megawatts, respectively. The per capita consumption of electric energy for the South Platte River basin in 1970 was 6,473 kwh (kilowatts-hours). For a 1970 basin population of 1,531,600, this amounts to a basin electric energy consumption of 9,917 terawatt hours. This compares with a production capacity for the basin of about 29.248 twh (terawatt-hours) for thermal and hydro power combined. This latter figure assumes all energy production facilities are operating constantly every hour during the 1970 year which was not true. Also, the Hayden power plant supplied an appreciable amount of electrical energy in 1970 through the Hayden-Archer 345-kv transmission line. However, the patterns of energy production, distribution and consumption are much more complex than might seem apparent at first glance. For example, regional power tools intertie a variety of production and load centers, power production and consumption within the South Platte River basin is a part of the Rocky Mountain Power Pool which is one of the regional power pools which tie together a variety of production and load centers.

Water Requirements for Thermal Power Production. Water requirements for electric power generation are calculated for proposed plants based upon pond cooling to 2010, and dry cooling thereafter. The water supply is not adequate for once through cooling. The rule of thumb for cooling pond size is 1,000 acres for a 1,000 megawatt power plant. The water requirement for each plant is assumed to be 10,000 acre-feet per year for a 1,000 megawatt plant. For plants with dry cooling, the water requirement is assumed to be 2,000 acre-feet for a 1,000 megawatt plant.

The cumulative usage of present, proposed and speculative plants to 2020 amounts to 115.013 thousand acre-feet. This water usage corresponds to a "high" projection electric energy demand curve. Of the total water diverted, about 97 percent is lost as evaporation.

Other Future Water Requirements of the Energy Sector. The major energy related water requirement within the basin is for electric power production. Other energy related activities, listed in Table 2-10 are difficult to project. Water requirements for secondary oil recovery are expected to not exceed the present 2,000 acre-feet annual use. Projected coal mining would use only 300 acre-feet annually.

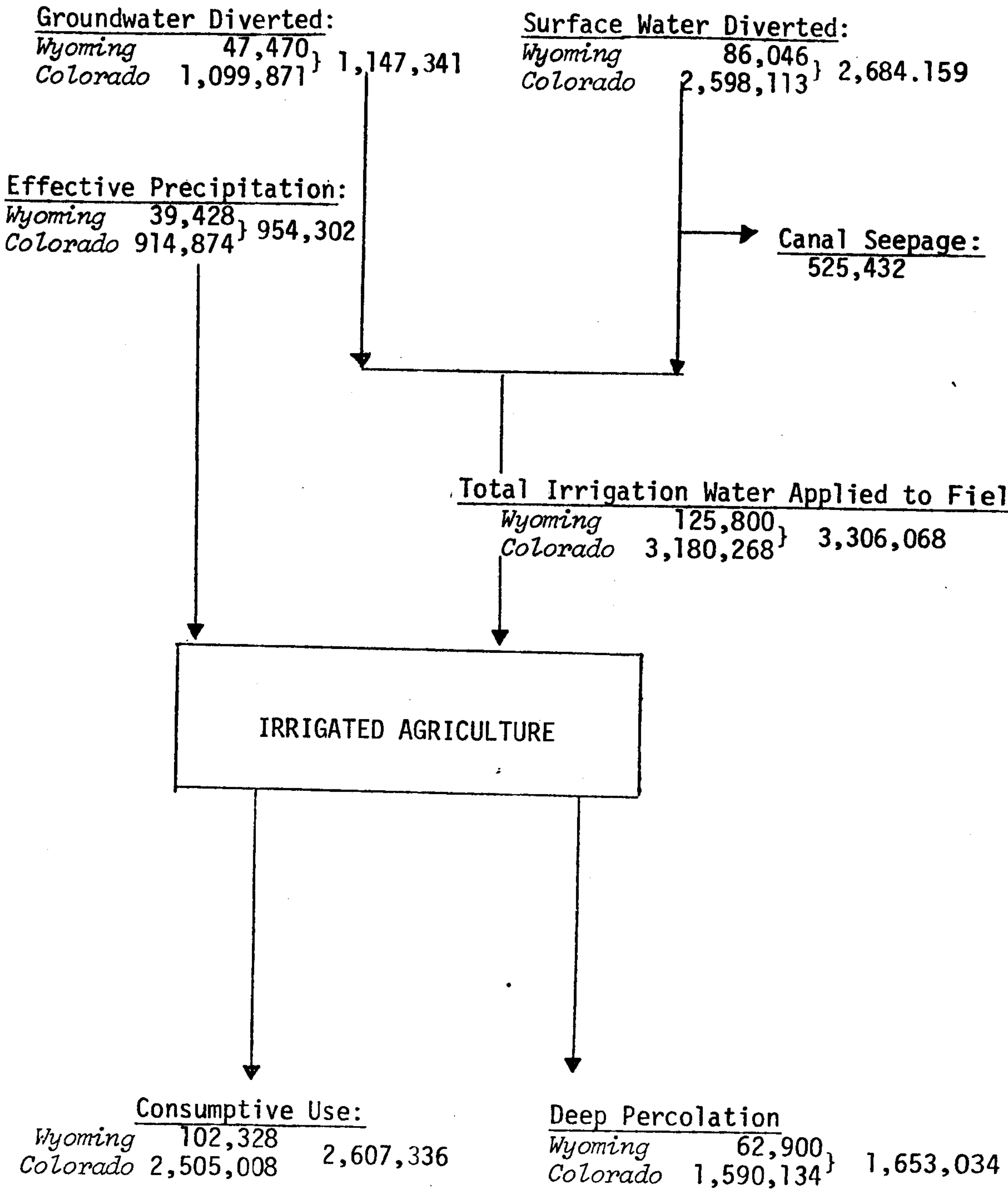
A coal gasification pilot plant, which is likely to be built would use about 15,000 acre-feet annually. Slurry transport of crushed coal is not likely to originate within the basin. Other energy related water uses are not believed to be significant.

A.6.4 *Agricultural Water Demands, 1970-2020*--The agricultural sector is by far the largest water use category in the South Platte basin. About 1,273,954 acres of land in the basin were irrigated in 1973 in Colorado. About 60 percent of this land is located along the Front Range urban corridor (i.e., the transition zone) where it is irrigated by diversions from South Platte tributaries (i.e., Boulder Creek, St. Vrain Creek, Big Thompson River, Cache La Poudre River), as well as from the main stem South Platte between Denver and Greeley. Most of the remaining irrigated land (about 25 to 30 percent) is located along the main stem from Greeley to the state line.

There are about 6,200 conditional and absolute water rights decrees in Colorado, supervised by the Division 1 engineer; most of these are agricultural water rights. These decrees proscribe the rules by which a very finely tuned interdependent system of diversions and return flows must operate. Both the physical system and its management are highly complex. The physical system consists of numerous diversion structures and headgates, countless miles of canals and ditches, and some 370 reservoirs of over 500 acre-feet capacity. The physical facilities are owned by individuals, mutual irrigation companies and water conservancy districts; in 1969 about 368 organizations were active in the basin.

Water Balance--1970. The "use" of water by agriculture infers more than the idea of a simple diversion. It is better understood in terms of a water balance, as shown by Figure A-15. This diagram, from Janonis and Gerlek (1977), shows the 1970 aggregate deliveries and disposals of water for the agricultural sector. Total water diverted from streams and pumped from wells, amounted to 2,684,159 acre-feet and 1,147,341 acre-feet, respectively, with a total of 3,831,500 acre-feet. Consumptive use amounted to 2,607,336 acre-feet. Of special interest is the canal seepage (525,432 acre-feet) and the amount of deep percolation from irrigated fields (1,653,034 acre-feet). This water is important in maintaining the lower South Platte River and its tributaries as effluent streams (i.e., gaining water from groundwater). In this manner, water that is not used consumptively returns to the South Platte River or is available for pumping from the riparian aquifer.

Projection of Agriculture Sector Water Demands, 1970-2020. In the State of Colorado, free market transfers of water are permissable, provided other appropriators are not damaged. Thus, ownership of water



Groundwater Recharge = Recharge from fields and seeps = 2,178,466.

Figure A-15. 1970 Annual Mass Balance of Irrigated Agriculture for the South Platte Basin in Colorado and Wyoming. All Data are in Acre-Feet (Janonis and Gerlek, 1977).

rights may pass to parties willing and able to bid the price high enough to induce irrigators to sell. Water use by municipal and industrial water users is essentially "price inelastic" (i.e., water in certain amounts is required for these uses regardless of price). Transfers of water have been occurring steadily since the 1950's as the Front Range urban corridor has both grown in population and sprawled into suburban areas. For example, the municipal share of Colorado Big Thompson project water has increased from about 13 percent in 1957 to about 27 percent in 1974, with a corresponding decrease in the agriculture sector share.

At the same time, the urban encroachment rate on irrigated lands was about .15 acres per capita increase during the 1950-1960 period and .05 acres per capita increase during the 1960-1970 period. These figures were used as assumed encroachment rates for areas classed as rural and urban, respectively. It is also assumed that farmers are likely to reinvest their capital in areas not likely to be later lost again by urban encroachment. The present irrigated acreage is not expected to increase more than five percent as an upper limit, nor decrease more than seven percent as a lower limit to year 2020 for low and high series population projections, respectively.

Another key assumption in projecting water use by agriculture relates to overall project efficiency. The lower limit assumption is that the present efficiency, assumed at 43 percent, prevails in the future. The upper limit assumes 73 percent efficiency by 2020. This figure is based upon studies of center pivot and trickle irrigation technologies and reported efficiencies of other areas in the United States (i.e., California). Whether this higher efficiency is desirable for the South Platte is another question. The interdependencies between return flows from excess water applied and downstream appropriations could become out of balance if higher efficiencies were achieved.

The combinations of projected irrigated acreage and projected irrigation efficiency are infinite, giving a wide continuum in projected agricultural water demand curves. Figure A-16 is an envelope of these projections. The lower limit curve combines the lower limit in projected irrigated acreage with the high limit of irrigation system efficiency. Similarly, the high limit curve of Figure A-16 combines the high limit of irrigated acreage with the low limit of system efficiency. In any case, even the high limit projection of Figure A-16 shows no significant increase in agricultural water demand. Any changes are likely to be toward using less water.

Agricultural water use is tied to the price of water. Further diversions by agriculture from the west slope are unlikely. This is not only because of lack of water rights and probable political controversy, but because the water would be too costly. However, the agricultural sector is highly "elastic" in the amount of water which it might use. If water is available at a reasonable cost, it will be used. If municipal and industrial users wish to bid the water away from agriculture, its water use will diminish. However, if further west slope diversions are brought to fruition, agriculture could benefit; since the municipal water use efficiency is about 70 percent. that amount of return flow could be made available for use by agriculture. However, since the municipal water users will most likely take advantage of their legal perogative to reuse imported water, they will probably

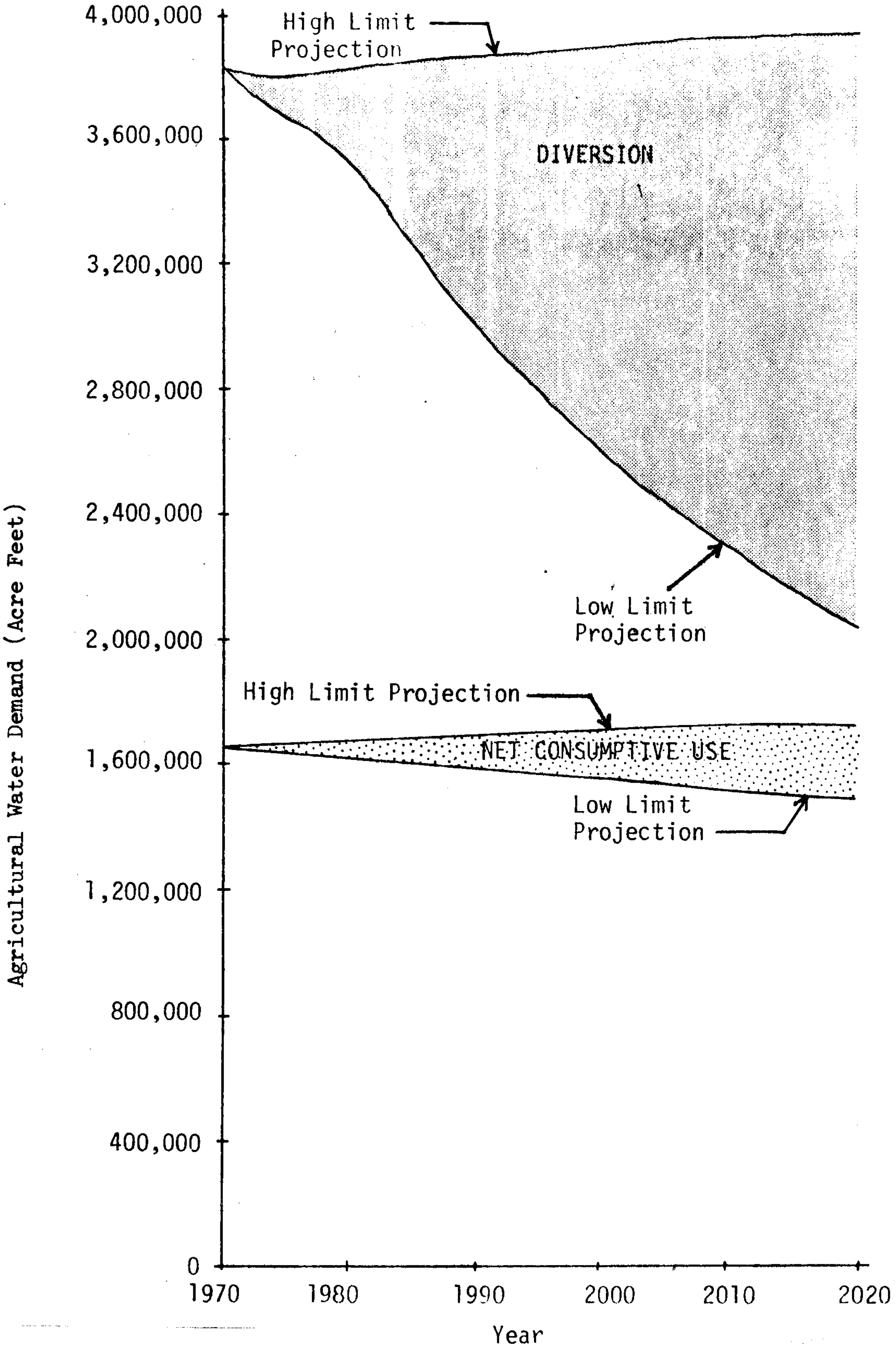


Figure A-16. Projected Envelope of Agricultural Water Demands for the South Platte River Basin in Colorado and Wyoming (Janonis and Gerlek, 1977) use the water two to two and a half times. Such reuse may take the form of exchange agreements with agriculture (i.e., the municipal sector uses agriculture's virgin water in exchange for the municipal sector's treated sewage effluent, plus a payment).

A.7 Cache La Poudre River Basin

The optimization research utilized the water system of the Cache la Poudre River basin for a case study. In addition, an input-output water balance model was constructed for this basin for 1970.

The water data for the Cache la Poudre River basin are contained within the previous description of the South Platte River basin. The former is described in considerable detail by Reitano (1978). Figure A-17 is a pictorial representation of the Cache la Poudre basin, showing the general water related structural features.

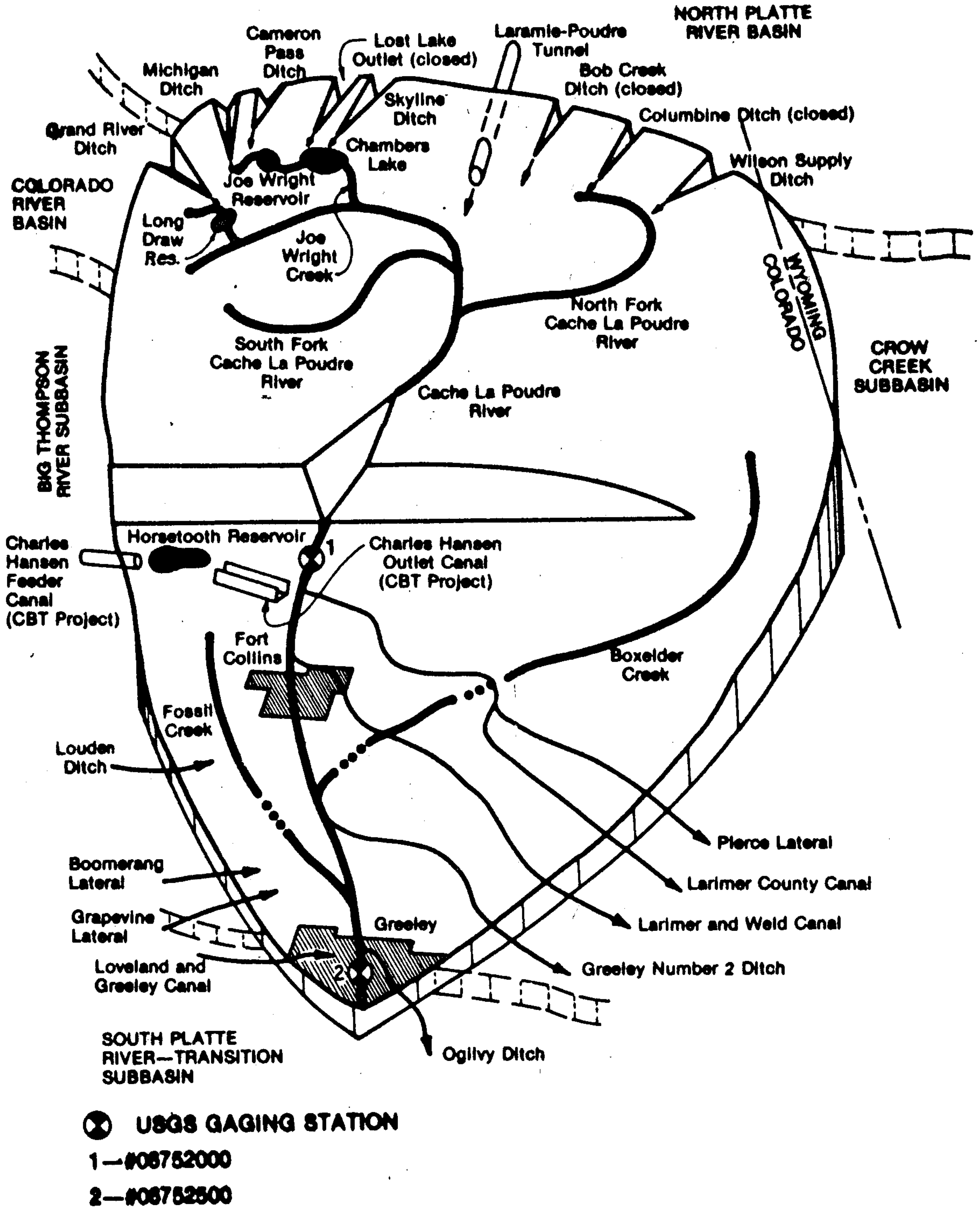


Figure A-17. Cache la Poudre River Sub-Basin (Gerlek, 1977).

APPENDIX B

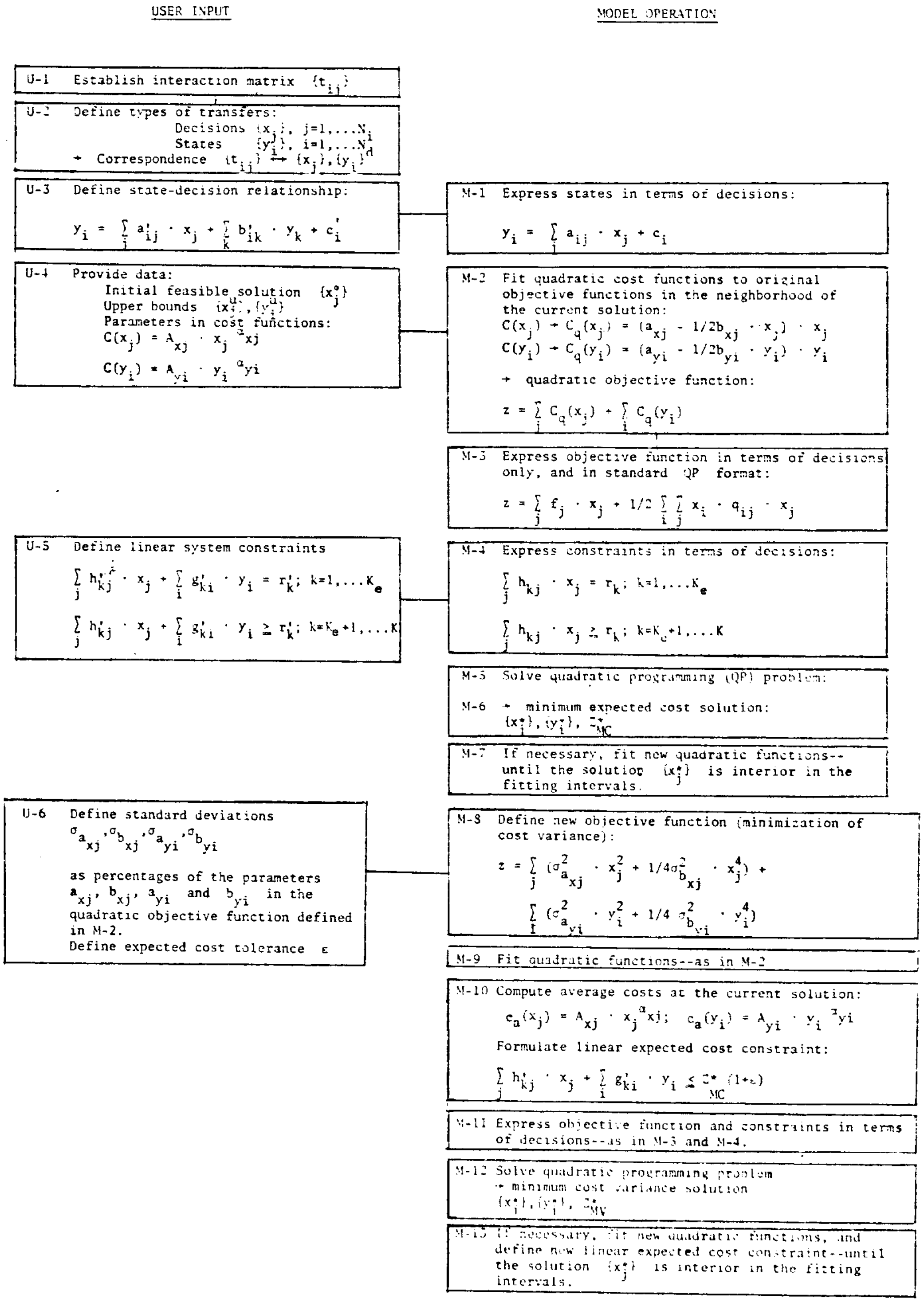
The Quadratic Programming Model--Summary Description

The methodology presented here is intended to be applied at two levels: (1) a single-period approach based on annual figures, and (2) a multi-period approach based on seasonal figures. The multi-period solution is based on a decomposition approach (multilevel optimization) in which individual seasons are optimized separately, with a master program (controller) adjusting the inter-seasonal linkages in an iterative manner until overall optimality is obtained. The single period allocation model--which is the core of the planning methodology--shall be described first; the multilevel structure of the seasonal model shall be described subsequently.

B.1 The Single-Period Allocation Model

In order to facilitate the description of the computer allocation model a generalized flow chart is provided in Figure B-1. The flow chart is divided in two parts: the left half describes the steps taken by the user, and the right half outlines the model operations. User steps are numbered U-1, U-2,... etc., model operation steps M-1, M-2,... etc., and the description of the model below will follow these steps. Detailed flow charts of the overall model and the quadratic programming algorithm can be found in Jønch-Clausen and Morel-Seytoux (1977,1978) and in Jønch-Clausen (1978). For a detailed description of how to use the computer program the reader is referred to the user's manual (Jønch-Clausen and Morel-Seytoux, 1978).

U-1 The planning problem is formulated and organized in an input-output framework. Matrix elements t_{ij} representing present or potential water transfers and treatments are identified.



USER INPUT

U-1 Establish interaction matrix $\{t_{ij}\}$

U-2 Define types of transfers:
Decisions $\{x_j\}$, $j=1,\ldots N_i$
States $\{y_i\}$, $i=1,\ldots N_d$
→ Correspondence $\{t_{ij}\} \leftrightarrow \{x_j\},\{y_i\}$

U-3 Define state-decision relationship:

$$y_i = \sum_j a'_{ij} \cdot x_j + \sum_k b'_{ik} \cdot y_k + c'_i$$

U-4 Provide data:
Initial feasible solution $\{x^{\circ}_j\}$
Upper bounds $\{x^u_j\},\{y^u_i\}$
Parameters in cost functions:
$C(x_j) = A_{xj} \cdot x_j^{\alpha_{xj}}$
$C(y_i) = A_{yi} \cdot y_i^{\alpha_{yi}}$

U-5 Define linear system constraints

$$\sum_j h'_{kj} \cdot x_j + \sum_i g'_{ki} \cdot y_i = r'_k;\ k=1,\ldots K_e$$

$$\sum_j h'_{kj} \cdot x_j + \sum_i g'_{ki} \cdot y_i \geq r'_k;\ k=K_e+1,\ldots K$$

U-6 Define standard deviations
$\sigma_{a_{xj}}, \sigma_{b_{xj}}, \sigma_{a_{yi}}, \sigma_{b_{yi}}$

as percentages of the parameters a_{xj}, b_{xj}, a_{yi} and b_{yi} in the quadratic objective function defined in M-2.
Define expected cost tolerance ε

MODEL OPERATION

M-1 Express states in terms of decisions:

$$y_i = \sum_j a_{ij} \cdot x_j + c_i$$

M-2 Fit quadratic cost functions to original objective functions in the neighborhood of the current solution:
$C(x_j) \rightarrow C_q(x_j) = (a_{xj} - 1/2b_{xj} \cdot x_j) \cdot x_j$
$C(y_i) \rightarrow C_q(y_i) = (a_{yi} - 1/2b_{yi} \cdot y_i) \cdot y_i$

→ quadratic objective function:

$$z = \sum_j C_q(x_j) + \sum_i C_q(y_i)$$

M-3 Express objective function in terms of decisions only, and in standard QP format:

$$z = \sum_j f_j \cdot x_j + 1/2 \sum_i \sum_j x_i \cdot q_{ij} \cdot x_j$$

M-4 Express constraints in terms of decisions:

$$\sum_j h_{kj} \cdot x_j = r_k;\ k=1,\ldots K_e$$

$$\sum_j h_{kj} \cdot x_j \geq r_k;\ k=K_e+1,\ldots K$$

M-5 Solve quadratic programming (QP) problem:

M-6 → minimum expected cost solution:
$\{x^*_j\}, \{y^*_i\}, z^*_{MC}$

M-7 If necessary, fit new quadratic functions--until the solution $\{x^*_j\}$ is interior in the fitting intervals.

M-8 Define new objective function (minimization of cost variance):

$$z = \sum_j (\sigma^2_{a_{xj}} \cdot x_j^2 + 1/4\sigma^2_{b_{xj}} \cdot x_j^4) +$$

$$\sum_i (\sigma^2_{a_{yi}} \cdot y_i^2 + 1/4\ \sigma^2_{b_{yi}} \cdot y_i^4)$$

M-9 Fit quadratic functions--as in M-2

M-10 Compute average costs at the current solution:
$c_a(x_j) = A_{xj} \cdot x_j^{\alpha_{xj}};\ \ c_a(y_i) = A_{yi} \cdot y_i^{\alpha_{yi}}$
Formulate linear expected cost constraint:

$$\sum_j h'_{kj} \cdot x_j + \sum_i g'_{ki} \cdot y_i \leq z^*_{MC}(1+\varepsilon)$$

M-11 Express objective function and constraints in terms of decisions--as in M-3 and M-4.

M-12 Solve quadratic programming problem
→ minimum cost variance solution
$\{x^*_j\}, \{y^*_i\}, z^*_{MV}$

M-13 If necessary, fit new quadratic functions, and define new linear expected cost constraint--until the solution $\{x^*_j\}$ is interior in the fitting intervals.

Figure B-1. Single-Period Allocation Model

U-2 The variables t_{ij} are partitioned into decisions $x_j (j=1,\ldots,N_i)$ and states y_i $(i=1,\ldots,N_d)$, and a table of correspondence identifying each matrix element as either a decision or a state is established.

U-3 States y_i are expressed in terms of other states and decisions x_j:

$$y_i = \sum_{j=1}^{N_i} a'_{ij}\ x_j + \sum_{k=1}^{N_d} b'_{ik}\ y_k + c'_i\ ,\ i=1,\ldots,N_d \qquad \text{(B-1)}$$

The matrices $\{a'_{ij}\}$ and $\{b'_{ik}\}$ and the vector $\{c'_i\}$ are provided as input by the user.

M-1 The user provided relation (B-1) is reduced to an expression of states in terms of decisions only:

$$y_i = \sum_{j=1}^{N_i} a_{ij}\ x_j + c_i,\ i=1,\ldots,N_d \qquad \text{(B-2)}$$

This is accomplished by solving the system of Equations (B-1) written as:

$$\sum_{k=1}^{N_d} (\delta_i - b'_{ik})\ y_k = \sum_{j=1}^{N_i} a'_{ij}\ \ x_j + c'_i\ ,\ i=1,\ldots,N_d$$

where $\delta_i = 0$ for $k \neq i$, and $\delta_i = 1$ for $k=i$

These equations are solved by the Gaussian elimination procedure; when in the course of this procedure the square, non-singular matrix $\{\delta_i - b'_{ik}\}$ is reduced to the identity matrix, the matrix $\{a'_{ij}\}$ and the vector $\{c'_i\}$ reduce to the matrix $\{a_{ij}\}$ and vector $\{c_i\}$ in Equation (B-2).

In the following the relations (B-2) shall be referred to as the *state-decision relations*.

U-4 The following information is provided by the user:

(1) An initial feasible solution $\{x_j^o\}$ (decisions only)

(2) Upper bounds on states $\{y_i^u\}$ and decisions $\{x_j^u\}$

(3) Parameters defining the cost functions:

$$C(x_j) = A_{xj}\ x_j^{\alpha_{xj}} \quad \text{(some j's)} \tag{B-3}$$

$$C(y_i) = A_{yi}\ y_i^{\alpha_{yi}} \quad \text{(some i's)} \tag{B-4}$$

M-2 The cost functions (B-3) and (B-4) are approximated by the quadratic cost functions:

$$C_q(x_j) = (a_{xj} - \frac{1}{2} b_{xj}\ x_j)x_j \tag{B-5}$$

$$C_q\ (y_i) = (a_{yi} - \frac{1}{2} b_{yi}\ y_i)y_i \tag{B-6}$$

in prescribed intervals around current values of the variables. This fitting procedure is performed by simple linear regression on the cost function derivatives. Leaving the subscripts out the derivative of the original cost function becomes:

$$c(x) = \frac{d}{dx} C(x) = A \cdot \alpha \cdot x^{\alpha-1} = B \cdot x^{\beta} \tag{B-7}$$

The derivative of the quadratic function is simply:

$$c_q(x) = \frac{d}{dx} C_q(x) = a-bx \tag{B-8}$$

In a least squares fitting procedure the parameters a and b in (B-8) are obtained by fitting the straight line given by (B-8) to the cost function derivative given by (B-7) in an interval around the current value of the variables x. The length of the fitting interval is specified as a fraction of the variable range, and the number of grid points in the fitting procedure is specified as a number J.

Minimizing the sum of the squares of the deviations between the cost function derivative and the straight line, given by the expression:

$$\underset{a,b}{\text{Min}} \{ \sum_{j=1}^{J} \Delta_j^2 \} = \underset{a,b}{\text{Min}} \{ \sum_{j=1}^{J} (Bx_d^{\beta} + bx_d - a)^2 \} \qquad \text{(B-9)}$$

the standard linear regression procedure yields the following expressions for the parameters a and b:

$$a = B \frac{\sum_{j=1}^{J} x_j^2 \cdot \sum_{j=1}^{J} x_j^{\beta} - \sum_{j=1}^{J} x_j \cdot \sum_{j=1} x_j^{\beta+1}}{J \cdot \sum_{j=1}^{J} x_j^2 - [\sum_{j=1}^{J} x_j]^2} \qquad \text{(B-10)}$$

$$b = B \frac{\sum_{j=1}^{J} x_j \cdot \sum_{j=1}^{J} x_j^{\beta} - J \cdot \sum_{j=1}^{J} x_j^{\beta+1}}{J \cdot \sum_{j=1}^{J} x_j^2 - [\sum_{j=1}^{J} x_j]^2} \qquad \text{(B-11)}$$

These are the parameters a_{xj}, b_{xj}, a_{yi}, and b_{yi} in the quadratic functions given by (B-5) and (B-6)--obtained for each of the cost functions in the system, whether expressed in terms of states or decisions. In the computer program the initial fitting intervals are the entire variable ranges; the intervals are subsequently reduced to 5 percent of the ranges.

Having obtained the appropriate parameters the quadratic objective function is defined:

$$z = \sum_{j=1}^{N_i} C_q(x_j) + \sum_{i=1}^{N_d} C_q(y_i) \qquad \text{(B-12)}$$

M-3 The quadratic objective function is reduced to a function of the decisions only by using the state-decision relations (B-2). In standard quadratic programming format the objective function becomes:

$$z = \sum_{j=1}^{N_i} f_j \; x_j + \frac{1}{2} \sum_{i=1}^{N_d} \sum_{j=1}^{N_i} x_i \; q_{ij} \; x_j \qquad \text{(B-13)}$$

U-5 Constraints are expressed in terms of states and decisions:

$$\sum_{j=1}^{N_i} h'_{kj} \; x_j + \sum_{i=1}^{N_d} g'_{ki} \; y_i = r'_k \qquad k = 1,\ldots,K_e \qquad \text{(B-14)}$$

$$\sum_{j=1}^{N_i} h'_{kj} \; x_j + \sum_{i=1}^{N_d} g'_{ki} \; y_i \geqq r'_k \qquad k = K_e + 1,\ldots,K \qquad \text{(B-15)}$$

The matrices $\{h'_{kj}\}$ and $\{g'_{ki}\}$ and the vector $\{r'_k\}$ are provided as input by the user.

M-4 Using the state-decision relations (B-2) the user-provided relations (B-14) and (B-15) are reduced to an expression of constraints in terms of decisions only:

$$\sum_{j=1}^{N_i} h_{kj} \; x_j = r_k \qquad k = 1,\ldots, K_e \qquad \text{(B-16)}$$

$$\sum_{j=1}^{N_i} h_{kj} \; x_j \geqq r_k \qquad k = K_e + 1,\ldots,K \qquad \text{(B-17)}$$

M-5 Having formulated the quadratic programming problem:

Minimize $\{z\}$, given by (B-13)

Subject to constraints given by (B-16) and (B-17)

the quadratic programming routine is called to find the minimum expected cost solution: $\{x_j^*\}$, z_{MC}^* . The quadratic programming routine is described in the following section.

M-6 Using the state-decision relations (B-2) the states corresponding to the optimal solution, $\{y_i^*\}$, are computed.

M-7 A check is made to see whether or not the optimal solution is interior in the prescribed fitting intervals. If it is interior, the true minimum expected cost solution:

$$\{x_j^*\}, \ \{y_i^*\}, \ z_{MC}^*$$

has been obtained. If it is not interior, new quadratic cost functions are fitted, and steps M-2 through M-7 are repeated until the optimal *and* interior solution is obtained.

If the user is interested in the minimum expected cost solution only, the allocation procedure stops here, and the optimal solution is "translated" back into optimal values $\{t_{ij}^*\}$ in the input-output table.

The curve fitting operation can be bypassed by providing quadratic cost function parameters $\{a_{xj}, b_{xj}\}$ and $\{a_{yi}, b_{yi}\}$ directly (step U-4). The special case $b_{xj} = b_{yi} = 0$ for all j and i represents a situation with constant unit costs, and the quadratic programming reduces to linear programming.

U-6 Cost uncertainty information is provided in the form of estimated coefficients of variation associated with the parameters a_{xj}, b_{xj}, a_{yi}, and b_{yi} in the quadratic cost functions (B-5) and (B-6). The respective standard deviations $\sigma_{a_{xj}}$, $\sigma_{b_{xy}}$, $\sigma_{a_{yi}}$, and $\sigma_{b_{yi}}$ are then computed.

M-8 The cost variance objective function is defined as:

$$z = \mathrm{Var}\ \{\sum_{j=1}^{N_i} C_q(x_j) + \sum_{i=1}^{N_d} C_q(y_i)\} \qquad \text{(B-19)}$$

where $C_q(x_j)$ and $C_q(y_i)$ are the quadratic functions in (B-5) and (B-6). Assuming that cost parameters are independent random variables the new objective function becomes:

$$z = \sum_{j=1}^{N_i} (\sigma^2_{a_{xj}} x_j^2 + \frac{1}{4} \sigma^2_{b_{xj}} x_j^4) + \sum_{i=1}^{N_d} (\sigma^2_{a_{yi}} y_i^2 + \frac{1}{4} \sigma^2_{b_{yi}} y_i^4) \qquad \text{(B-20)}$$

M-9 As previously, in step M-2, quadratic functions are fitted to the actual cost variance functions in a prescribed interval around the current solution.

The fitting procedure is the same as the one previously described. Leaving the subscripts out, the original cost variance function

$$f(x) = \alpha x^2 + \beta x^4 \qquad \text{(B-21)}$$

is approximated by the quadratic function

$$g(x) = (a - \frac{1}{2} bx)x \qquad \text{(B-22)}$$

The linear regression on the derivatives of these functions yields the following expressions for the parameters a and b in (B-22):

$$a = 4\beta \frac{\sum_{j=1}^{J} x_j^2 \cdot \sum_{j=1}^{J} x_j^3 - \sum_{j=1}^{J} x_j \cdot \sum_{j=1}^{J} x_j^4}{J \cdot \sum_{j=1}^{J} x_j^2 - [\sum_{j=1}^{J} x_j]^2} \qquad \text{(B-23)}$$

$$b = 4\beta \frac{\sum_{j=1}^{J} x_j \cdot \sum_{j=1}^{J} x_j^3 - J \cdot \sum_{j=1}^{J} x_j^4}{J \sum_{j=1}^{J} x_j^2 - [\sum_{j=1}^{J} x_j]^2} -2\alpha \qquad \text{(B-24)}$$

M-10 Average costs at the current solutions are computed, and using these average costs as coefficients a linearized additional constraint is formulated, expressing that expected costs should not exceed minimum expected costs by more than a prescribed fraction ε:

$$\sum_j h'_{kj} x_j + \sum_k g'_{Kk} y_k \leqq z^*_{MC} (1+\varepsilon) \qquad \text{(B-25)}$$

M-11 As previously in steps M-3 and M-4, the objective function and the additional constraint are reduced to be functions of decisions only.

M-12 The quadratic programming routine is called to find the minimum cost variance solution, and corresponding optimal states are computed:

$$\{x_j^!\}, \ \{y_i^*\}, \ z^*_{MV}$$

M-13 As previously in step M-7 a check is made to ascertain that the optimal solution is interior in the prescribed fitting intervals. If it is interior, the true minimum cost variance solution has been obtained. If it is not interior, new quadratic functions, and a new linearized minimum expected cost constraint is determined, and steps M-9 through M-13 are repeated until the optimal *and* interior solution is obtained.

B.2 The Dual-Period Allocation Model

The single-period allocation model just described is rather general in scope, and should be applicable without change in a variety of planning situations. All characteristics of the particular planning problem are expressed in the state-decision relations, the objective function(s) and the constraints.

In multi-seasonal planning, however, models are less general and more problem specific. The inter-seasonal linkages vary from one planning situation to the other, and multi-seasonal models must be tailored accordingly. The seasonal model presented here is specific to the case study of the Cache La Poudre River basin.

Only a very simple *dual-period* allocation model is required in the analysis of the Cache La Poudre system. The two winter seasons can be analyzed separately and independently, whereas the summer seasons are linked through storage. This linkage is necessary because water is being diverted to storage in spring and early summer, when streamflows are high, for subsequent use in mid- and late summer when irrigation demands are at their maximum. Thus, from a modeling point of view, the simplest conceivable situation exists: only two seasons are interdependent, and only one variable (storage) links them.

Two different approaches may be taken to the optimal allocation of water in the two interdependent summer seasons. The periods can be treated together in a single-period model with twice the number of variables and constraints as necessary in any one period; or the problem can be decomposed by optimizing the periods separately, and let a controller or master program, adjust the linking variable in an iterative manner until overall optimality is obtained. Computer storage and execution time requirements increase geometrically with the number of variables and constraints in the problem, whereas execution time increases only arithmetically with the number of single-period optimizations, storage requirements remaining virtually constant. For these reasons decomposition is generally computationally advantageous, and shall be pursued here.

The multilevel structure of the decomposed problem is shown in Figure B-2. An initial decision is made with respect to the diversion to storage in the first period, and the optimal solution for this period corresponding to the initial storage diversion is found, as well as the carry-over storage available for the second period after seepage and evaporation losses. Then the optimal solution for the second period corresponding to the just determined carry-over storage is found, and the overall objective value evaluated. Storage is adjusted iteratively until the optimal overall objective value is obtained, i.e., when any feasible change in use of storage will result in higher expected costs, or higher cost variance, whatever the objective might be.

The control and storage iteration procedure takes place in a master program, which calls on the single-period allocation model described

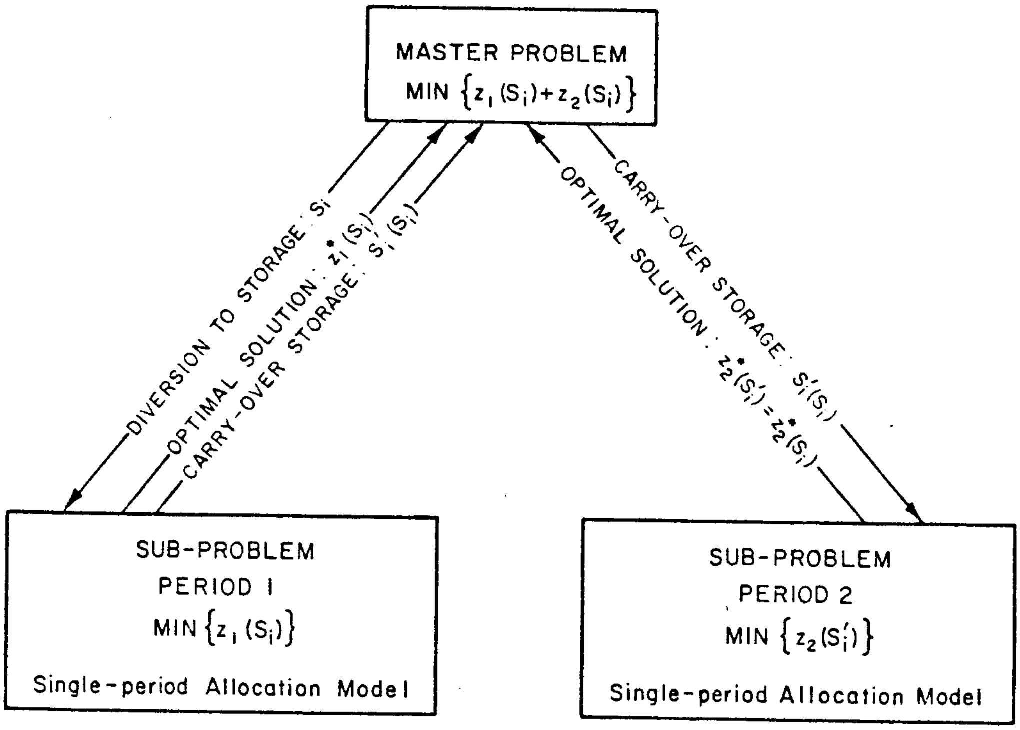


Figure B-2. Multi-Level Optimization Scheme (Jønch-Clausen, 1978) above for solution of the subproblems. These subproblems generate the optimal solutions for the individual time periods (direct coupling, feasible controller).

B.3 Description of the Quadratic Programming Algorithm

B.3.1 *The Convex Programming Problem*--In quadratic programming a second order objective function is optimized (i.e., minimized or maximized) over a set of variables, subject to constraints, equalities and inequalities, that are linear in these variables. In the standard formulation of the quadratic programming problem all inequality constraints are converted into equality constraints by introducing additional variables (slack variables) into the problem; thus the second-order objective function is optimized over a larger set of variables, but subject to equality constraints only. Variables may be non-negative or free (i.e., with a permissible range from $-\infty$ to ∞), and upper bounds on variables may be specified. Only minimization is considered here; maximization is equivalent to minimizing the negative of the objective to be maximized.

Starting with an initial feasible solution (i.e., a solution which satisfies the constraints and variable bounds) the quadratic programming algorithm decreases the value of the objective function in an iterative process. At each step one variable changes value in such a way that the value of the objective function is decreased, while keeping the constraints and variable bounds satisfied. The variable to be changed is the one which has the greatest single effect on the objective function at each step. A set of conditions, known as the Kuhn-Tucker conditions, determines when the optimum has been reached. At the optimum no or only insignificant decrease of the objective function will result from changing one of the variables.

The computer routine for solving the quadratic programming problem has been developed using an algorithm known as the *General Differential Algorithm*. The theory behind this algorithm is presented in Wilde and Beightler (1967) and in more computational details by Morel-Seytoux (1972). These references should be consulted for details.

The quadratic programming algorithm follows the computational approach by Morel-Seytoux (1972) very closely, the only major improvement being the inclusion of upper bounds on the variables. The changes necessitated by this improvement appear from the detailed mathematical flow chart of the algorithm in Appendix C of Jønch-Clausen (1978). The logic and mathematical equations in this flow chart--in which the terminology and notation from Morel-Seytoux (1972) is used--forms the basis for the computer routine. A separate user's manual for the quadratic programming routine has been prepared by Jønch-Clausen and Morel-Seytoux (1977).

Quadratic programming is a convex programming procedure which means that only minimization of a convex objective function over the linear (convex) constraint set will guarantee a global, or absolute minimum. The cost functions in this study, as well as their quadratic approximations, are concave, not convex, and consequently the Kuhn-Tucker conditions may be satisfied at a local, non-global minimum in the expected cost minimization. (The cost variance objective is convex and represents no such problem). In order to solve this problem and try to obtain global solutions when minimizing concave objective functions a special procedure has been added to the standard quadratic programming algorithm which in almost all cases ensures a global solution, or at least a good and very consistent local one.

3.2 *The Non-Convex Programming Problem*--The problem associated with the minimization of a strictly concave objective function is illustrated in Figure B-3. The figure is a simple two-variable illustration of the shortcomings of convex programming techniques in solving non-convex problems.

ABCDEF in Figure B-3 represents the boundary of the convex feasible region given by the linear constraints, and the closed curves represent contours of the strictly concave objective function for objective values between 1 and 5.

In general, if the feasible region is convex and the objective function is concave, it can be proven that the global minimum will be taken on at one or more extreme points of the convex set (Bishop et al., 1975a). However, in a convex programming procedure this global minimum may be hard to find. Assuming that an initial feasible solution for the quadratic programming problem is represented by point I, the point A may be obtained as the minimum in the quadratic programming procedure. The termination criterion in this--as in any other convex programming procedure--is based on local conditions: the Kuhn-Tucker conditions in this case are satisfied because the objective value at the neighboring points B and F are greater than the objective value at A. (In the figure, the objective values at A, B and F are approximately 3, 3.2, and 3.9 respectively). It is evident, however, that point A represents a *local* minimum, the *global* minimum being at point D (objective value: 1).

A possible approach for obtaining the global minimum is illustrated in Figure B-3. Having reached the local minimum at point A, the variables x_i and x_j are changed, one at a time, to the maximum

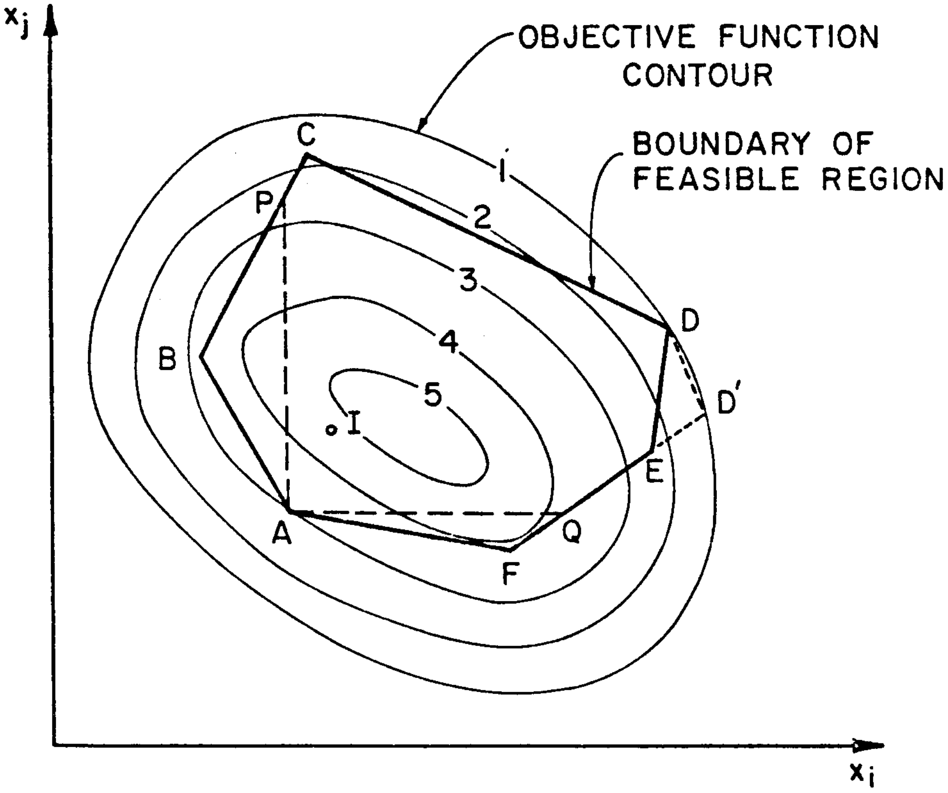


Figure B-3. Minimization of Concave Objective Function (Jønch-Clausen, 1978) possible extent within their feasible ranges. In this case, x_i can be increased until the solution represented by point Q is reached, while x_j can be increased until point P is reached. The objective values at the new feasible solutions obtained this way--represented here by the points Q and P--are compared to the local minimum value to see if any reduction of this value is possible. In this case it is evident that the solution at P is better than the local minimum at A (the objective value at P is 2.5), whereas the solution at Q is worse (objective value 3.8). Taking P as a new initial feasible solution, the quadratic programming procedure is repeated; a new--local or global--minimum is obtained; variables are changed, one at a time, in a search for a better solution etc., until no reduction in objective value is possible. In this case that will happen when the global solution represented by point D is reached.

A search procedure based on the principles outlined above has been programmed and added to the standard quadratic programming routine (subroutine SEARCH). Having obtained a solution for which the Kuhn-Tucker conditions are satisfied, each one of the variables (original as well as slack variables) is increased or decreased as much as possible within the feasible region, and the resulting objective value is saved. The smallest of the objective values obtained in this process is then compared to the local minimum; if the local minimum value is smaller than or equal to the smallest value obtained in the SEARCH procedure, the local minimum is considered global; if on the other hand, a better solution was identified in the SEARCH procedure, that solution is taken as initial feasible solution in a new quadratic programming procedure. This process of alternating between quadratic programming and the

SEARCH procedures is continued until no improvement results in SEARCH. A detailed flow chart of subroutine SEARCH is provided in Appendix C of Jønch-Clausen (1978).

It should be emphasized that Figure B-3 serves as an illustration only; many other situations--different from the one depicted in that figure--may be visualized. However, the basic principles of the SEARCH procedure as derived from Figure B-3 have proven extremely useful. With the introduction of the SEARCH procedure in the quadratic programming routine minimization of concave objective functions have resulted in global minima (or at least good and very consistent local minima) in practically all cases, regardless of the chosen initial feasible solution.

Obviously the approach to non-convexity taken here is possible only because a concave objective function is considered, for which the optimum is known to be at one or more of the extreme points of the convex set (Multiple optima are possible: if in Figure B-3 the convex feasible region were bounded by ABCDD'F, rather than ABCDEF, both of the solutions represented by the points D and D' would be global minima). For a general non-convex objective function the global optimum may be interior in the feasible region, and finding it in a combination of convex programming and some search procedure may be almost impossible. One approach in this situation is to start the optimization process from a number of different initial feasible solutions, accepting the best solution generated in this process as the "optimal" solution to the problem.