

VOLUNTARY BASINWIDE WATER MANAGEMENT
SOUTH PLATTE RIVER BASIN
COLORADO

by
South Platte Research Team

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Report by

South Platte Research Team
Colorado Water Resources Research Institute

Henry P. Caulfield, Jr.
Norman A. Evans
J. Ernest Flack
Neil S. Grigg
David W. Hendricks
John W. Labadie
David McWhorter
Hubert J. Morel-Seytoux
William L. Raley
Robert A. Young
and
J. Gordon Milliken

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Colorado Water Resources Research Institute
Colorado State University
Fort Collins, Colorado 80523
Norman A. Evans, Director

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TABLE OF CONTENTS

	<u>Page</u>
Table	iii
List of Figures	iii
Foreword	v
Summary of the Report	vi
I. Introduction and Purpose	1
1.1 Introduction	1
1.2 Historical Perspective	3
1.3 Stages of Water Management in the South Platte Basin	6
1.4 Water Issues	9
1.5 Some Premises	11
1.6 Objectives	12
1.7 Study Design	14
II. Hydrologic Setting	17
III. Water Management Institutions	27
3.1 Introduction	27
3.2 Water Law	28
3.3 State Administration and Adjudication	31
3.4 Management Institutions	31
3.5 Summary	34
IV. Current Water Management in the Basin	36
4.1 Introduction	36
4.2 Basin Water System	38
4.3 Exchange of Water	40
4.4 Reuse of Imported Water	42
4.5 Conjunctive Surface-Groundwater Management	45
4.6 Water Markets	51
4.7 River Administration	54
V. Management Problems and Issues	58
5.1 Increasing Litigation and Water Use Conflicts	58
5.2 Growing Urban Demands	59
5.3 Water Quality	65
5.4 Use of the Deep Denver Basin Bedrock	67
5.5 Other Issues	74
VI. An Approach for Achieving Integrated Voluntary Management	76
6.1 Types of Voluntary Changes	77
6.2 Possible Formal Institutional Changes	80
6.3 Current Status of Cooperation	83
6.4 A Proposed Experiment	85

	<u>Page</u>
VII. Computer-Based Models: New Ways to Provide Decision Information	91
7.1 Models and Decision Information	91
7.2 CONSIM, A Network Optimization Model	101
7.3 A Stream-Aquifer Model - (SAMSON)	113
7.4 Economic Modeling	124
VIII. Conclusions and Implementation Plan	129
Appendix A: South Platte Bibliography	132
Appendix B: General Problems and Issues	149

TABLE

	<u>Page</u>
Table 1-1 Optimal Evolution of Arid-Area Water Allocation, Charging and Regulatory Institutions	8

FIGURES

Figure 2-1 South Platte River Basin in relation to states boundaries . .	18
Figure 2-2 Monthly distribution of discharge, South Platte River at South Platte Gaging Station (RK 563.5) for Period 1968-82 . .	20
Figure 2-3 Average Annual Discharge, 1968-72, at Gaging Stations along the South Platte River	20
Figure 2-4 Map of irrigated lands in the South Platte River Basin . . .	21
Figure 2-5 Map of Groundwater Study Area of the South Platte River in Colorado	23
Figure 4-1 Reuse of Imported Water by Exchange	43
Figure 5-1 Surface Outcropping of Denver Basin Aquifers	69
Figure 5-2 Aquifers of the Denver Basin: Vertical Profile	70
Figure 6-1 Sequence of Decisionmaking for a "South Platte Federation" .	87
Figure 7-1 How Water Decisions Affect Economic Outcomes	93
Figure 7-2 The Decision Support System	94
Figure 7-3 General Model Formulation and Use	97
Figure 7-4 Network Representation of the Cache la Poudre River Basin's Physical Features	102
Figure 7-5 City of Fort Collins Water Supply System	105
Figure 7-6 Link-Node Configuration for Fort Collins Case Studies	106
Figure 7-7 Approximate Spatial Decomposition of the Case Study Area . .	108
Figure 7-8 Network Representation of the Case Study Area	109
Figure 7-9 Change in Subsurface Storage with Artificial Recharge and without Artificial Recharge	110

	<u>Page</u>
Figure 7-10	Example of Demand Satisfaction for Node 32, Iliff and Platte Valley 111
Figure 7-11	General Boundaries of the Grid System 115
Figure 7-12	Detail of Descretized Physical Systems Near Balzac 116
Figure 7-13	Structural Features and Operation of SAMSON 117
Figure 7-14	How SAMSON Works, a Conceptual Depiction 118
Figure 7-15	Comparison of Historical and Computed Monthly Values at Kersey 120
Figure 7-16	Comparison of Historical and Computed Monthly Values at Weldona 121
Figure 7-17	Comparison of Historical and Computed Monthly Values at Balzac 122
Figure 7-18	Comparison of Historical and Computed Monthly Values at Julesburg 123

FOREWORD

This report is about the stewardship of one of Colorado's most valuable natural resources--the South Platte River and its tributaries. It considers ways that scientific knowledge and the experience of water users and administrators can be used for voluntary decisionmaking. It is intended to help set the stage for individual and group actions that will result in increased opportunities for integrated water management in the South Platte Basin, with corresponding improvements in efficiency of water use and reduction of conflicts over its use. Workshops are proposed to demonstrate the expected utility of new technological advances discussed in the report, to encourage discussion of ways these technologies can best be utilized and to solicit comments and suggestions for their implementation.

The report has been prepared by the "South Platte Research Team," an interdisciplinary and inter-university group working through the Colorado Water Resources Research Institute (CWRRI). Members of the team include: Norman A. Evans and William Raley of the Institute staff; CSU faculty members Henry Caulfield (Political Science), Robert Young (Agricultural and Natural Resource Economics), Neil Grigg, David Hendricks, John Labadie and Hubert Morel-Seytoux (Civil Engineering), David McWhorter (Agricultural and Chemical Engineering); and CU Faculty member J. Ernest Flack (Civil Engineering). J. Gordon Milliken, formerly of the University of Denver Research Institute, participated as a corresponding member.

SUMMARY OF THE REPORT

Demands for water in the South Platte River Basin are the most intense in Colorado and the result is increasing conflict over water use. The resulting litigation places financial burdens on water right owners, increasingly impacts the judicial system and stresses the capacity of the state administrative agencies to make their decisions.

A voluntary association of water right owners is proposed as a mechanism to increase the options of water users and reduce conflict over water use. The initiative for organizing the association would be by the water right owners themselves. The South Platte Research Team believes that such an association could help achieve voluntary integrated basinwide water management.

An association of water right owners would need information on management and exchange possibilities and the resulting impacts on both surface and ground waters. Computer-based models can provide the information. Two hydrologic and decision models which are available at Colorado State University for this purpose are described. Other hydrologic models and economic models can also be utilized by the association.

Finally, the report sets forth a plan of implementation. Through workshops, water right owners or representatives of their associations can become familiar with the potentialities of computer-based models for testing the feasibility of possible water exchanges and transfers. They can also consider the feasibility of a South Platte Federation in facilitating such actions with the help of technically available knowledge. If they deem these potentialities practicable and they accept them, further steps in implementation are proposed.

VOLUNTARY BASINWIDE WATER MANAGEMENT:
SOUTH PLATTE BASIN, COLORADO

I. INTRODUCTION AND PURPOSE

1.1 Introduction

The focus of this study is the South Platte River, the most developed and over-appropriated of Colorado's major streams. Managing the South Platte has become very difficult due to the complexity of the rules, laws and actual water use practices in effect. Since property rights are involved, the stakes are important to many individuals and organizations, and litigation over water matters has been increasing steadily. These issues are made more complex by urban growth pressures, industrial development and agricultural shifts.

The study is based on the assumption that computer-assisted modern technology can provide information that will lead to better water decisions on the South Platte River and its tributaries. Better water decisions are needed to enable water right owners to use and exchange or transfer their water with a minimum of uncertainty and conflict, and with minimum administrative cost. The technology takes the form of "models," most of which are computer-based, data and new information and knowledge that results from studying the basin.

The basic premise of this report is that voluntary, cooperative decisionmaking and operations can reduce the administrative cost and conflict to South Platte water right owners, and increase their ability to take advantage of both surface and ground water supplies. If there is to be more cooperation, then water right owners must have full and clear information about the courses of action available to them. Still, the problem is difficult, and the team presents this report as a contribution, not the final answer to the problem.

The research team recognizes that it is economic self-interest that motivates decisions about water, not a more general sense of the "public interest." The team fully recognizes that what we sometimes call "water management" is, in reality, the collection of many individual and group actions, each responding to self-interest. These actions can be aided by the application of informed group decisionmaking. No overall water authority can make decisions about how to manage the basin's water resources that will gain widespread acceptance, but there are ways that benefits from individual decisions can be increased for all concerned through cooperation. This is the "win win" goal of this research effort.

The need for more cooperation has been recognized for years. For example, in 1960, Edward Moulder, of the US Geological Survey, called for a "practical approach" to decisionmaking by voluntary groups (1). More recently, there have been moves to form associations of water users to improve water use alternatives. There seems to be a trend in public thinking about the need for more cooperation in water decisionmaking, and it may be that voluntary, cooperative water management is an "idea whose time has come" within the basin. It is expected that if water right owners know the opportunities for mutual improvement they will act accordingly.

In effect, the research team is proposing a more comprehensive and informed approach to administering the water law. In the beginning there was no control on water use, but quickly the river was developed and the state put into effect a system of surface water rights. Later it became clear that groundwater also needed regulating. Since the

water law was assembled incrementally, the system of surface-ground water management has become somewhat cumbersome. New mechanisms are needed to improve its operation.

Water management policies and procedures within the South Platte Basin are deeply intertwined with history. For this reason, it is necessary to provide an historical perspective on those now in effect. Following the next section on historical perspective, an analysis is provided of the stages through which water management has proceeded. This section is further elaborated in Chapter III, and Chapter IV.

1.2 Historical Perspective

Major Stephen H. Long and General John C. Fremont came up the South Platte River in 1820 and 1842. Both of them questioned the value of "The Great American Desert." They found nothing but shallow valleys and flat prairies populated by enormous buffalo herds and roaming Indians. The fur trappers followed the military explorers and established trading posts at Ft. St. Vrain and Ft. Lupton to barter with the Indians. Next came the cattlemen who established ranch headquarters on the South Platte; but they ranged their cattle herds widely, wherever grass and water could be found.

The population on the river remained quite sparse until the "gold rush" of 1859. This started a large influx of opportunityseekers. However, the lure of gold brought only disillusionment to many who eventually turned to more stable enterprises such as growing crops and selling them to the "boom town" of Denver and the mountain mining camps.

Of necessity, these miners-turned-farmers became pioneer irrigators. The rush for gold turned into a scurry to the river.

Diversions and ditches were built as these novice westerners learned of the necessity for irrigation to raise a crop in this "Great American Desert." All of these activities were initially performed in the spirit of rugged individualism. Very little, if any, cooperative enterprise took place. Each person "pulled himself up by his bootstraps." Very soon, however, these rugged individualists learned that building major irrigation works was a costly and difficult task, and they began to pool their resources. By 1882 the Cache La Poudre River, a major tributary of the South Platte, was a vast network of irrigating canals.

A century of water development began with the first ditch, built by the Lower Boulder Irrigation Company in 1859. This development was followed by the construction of many other ditches throughout the South Platte Basin. One of the most famous irrigation developments was accomplished by the Union Colony. This cooperative was organized by Nathan Meeker and promoted by Horace Greeley of New York with his famous saying, "Go West, young man. Go West!" While the colony members had little knowledge of farming and none of irrigation, they succeeded in one of the first large irrigation developments in the South Platte Basin.

Initially, it was generally believed that the mountain streams could supply all the land that could ever be brought under a ditch. However, for the first time in the mid-1870's, some of the ditches lacked enough water. Visionary farmers began to look for ways of increasing the water supply. Irrigators pooled their resources to build storage reservoirs and eventually the idea of diverting water through the mountains from the Colorado River Basin began to evolve. Several diversions were accomplished before 1900.

A preliminary survey was made in 1881, and in 1905 a group of Colorado A & M students made a study of the feasibility of the diversion of water from Grand Lake. This was a sizable task which was eventually accomplished by construction of the Colorado Big Thompson Project.

It was authorized in 1938 and was completed in 1955, after a major interruption caused by World War II. This gigantic project undertaken by the U.S. Bureau of Reclamation was made possible only through the cooperative efforts of many individuals, local ditch companies, irrigation districts, state government, water user associations, and cities, with the federal government. The formation of the Northern Colorado Water Conservancy District, which has provided the reimbursement of costs assigned by federal law to local interests, was essential to accomplishment of this project.

In retrospect, history has shown that the people of the South Platte Basin have learned to work together to accomplish mutually beneficial tasks. It was impossible for individuals working alone to build most of the existing facilities. As we look to the future we may be making a transition from an era of water development to an era more of water management. With our system of water law, it is impossible for a single individual to manage the South Platte River and its tributaries. However, those same principles of cooperation that brought us through the era of development should also be able to take us into a new era of voluntary basinwide water management. Stated another way, for individual water right owners to maintain their water rights in the face of increased pressure, a new approach to cooperation will be required. Everyone stands to gain if the new approach succeeds; if not, the losses could be very damaging.

1.3 Stages of Water Management in the South Platte Basin

A general concept underlying the analysis is that as the complexity and intensity of water demands increase (from a growing population and economy), the value of water rises and the appropriate technological and institutional mix evolves and changes. Such changes are observable in the South Platte Basin. It is our intent to be prepared with analytic procedures and institutional means to ease the transition among stages. We attempt to elaborate on this general concept below.

First, water allocation and pricing institutions are costly to administer. These costs, termed transaction costs in economic jargon, increase with the complexity of the institutional arrangements. (Transaction costs include (a) the information costs of the providers and recipients of goods and services in the economy; (b) the cost of making contracts and agreements; and (c) the costs of policing these contracts.)

Second, social benefits (in the form of more productive and equitable resource allocation and reduced conflicts) are derived from improved water allocation institutions.

Third, as with all productive activities in the economy, resources devoted to administration are subject to diminishing returns.

Hence, the optimal degree of social expenditure on administration depends on the stage of economic development and the unit value of water. Where water is plentiful relative to demands, little or no regulatory effort is required (e.g. the riparian doctrine of water law can suffice). Where demand presses against supplies, more complex institutional arrangements are called for. Water rights first must be secure, affording protection of tenure and from physical uncertainties

(e.g. the basic prior appropriation doctrine). At a later stage, procedures for exchange of water rights within and between economic sectors are called for.

Table 1-1 shows a generalization of the above propositions. Drawing on the work of Rostow and his framework of stages of economic growth, together with Boulding's and Ruttan's concepts of induced institutional and technological innovation, a five-stage model of the optimal evolution of a water allocation system is presented (2,3,4).

The first portion of the Figure identifies objective characteristics of the water economy through the various stages. The growth process in the regional economy is seen to increase the complexity of water demand. (Higher valued crops come in to compete for water, later abetted by growth in non-agricultural sectors). The economic value of water rises in concert with these changes.

Ultimately, growth and change lead to an increased return to expenditures for new technologies of water supply and delivery and to new institutional arrangements. The five steps in Figure 1-1 identify hypothesized discrete steps occurring as water becomes more scarce and valuable. With each higher numbered stage, the technological-institutional system becomes more complex. In later stages water pollution and other unpriced environmental costs become evident.

The columns on the second half of the Figure represent various hypothesized institutional reactions to the changes identified in the left columns. Evolution of water allocation institutions proceed from "open access" (no effective regulation) to a fully articulated water rights system. Similarly, hypothesized progression through stages of pricing and environmental regulations are shown.

Stage	Status of the Water Economy				Appropriate Institutional and Management Responses				Representative Example
	Character of Water Supply	Character of Water Demand	Equilibrium Water Value	External Damages	Allocative Mechanism	Water Measurement Techniques	Pricing/Charging Mechanisms	Regulation of External Damages	
I	plentiful self or small-group supply	demand limited; primarily homogeneous agriculture	zero	none	open access (right to use; minimally circumscribed)	none	none (self supplied or flat land charge)	none	Riparian doctrine (eastern U.S.); Egypt
II	largely allocated	nonhomogeneous agriculture; emerging M & I	low	some (from neighbors) and M & I discharges	simple property right; (use plus exclusion)	ditch, flow time	flat charge or crop charge	protection against immediate source of damage	early appropriation doctrine (western U.S.); Warabandi System (India, Pakistan)
III	fully allocated; high-cost local supply	complex agriculture; growing M & I sector	medium	ag damages from distant sources (salinity, waterlogging)	advanced property right (use, exclusion exchange within sector)	flumes, flow time	fixed charge for capital recovery + variable O & M (marginal) cost recovery	above plus protection from complex, distant sources; public subsidy for remedial programs	advanced appropriation doctrine (western U.S.); Valencia (Spain), NW Mexico
IV	fully allocated; perhaps interbasin supply	highly complex agriculture; large M & I sector; emerging instream demands	high	instream uses impaired	complete property right (use, exclusion exchange between off-stream sectors)	partially metered	above plus market to reflect opportunity cost of water in withdrawal sectors	above plus effluent standards	Northern Colorado Water Conservancy District; Metropolitan Water District of Southern California
V	fully allocated, high-cost interbasin supply	high-valued agriculture; large M & I; large instream demand	very high	internalized or controlled	complete property rights for instream & offstream uses	fully metered	above plus market to reflect opportunity cost in instream uses	above plus effluent charges; marketable effluent permit	Israel; northern Colorado water markets

Table 1-1. Optimal Evolution of Arid-Area Water Allocation, Charging and Regulatory Institutions

1.4 Water Issues

Turning now to the current situation, what are the issues facing the State and water right owners as they seek to find the best ways to operate the South Platte River and its tributaries? These issues have been summarized in several recent studies, such as the five-year research plan of the Colorado Water Resources Research Institute and studies by the Colorado Water Conservation Board and several citizens' groups (5,6,7,8,9). Two of the issues that are described in the five-year research plan underscore the economic importance of water problems facing the State: excessive loss of entitlement water from the South Platte River Basin; and sub-optimum use of the available water in the alluvial river-aquifer system of the river and its tributaries. These two problems are at the heart of the concerns addressed by the research team, and are important to individual water right owners and to the public at large.

The Colorado Front Range Project, under the auspices of the Governor's Office (8), summarized the basin's water problems in the form of five objectives, all of which can be addressed in the approaches suggested in this report:

- (1) increasing cooperative decision-making;
- (2) increasing efficiency of water use;
- (3) developing Colorado's compact entitlements;
- (4) reducing agricultural vulnerability; and
- (5) minimizing adverse ecological impacts.

These objectives pose a challenge to water right owners and water officials and administrators as well as legislators.

The proposals in this report cannot achieve all of these objec-

tives; but they can contribute to their achievement. They provide avenues for improving the operation of the water available in the basin, and for developing better information leading to future decisions about the location, timing, and size of new development projects.

The water management system of the basin has evolved over decades on an "as needed" basis. A number of different management organizations have been created, each of whose decisions could affect every other entity to some degree. Thus, intentions for decisions need to be communicated among the management entities so that conflicting interests may be identified and resolved as needed. Their interaction and interdependency between and among a growing number of water management entities, as well as the number and complexity of the political and institutional entities involved, complicates communication. Such communication is vital in forestalling conflict and avoiding counter-productive decisions from a basinwide, statewide or national perspective.

The basin's water right owners need a way to achieve a healthy balance between new projects and more effective use of existing management opportunities, such as aquifer storage and planned exchanges. Conjunctive use of surface and groundwater offers a possibility for approaching optimal use of the basin water supply. Good long-range planning would seek the optimal mix of groundwater and surface water use together with surface and groundwater storage, to provide the least-cost supply to the array of water users.

There can easily be conflict between local government and conservancy districts or other large entities concerning strategy for meeting water supply needs of a local entity. The local perspective is to

seek management improvement measures as a means of extending the utility of present supplies as well as in the acquisition of new supplies. A large-scale, capital-intensive developmental strategy may not harmonize with this viewpoint. The important consideration of integrating the large-scale system with local supply options and fiscal constraints has been given too little consideration in the past.

Water rights issues have seldom involved water quality constraints, but they probably will in the future. How could basinwide water management contribute to improving quality for some water requirements, where quality is crucial? Management options in this regard may offer considerable opportunities for substantial economic gain. Beneficiaries might be able and willing to pay the cost of certain management changes to maintain and improve water quality.

Groundwater recharge for storage and later recovery over several years ought to be given strong emphasis in the future. Strategies for implementing recharge at the most efficient and effective locations with respect to conjunctive surface-groundwater management ought to be investigated.

These issues, along with some broader management questions, are discussed in greater detail in Chapter V.

1.5 Premises

In designing this study, various projections of the future operating climate were necessary. Projections made by the study team included the following:

- (a) The Federal Government is not expected to try to solve most water planning problems in the future.

- (b) Water problems are sufficiently urgent that local-level water managers will not and should not wait for State-level initiatives.
- (c) Local-level water managers are searching for comprehensive plans, ways of evaluating options, and methods for integrating (coordinating) leadership in developing supplies and/or improving management.
- (d) All water exchanges agreed upon by all parties affected, in principle, improve efficiency in the direction of optimal use.
- (e) Quasi-public organizations offer great potential to take leadership in the improvement of water right owner decisions for their benefit.
- (f) The opportunity is before the water users and water right owners within the basin to move toward a cooperative process for policy direction and decisionmaking.

1.6 Objectives

In a recent study of Colorado water institutions, Foss (10) identified two general approaches to improve the effectiveness of water management:

(a) improvements in water technology; and (b) changes in the institutions for managing water. The objectives of this report involve both of these approaches. New technological tools which are available to improve the effectiveness of water management depend on the computer and its capacity to store millions of numbers and perform computations at high speed. Recent research and technological development has permitted the development of two computer models for use in the South Platte Basin: SAMSON and CONSIM.

A model for simulating basinwide surface-groundwater interaction (SAMSON) has been developed independently of this project and demonstrated for the lower 100 miles of the basin. This new technology, with required data inputs, can provide the means to test day-by-day responses in the surface-groundwater system throughout the basin for any proposed project or change in management strategy. It also affords a new tool for improving conjunctive administration of surface and groundwater rights which can facilitate more optimal basinwide water use.

The second model, CONSIM, can provide for planning the optimization of water availabilities throughout a river basin, subject to water rights constraints and operational decisions. The effects of reservoir location, size, and operational rules on water availability can be evaluated.

Both of these models are discussed more fully in Chapter VII. In addition, economic models are discussed.

The second objective, to improve the effectiveness of water management through institutional change, is treated in Chapter VI. An approach for achieving integrated voluntary management is proposed: The South Platte Federation. The basic function of the Federation would be to facilitate the provision of necessary information and the making of mutually advantageous water exchange among its members. It would have no plenary authority to order anybody to do anything against their interest.

With many interest groups concerned with water in the Basin, and with the personal-property character of water rights, it will never be possible, nor would it be desirable, for state government alone to make all the necessary decisions. There must be a base of comprehensive information and potential impact evaluation (basinwide) such that

conflicts can be resolved and best decisions made. Scientific modeling and information systems can provide the basis for this kind of mutually beneficial decision-making.

1.7 Study Design

The general approach of this research project was to work to integrate the expertise of Colorado water scientists and engineers with the practical concerns of water administrators and water right owners and to make a critical analysis of the ways in which computer-assisted technologies could be used to provide information that would lead to better water decisions. The research team was selected to take advantage of the researchers' capabilities and experience in several areas of concern in the South Platte Basin, and to integrate their knowledge about the demands for decision information and the supply of technologies available to furnish it. The result was this report, covering the concepts necessary to support new approaches to decision-making, the information resources available and the institutional developments which might enable the use of information to improve decision-making. Since research and problem-solving are continuous processes, this report should be viewed as a part, rather than the end, of the research process.

Although this report is not a "final solution," the research team sees it as a document which can serve as the starting point for very significant practical action. Every study must start with an assumption. In this case the assumption is that operation of the basin can be improved. This is not a simple question, since the existing system of checks and balances has evolved over many years and involves substantial property rights and powerful interest groups. The research

team did not begin with the naive assumption that a single research report could have a dramatic impact on water management in the basin without a convergence of additional forces. Neither did it accept the popular feeling within the basin that water management is already "optimal". The assumption is simply that improvements can be made, and that the means to do so will be tested in the years ahead.

Due to the complexity of the issues involved, it is not possible to fully test this assumption in a single effort. Additional steps constituting a plan of implementation will be necessary, as set forth in Chapter VIII. The stakes are large, and a great deal of additional work will be necessary. This work is obviously not in the hands of the researchers alone. The full process is likely to take a long time and require leadership from many quarters especially from the basin's water right owners. Considerable perseverance on the part of both researchers and owners will be required.

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II. HYDROLOGICAL SETTING

The South Platte water system in Colorado has evolved from the "natural" state to one which is highly developed. The natural hydrology is, in fact, dominated by man in the plains. It is managed by a multitude of institutions. A social-political-hydrological equilibrium generally exists. This chapter describes some of the salient physical features of this system (1).

Area. The South Platte River Basin has an area of 24,030 square miles (62,238 sq. km), with 19,020 square miles (49,262 sq. km) in Colorado. Figure 2-1 shows the basin on a map in relation to the State of Colorado and also Wyoming and Nebraska.

Physiography. The western part of the basin is dominated by mountains known as the "Front Range," which are a part of the Colorado Rockies. Several peaks rise above 14,000 feet (4267 m).

The mountain snowpack is, of course, the main source of water. The tributary streams drain the snowpack, with drainage occurring mostly as spring runoff. Then throughout the rest of the year groundwater derived from the snowpack sustains a modest base flow. As the streams emerge from their mountain canyons, canal diversions form a reverse dendritic pattern carrying water to off-stream storage reservoirs and adjacent irrigated lands. Figure 2-4 is a map of the basin showing the stream system and irrigated lands.

Precipitation. The average October-April precipitation in the Basin varies from 3.5 inches in the lower plains to 22.5 inches in the mountains, occurring mostly as snowfall. The average May-September precipitation varies from 6.5 inches in the lower plains to 15.0 inches in the mountains.

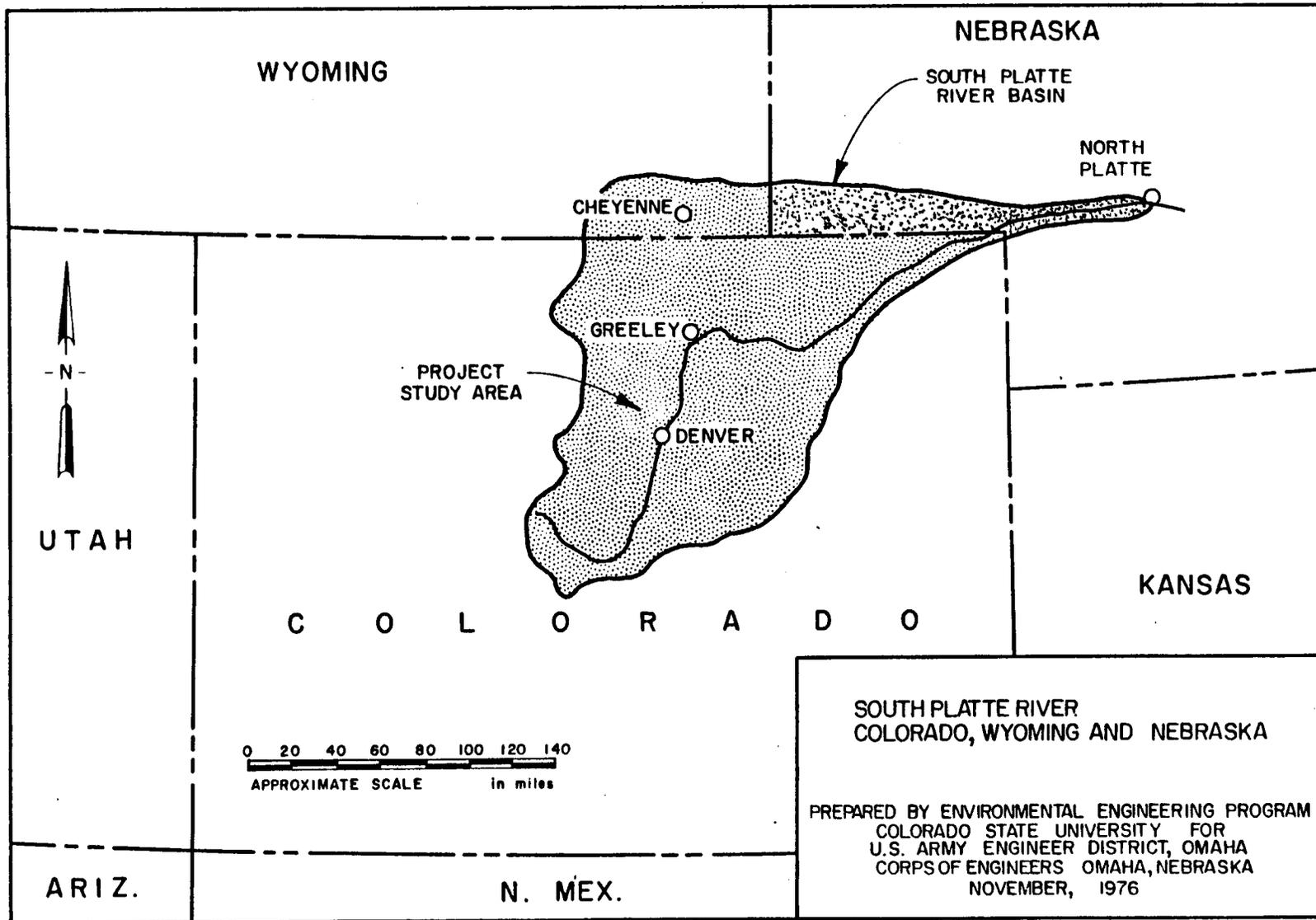


Figure 2-1. South Platte River basin in relation to states boundaries

Streamflows. Figure 2-2 shows the monthly distribution of average stream discharge for the South Platte River at the gaging station at South Platte, Colorado. Typically, about 70 percent of the annual discharge occurs during spring runoff. The three hydrographs shown are representative of the yearly variations in annual discharge. The lower hydrograph is a drought condition while the upper one is a year of high runoff.

Figure 2-3 shows how the river flow changes with distance from the South Platte Gaging Station to Julesburg. During spring runoff in June the tributaries between Denver and Kersey, e.g. Clear Creek, St. Vrain Creek, etc., contribute flow while diversions occur from Kersey to Julesburg, reducing the streamflow. The high flows at Kersey reflect the contribution of the Cache La Poudre River.

Summer flow conditions prevail in August with diversions from the tributaries and main stem, while the reaches below the tributaries are replenished by return flows. In February, the return flows dominate the flow pattern, but diversions from Kersey to Julesburg cause precipitous declines in flow. Flows then steadily increase along the reaches by return flows from the adjacent aquifer.

The average monthly runoff is highly variable, as indicated in Figure 2-2. The average annual native runoff is about 1,440,000 acre-feet. However, in 1970, which was a wet year, the runoff was 1,900,000 acre-feet and during the 1953-56 drought, it averaged 842,000 acre-feet per year.

Imported Water. Some twenty ditches and tunnels carry 370,000 acre-feet of imported water from the North Platte, the Colorado, and the

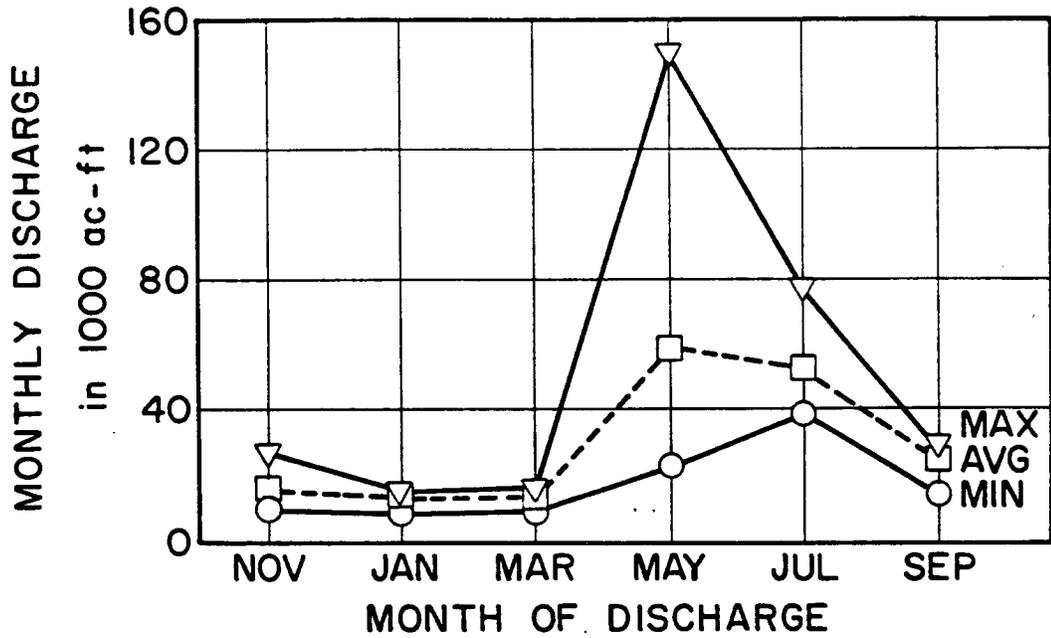


Figure 2-2. Monthly distribution of discharges, South Platte River at South Platte Gaging Station (RK 563.5) for period 1968-82.

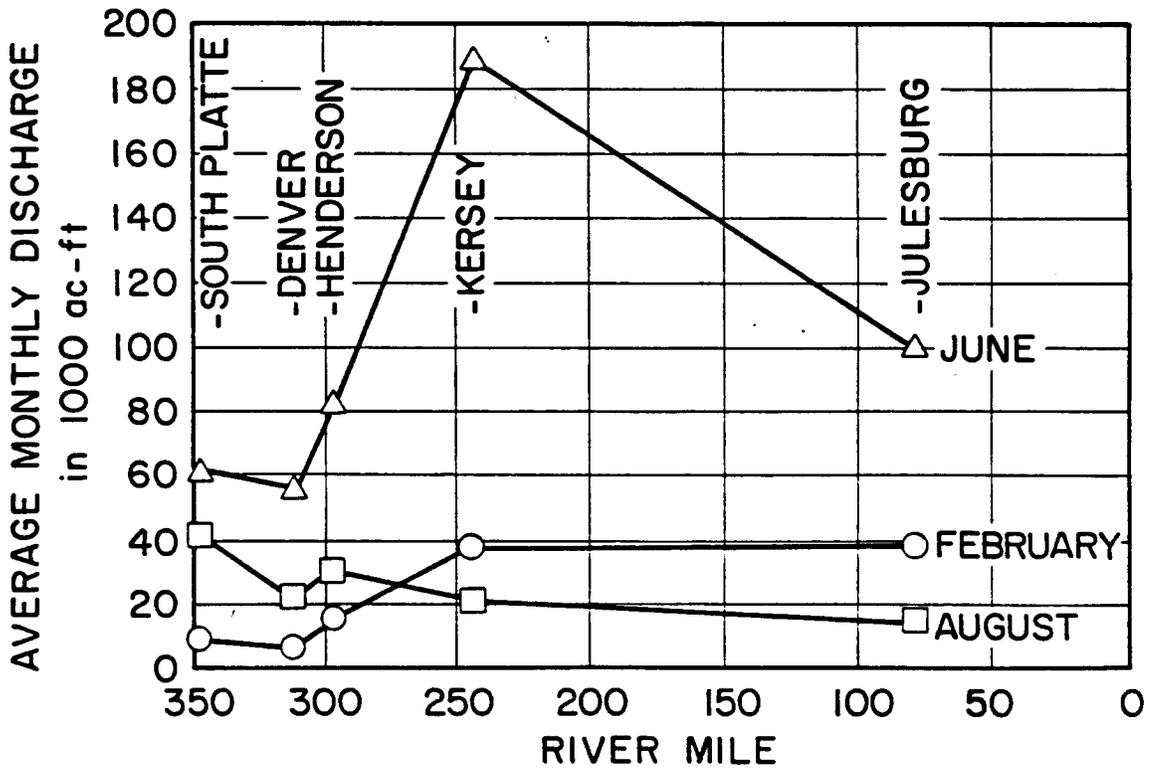


Figure 2-3. Average annual discharge, 1968-72, at gaging stations along the South Platte River.

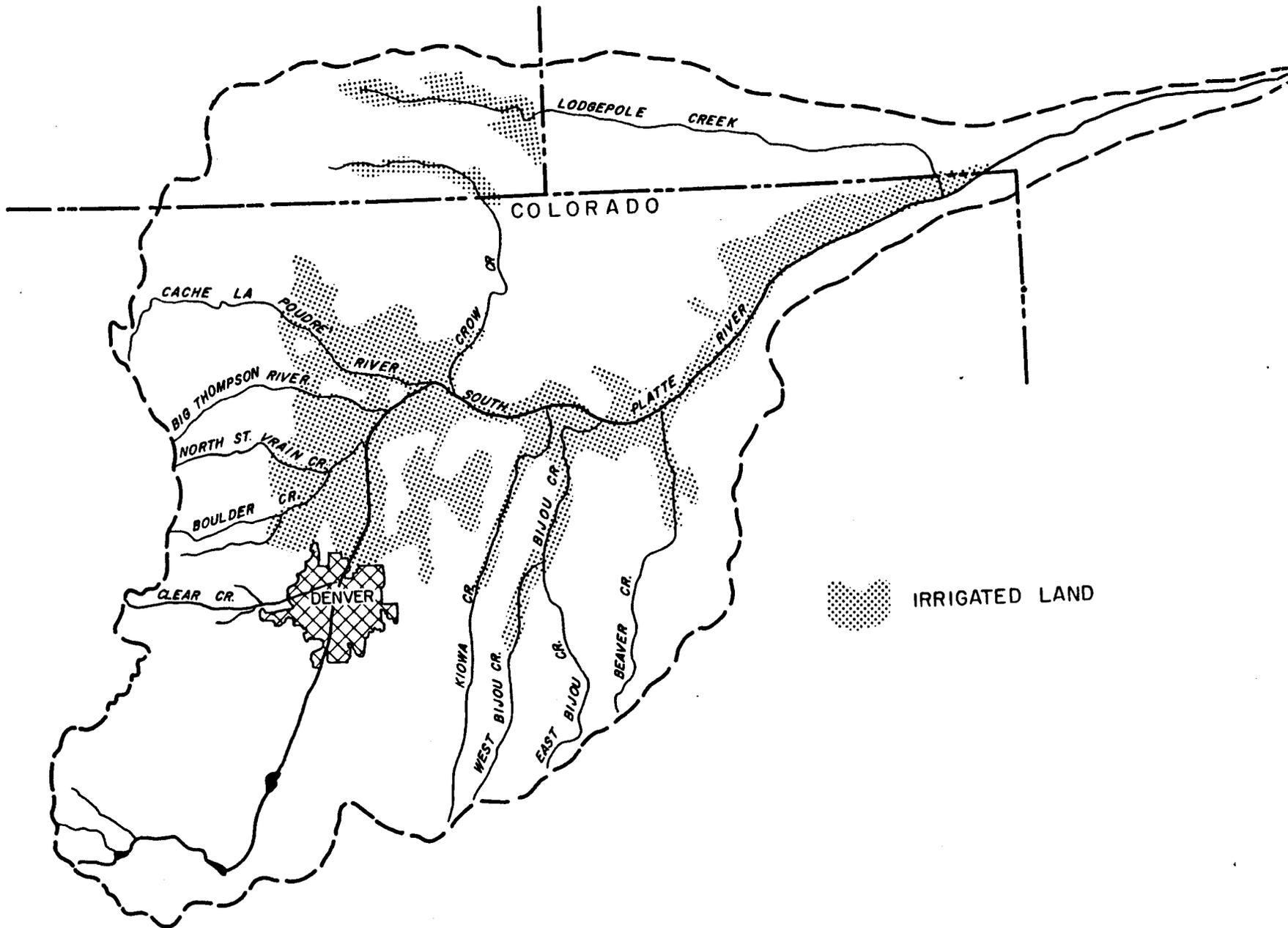


Figure 2-4. Irrigated lands in the South Platte River basin (Turner and Hendricks, 1984).

Arkansas River basins into the Basin. The Colorado-Big Thompson Project alone accounts for 227,000 acre-feet per year from the Colorado River Basin.

Ground Water. Most of the interest in ground water has been focused on the alluvial aquifer extending from Denver to Nebraska. Some 1,600,000 acre-feet was pumped from this aquifer in 1970, a year which just followed the start of groundwater regulation. The estimated storage is 8,330,000 acre-feet (2). In addition, the tributaries of the South Platte are underlain with tributary groundwater that adds to the Basin's total supply. Clearly groundwater is an important part of the South Platte water resource system. (Figure 2-5).

Deep aquifers of the Denver basin have not been exploited extensively. The volume of water in storage in these aquifers is estimated to be 250 to 300 million acre-feet, with 40,000 to 100,000 acre-feet/year recharge. The annual pumped volume is on the order of 150,000 acre-feet. These aquifers have an important role strategically, particularly if they were mined only during times of drought.

Reservoirs. There are some 370 reservoirs in the basin having storage capacities in excess of 500 acre-feet. The collective storage volume, excluding Horsetooth Reservoir and Carter Lake, is about 1,300,000 acre-feet, secured by 1,200 decreed storage rights. Horsetooth Reservoir and Carter Lake, which add another 263,000 acre-feet of storage, are used for Colorado-Big Thompson Project water. The total storage capacity of offstream reservoirs in the Henderson-Julesburg reach is 274,000 acre-feet.

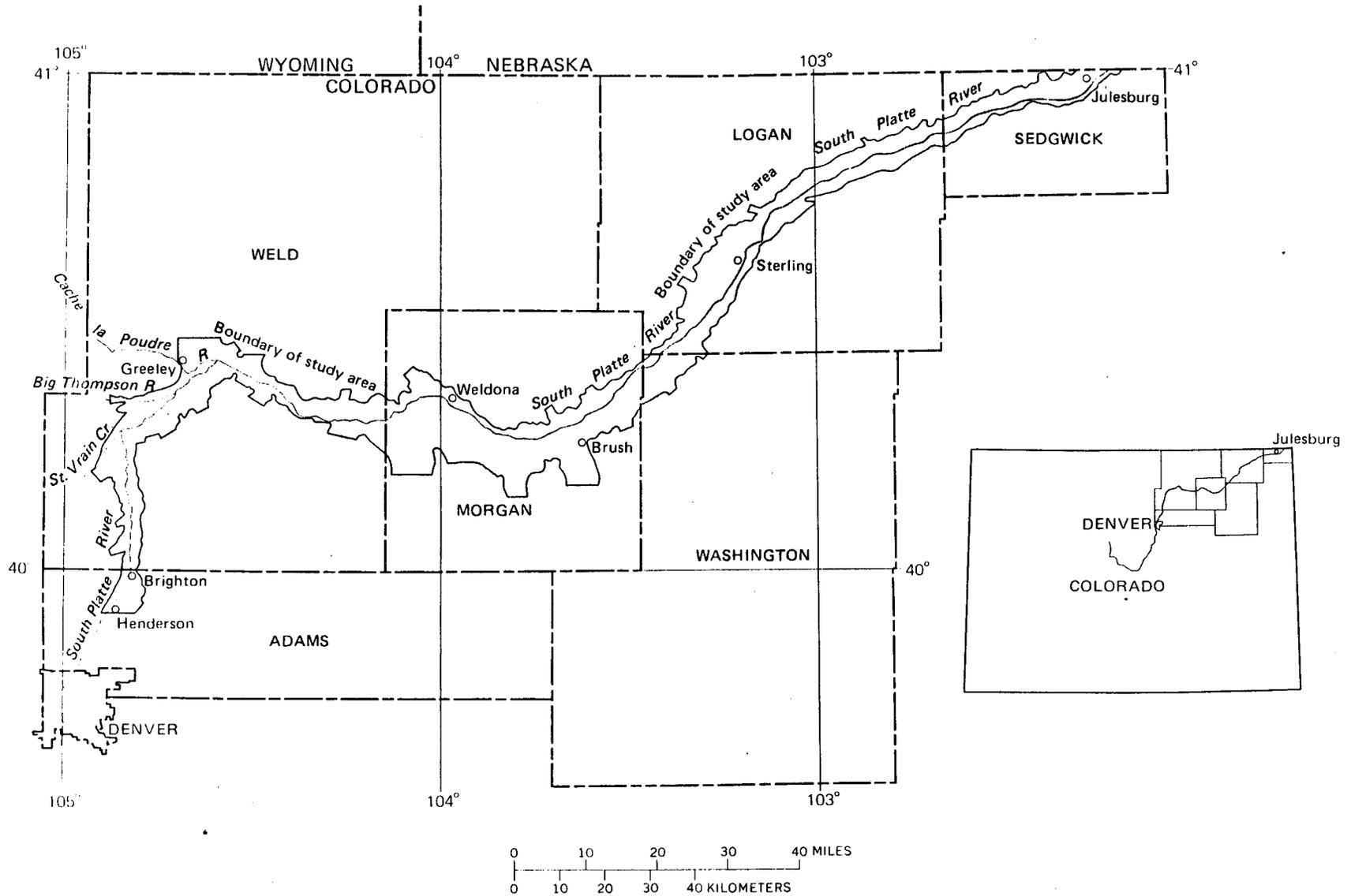


Figure 2-5. Map of Groundwater Study Area of the South Platte River in Colorado.

Source: Colorado Water Resources Circular No. 28, U.S. Geological Survey and Colorado Water Conservation Board, 1975, p.3.

Diversions. During the 1970 water year the total surface water diversions within the basin were nearly 3 million acre-feet. Irrigation withdrew over 2.5 million acre-feet and municipal and industrial water users took 471,000 acre-feet, of which 110,000 acre-feet was for industrial use. Some 542 canals diverted water from the South Platte and its tributaries.

Water Rights. About 4,500 direct flow rights have been decreed, with a collective entitlement of 30-million acre-feet if exercised continuously. As previously noted, there are 1,200 decreed storage rights within the Basin, which yield collectively 1.3 million acre-feet of storage. But most such rights are restricted to periods of time and quantities of flow for use.

Irrigation. Figure 2-4 shows the areal distribution of irrigated lands in the South Platte River basin in Colorado. Total acreage is about 1,300,000 acres.

About 500,000 acres of land are irrigated along the main stem of the South Platte River between Henderson and Julesburg having average diversions of 950,000 acre-feet per year between 1965 and 1977. Some 57 canals divert water in this reach. The lands are irrigated by direct flow rights from canals, by storage from reservoirs, and by pumping from alluvial aquifers.

Municipal Use. A continuous urban region is emerging from Denver to Fort Collins (and indeed to Colorado Springs) (3). The nominal per capita domestic water use has been about 220 gal/person/day (gpcd) in the past, but ranged from 170 for Boulder to 230 for Denver. The 220 gpcd is about 9.25 acre/person/year.

Salt-Balance. The salinity of the native flows and imported water, expressed as total dissolved solids, are nominally about 50 mg/L. This water is applied to the irrigated lands adjacent to the tributary streams. After spring runoff, about July, the flows in the tributary streams are comprised mostly of return flows, and salinity levels are about 1200 to 1400 mg/L. These are the waters diverted to the lower lands on the tributaries and the main stem. Thus salts are leached from the upper irrigated lands and are applied to the lower irrigated lands. It is especially important, then, that the salt balance for these lower lands be restored if irrigated agriculture is to be continuous. Preliminary evidence indicates salts may be accumulating on some of the lower lands within the Basin.

Summary. Despite the availability of only 1.5 million acre-feet/year replenishment in native surface water flows and imports, the annual surface withdrawals are 3.5 million acre-feet. This results in a re-use factor of about 2.5 to 3.5; in other words the virgin water supply is withdrawn an average of about 2.5 times. With each withdrawal, consumptive use occurs, depleting the available supply until only a part of the original flow remains at the Colorado-Nebraska state line. The water is used to the point that flows across the Colorado-Nebraska state line average only about 300,000 acre-feet annually.

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III. WATER MANAGEMENT INSTITUTIONS

3.1 Introduction

In Chapter II the basic physical dimensions of the management problem were discussed. Colorado has pioneered in the establishment of water institutions and in adopting those institutions to changing needs. In this chapter an overview of the existing institutions is presented.

Institutions can be defined as "relationships between people which define their rights, privileges, and responsibilities." Through the recognition of rights of individuals, institutions facilitate the achievement of individual objectives, but they also constrain those rights to protect the individual rights of others and the common concerns of all (1).

Within this definition three institutional levels can be distinguished:

- (a) informal institutions such as modes of behavior and social values;
- (b) contractual arrangements; and
- (c) formal institutions such as laws and regulations.

The "work ethic," as an informal institution, facilitates achievement by stimulating individual productive action while other values constrain individual actions that would harm other individuals. Contractual arrangements facilitate and control valuable, mutually advantageous exchanges. Water rights are formal institutions under Colorado water law which facilitates individual action in the rightful use of water subject to the wellknown constraint of "first in time is first in right."

All three levels of institutions are necessary to make voluntary basinwide water resources management work. The principal thrust of this research report, as previously indicated, is to find ways to make it work through advantageous mutual action. Institutionalization of such mutually advantageous action can then be effected by contract, but such contractual arrangements must be consistent with laws and regulations.

The formal institutions of concern to those seeking new opportunities for mutually advantageous action in the South Platte River Basin are briefly discussed below under three major headings: (1) Water Law; (2) State Administration and Adjudication; and (3) Management Institutions.

3.2 Water Law

Water law for surface waters in Colorado relies on the Prior Appropriation Doctrine and has four major elements (2):

- (1) water is state property not subject to private ownership;
- (2) a vested right to the use of water may be acquired by appropriation for beneficial use;
- (3) the first person in time to use the water is first in right; and
- (4) beneficial use is the basis, the measure, and the limit of the right.

Over time a variety of supplemental principles and assumptions have been used to modify and adapt these basic elements of law to changing conditions. A statute (Colorado Revised Statutes, 37-92-103) provides that

"Beneficial use is the use of that amount of water that is reasonable and appropriate under reasonably efficient practices without

waste for the purpose for which the appropriation is lawfully made..."

The amount of water diverted for use directly from a water course is measured in cubic feet per second. The amount of water stored in a reservoir is measured in acre-feet.

Beneficial uses include domestic, agricultural, and industrial uses, but also include impoundment of water for recreation purposes, including fish and wildlife. Appropriation by the state to provide water for minimum flows of natural streams and levels of lakes is also considered a beneficial use.

Priorities among beneficial uses do not affect the rule of "first in time is first in right." However, a preferred water use (for example, domestic use) can take water by public condemnation from a less-preferred use (for example, agriculture), but only by payment of just compensation.

Water rights are dated from the time when the first clear appropriative step was taken, assuming that the water project then contemplated was diligently pursued.

Water rights may be sold separate from land. They may also be exchanged. But exchanges or transfers of water may not injure any existing vested rights.

Groundwater is also subject to regulation. With respect to use of non-tributary groundwaters (i.e., those subsurface waters which are not hydraulically connected to natural streams), permits are required.

With respect to use of tributary groundwaters (i.e., those sub-surface waters that are hydraulically connected to natural streams), the doctrine of prior appropriation applies. Most of these rights are junior to surface water rights.

Augmentation plans are one solution to the problem of integrating ground and surface-water use. Persons and water entities (e.g., irrigation districts, municipalities, and mutual irrigation companies), alone or in concert, may implement plans for augmentation including water exchanges. Such plans are defined by law as a "detailed program to increase the supply of water available for beneficial use...by development of new or alternative means or points of diversion, by pooling water resources, by water exchange projects, by providing substitute supplies of water, by the development of new supplies of water or by other appropriate means" (Colorado Revised Statutes 37-92-103).

Finally, in this section on water law, interstate compacts need to be mentioned, and in particular, the South Platte Compact approved by Colorado and Nebraska in 1923. Interstate surface water compacts specify the amount of water that must be allowed to flow to other states. Key provisions of the South Platte Compact are that: (a) between October 15 and April 1, Colorado is allowed full use of all river water flowing within its boundaries, except for one canal beginning near Ovid, Colorado, and flowing into Nebraska; (b) between April 1 and October 15 of each year, Colorado will only divert water for rights with a priority after June 14, 1897 if the mean flow at the Interstate Station is greater than 120 cubic feet per second; and (c) Nebraska is not entitled to receive any water beyond that necessary to supply entitled beneficial uses in Nebraska. Because of the lateness of the

priority and the fact that return flows usually provide in excess of the 120 cfs, this latter provision has not, to date, created any administrative difficulty.

3.3 State Administration and Adjudication

The State Engineer, who is also Director of the Water Resources Division within the Department of Natural Resources, has general administrative responsibility for public waters of the state. That office is responsible for protecting the State's interest in, and enforcing the provisions of, interstate compacts and for the administration and distribution of the state's waters in accordance with the water laws as they are interpreted by Water Courts and the Supreme Court. The state is divided into 8 divisions for administrative purposes. Division 1 covers the South Platte Basin with headquarters in Greeley.

Adjudication of water rights is accomplished by Water Courts and by appellate procedures to the Supreme Court. Certain District Court judges are appointed by the Supreme Court as water judges. They preside over the Water Courts assisted by referees and water clerks in each water division. The State District Courts collectively, acting through the water judges, have exclusive jurisdiction of water matters within the divisions.

Some federal laws relating to water could impact voluntary basin-wide water resources management in the South Platte River Basin. Issues with respect to federal reserved rights and the Endangered Species Act of 1973, as amended (particularly as regards endangered waterfowl on the Platte River in Nebraska), are examples.

3.4 Management Institutions

Water management institutions are largely public water districts, municipalities, and incorporated, private non-profit development or

management companies. Such institutions in the South Platte River Basin include the following:

Private, incorporated companies that divert water from natural water courses and convey water via canals to irrigators and private entities and operate reservoir(s). Two examples are the North Poudre Irrigation Company and the Water Supply and Storage Company, both near Fort Collins.

Public irrigation districts, authorized in 1905 (Colorado Revised Statutes, 37-41), formed by the majority of landowners within a county to provide irrigation and drainage works and acquire water rights, etc. An example is the Bijou Irrigation District, Fort Morgan.

Conservancy districts authorized by statute (Colorado Revised Statutes, 37-45) have broad powers to own water rights and to plan, finance, construct, operate, and maintain water resources development projects on a multi-county basis itself or via contract with federal government. An example is the Northern Colorado Water Conservancy District, Loveland.

Groundwater management districts are authorized to be formed (Colorado Revised Statutes, 37-90) once the State Groundwater Commission establishes a designated groundwater basin (Colorado Revised Statutes, 37-90-106). These districts for the management of non-tributary groundwater have the authority to regulate the use, control, and conservation of the district's groundwater. No groundwater management districts currently exist in the South

Platte River Basin. However, part of the Denver Basin bedrock aquifer falls under the authority of the Groundwater Commission.

A groundwater association is a private non-profit mutual corporation formed to develop and operate augmentation plans of benefit to its members. Members are well-owners. The Groundwater Appropriators of the South Platte, Inc., with headquarters in Fort Morgan, is one example. The Central Colorado Conservancy District has a subdistrict which performs similar functions.

Water users associations have been established in parts of the South Platte River Basin. These are voluntary associations composed of representatives of irrigation districts, mutual water companies, conservancy districts, municipalities, domestic water districts and industry. Their purposes are to share information, to concert members views in testimony on proposed state legislation, and to otherwise encourage cooperation between water interests. An example is the Cache La Poudre Water Users Association.

Municipalities and domestic water districts are authorized to own water rights, develop water supplies, and provide water treatment and distribution services. Similar services within the basin are provided by a few small private cooperative or profit-making water utilities.

Municipalities also treat sewage under laws and regulations of the Federal Government; the state water quality districts which control the quality of these effluents, such as the South Fort Collins Sanitation District, perform a similar function.

River basin authorities have been authorized (Colorado Revised Statutes 37-93) for three segments of the South Platte as separate authorities. These authorities, which are to be governed by boards of directors appointed by county commissioners, would have the power to develop ground and surface water facilities; finance such facilities by taxation and issuance of bonds; and establish standards for the proper utilization of water. Although this legislative authority has existed since 1963, no such authorities have been established.

3.5 Summary

This chapter on Water Management Institutions has shown that the current water management institutions in the South Platte River Basin could be used to achieve voluntary basinwide water management. It is clear that they permit the transfer and exchange of water rights on a basis where other vested water rights are not adversely affected.

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IV. CURRENT WATER MANAGEMENT IN THE BASIN

4.1 Introduction

The physical works and management policies for water in the South Platte Basin have developed over the period since 1858 when the first water right was established on Clear Creek. The legal doctrine of appropriation, as already noted, is the cornerstone of present management policies. Management of water under a right is largely the unrestricted prerogative of the owner. A water right is like a property right in most respects. As a general principle, the owner of a water right is free to change the place or type of use provided the change does not injuriously affect the owner of another vested water right including a decreed conditional water right. Changes may include sale or rental of the right.

With time and pressures of competing water demands, innovative cooperation between owners of water rights has led to rather complex management strategies. The exchange of water between junior water right owners upstream and seniors downstream to minimize in-stream conveyance losses was one of the first of these. Later multi-party exchanges have extended the areal scope and introduced higher management complexity.

Legislative changes have allowed increasing water management flexibility. Change in the point of diversion of surface waters and change in the character of its use are permitted. Transfers of water from agriculture to urban uses have become increasingly frequent. Conversion of direct flow rights to storage rights occur quite freely. Purchase of agricultural rights by municipalities in excess of immediate

needs and then lease-back to agriculture until needed is possible. Alternate points of diversion are allowed in certain cases which permit greater use of groundwater.

The present system has evolved spontaneously out of necessity for increasing the utility of the limited amount of water available. It has not been the result of deliberate, comprehensive basin-wide governmental planning. After all, state government has no statutory power to impose a comprehensive water use plan upon the multitude of individual water right owners. The administrative role of government basically is to assure that withdrawals conform with priority of rights. However, there are incentives that government can offer (such as low interest loans) which can influence private decisions toward harmony with perceived public interests.

This chapter highlights the current management strategies and innovations which characterize the South Platte River basin. The research team finds that water right owners are eager to adopt changes in management practices which will improve water availability if the risk is low. That is why changes are made in small increments and with great caution. The major constraint to change is lack of assurance that existing water rights will not be adversely affected. Reliable information to provide such assurance is a critical need.

The management advances which have been made are relatively localized because water right owners intuitively knew that the result would be good. Voluntary, integrated water management on a local basis is really the character of current South Platte basin water management. The research team believes that this character can profitably be

extended to the entire basin with the aid of advanced technologies now available. The continuing stresses on the basin's water resources dictate that this be done. It is more important now than ever before that water right owners be able to project ahead the likely scenarios of water demands and the basinwide impacts of local management changes. It is precisely for this purpose that high technology products of research are needed.

4.2 Basin Water System

The South Platte basin is laced with a complex system of man-made streams, ditches, canals, reservoirs. Below the land surface is an underground aquifer containing about 8 million acre-feet of water in storage. The annual native supply for the basin due to precipitation and snowmelt runoff as previously noted is about 1.44 million acre-feet (2). Streamflow withdrawn in the upper reaches of the basin is applied to land for irrigation for the most part. Part of that water is used by crops in evapotranspiration; part of it percolates downward into the groundwater through which it eventually returns to the stream. Downstream water right owners in turn withdraw their entitled flow and the cycle repeats itself. Because of this recycle system, the total annual volume of water withdrawn for use in the basin ranges from 2 to 2.5 times the annual native supply (4).

The basinwide use of the native supply available is "efficient" in the physical sense. On the other hand, considering a single (local) withdrawal, say, for irrigation, the "local" physical efficiency might be very low. While many feel that if such "local" efficiency were

improved water would be saved for other users, that conclusion should be reserved for a hydrologic analysis of effect on the total. For example, the recycling system described above has some important benefits. The delay in subsurface return flow to the river produces increased flows late in the season that would otherwise not occur. Further, the flow increases are felt in the downstream section where water shortage is generally most severe.

Forty percent of the state's agricultural production occurs in the basin. A total of approximately 2.6 million acres is devoted to agricultural crop production with about 1.3 million acres used for irrigated agriculture and nearly 1.3 million acres used for dry land crops (1).

The Department of Interior estimated in 1974 that total of basin consumptive uses average 1.5 million acre-feet annually. This estimate was disaggregated in 1980 by the Colorado Department of Natural Resources (CDNR) as: irrigation, 1.25 MAF; Municipal including domestic and industrial (M/I), 0.164 MAF; other, 0.058 MAF, for a total of 1.473 MAF (2). This total suggests that the estimated consumptive use of water is approximately the same as the estimated native annual supply. The CDNR estimates average annual native supply at 1.441 MAF. With imports of 0.426, the total average annual supply is 1.867 MAF (2).

The South Platte River, mainstem and its tributaries exhibit substantial variations in stream flow from season to season and from year to year. Around 70 percent of the runoff of the tributary mountain streams, as noted previously, occurs during the months of May through July. On the other hand, summer thunderstorms over tributaries in the Plains zone may produce large streamflows during July through September. Pronounced seasonal and locational variations in runoff suggest the need

for water storage to make water available on a sustained yield basis. Toward this objective, much storage has been developed.

The alluvial aquifer of the South Platte extends from around Henderson downstream to the state line (Figure 2-4). The width of the aquifer varies from 1 mile to more than 10 miles. Its widest section is upstream from Fort Morgan where Kiowa and Bijou Creeks discharge into the South Platte River. Storage in the aquifer is estimated as about 8 million acre-feet. The saturated thickness of the aquifer ranges from 50 to 240 feet. Its transmissivity ranges from 100,000 to 1,200,000 gallons per day per foot. Wells in the aquifer are estimated to yield an average of 950 gallons per minute (3).

Groundwater development began in about 1900. This development occurred in part because most of the reliable direct-flow surface water had been appropriated by that time. Remaining unappropriated water was contained in the peaks of flood runoff during early spring. Wells were constructed for a supplemental supply during dry years of low surface runoff. While a few wells were drilled to supply dry lands with irrigation water, most of the wells furnished supplemental water to existing irrigated lands. By 1970, 3,000 large irrigation wells had been constructed in the basin and that number was up to 5,000 in 1980. A 1970 estimate of pumping withdrawals for the period 1947-1970 is 420,000 acre-feet annually. The estimated withdrawal for 1980 alone was 1 million acre-feet.

4.3 Exchanges of Water

Water users have been innovative in finding water management strategies which have "stretched" the limited water supply. One of these is

the exchange of water between upstream and downstream water right owners. Under strict interpretation of the priority doctrine, a downstream priority water right owner is entitled to have his water delivered through the length of the river before junior rights upstream may be withdrawn. This may mean that a large flow (cubic feet per second) must remain in the river channel to compensate for transit water losses, such as consumptive use by phreatophytes, seepage from the channel and direct evaporation.

The "common sense" solution conceived by junior water right owners is to provide storage in the lower reach of the river (generally off-channel storage) where off-season runoff can be stored. During the irrigation season, the junior right owner will divert water from the river in the upstream section and replace it in the downstream section with water from storage. That exchange is made voluntarily with the consent of the senior water right owner and with cooperation by the local representative of the State Engineer, the river commissioner. As a matter of fact, the river commissioner generally keeps an accounting of these exchanges as a service to the water users to improve the overall utility of the basin water supply.

Such exchanges occur throughout the South Platte River Basin and are being practiced increasingly between municipal and agricultural water right owners.

Colorado water law has been interpreted to provide that a water right owner is entitled to use the adjudicated flow of water once. Water not consumed in first use must be allocated back to the stream. The original water right owner cannot capture and reuse the return flow from his land. It becomes part of the supply for water right owners

downstream. This rule now applies to native water and to foreign water brought into the basin prior to 1969. At that time, the water law was clarified to allow imported water to be captured and reused, provided it could be identified and maintained under control of the original user.

4.4 Reuse of Imported Water

The legal right to capture and reuse imported water, where vested claims have not already been established, has opened new avenues for improving the effectiveness of water use. For example, the City of Fort Collins imports annually around 4,000 acre-feet from the North Platte River Basin into storage at the head of the Poudre River Basin (Joe Wright Reservoir). An irrigation company, Water Supply and Storage Company (WSS), imports foreign water from the Colorado River Basin into storage also at the Poudre headwaters (Long Draw Reservoir). In order to reuse as much of this imported water as possible, the two worked out an exchange plan enlisting the cooperation of a third water user, the North Poudre Irrigation Company (NP). The plan is diagrammed in Fig 4.1.

Fort Collins owns water in Horsetooth Reservoir which is delivered to WSS through the river (4581 AF). WSS credits Fort Collins with an equal volume in Long Draw Reservoir (the first exchange). Now Fort Collins owns 4581 AF of reusable foreign water. That water from Long Draw Reservoir plus 3055 AF of reusable foreign water already owned by Fort Collins in Joe Wright Reservoir is now delivered to NP through the river. In turn, NP credits Fort Collins with an equal volume of water it owns in Horsetooth Reservoir (the second exchange).

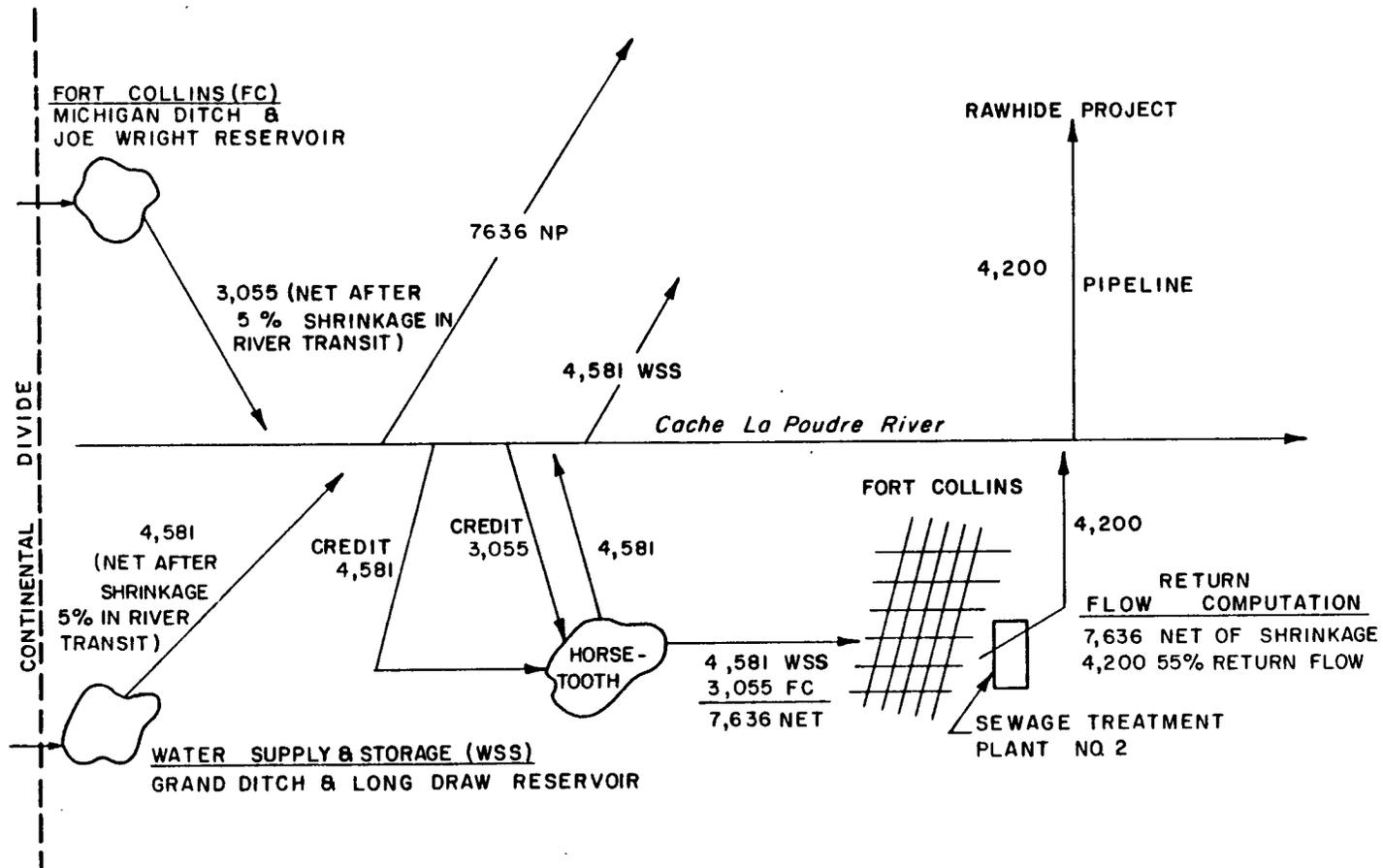


Figure 4-1. Reuse of Imported Water by Exchange.

Now Fort Collins owns 7636 AF of reusable foreign water in Horsetooth Reservoir. While none of that is actually the imported water it is counted as that because both exchanges have been carefully measured and monitored by the river commissioner.

A fourth cooperator enters the picture. Platte River Power Authority wishes to obtain 4200 AF of cooling water for its new Rawhide power plant 14 miles north of Fort Collins. This offers an ideal user of Fort Collins' treated sewage effluent, part of which is composed of the reusable foreign water now stored in Horsetooth Reservoir. Experience shows that 55 percent of the water delivered into the Fort Collins water system appears as effluent at the sewage treatment plant. Therefore, the 7636 AF of reusable water will produce 4200 AF of effluent which can be delivered to Rawhide--exactly the amount needed.

Finally, PRPA will deliver 4200 AF of reusable foreign water imported from the Colorado River via the Windy Gap project to Horsetooth Reservoir to the credit of Fort Collins (the third exchange). This is a clear gain of 4200 AF of reusable foreign water which can be used and reused (by exchanges or recycle) until it is fully consumed if possible. Three exchanges beginning with 4581 AF of non-reusable water stored in Horsetooth have produced 4200 AF of additional reusable water, all of which can legally be consumed by Fort Collins and its partner, WSS, in a division of water that they agree upon as equitable.

It should be noted that North Poudre Irrigation Company was a key facilitator in this series of exchanges. Without NP's voluntary cooperation, without gain for itself, the exchanges would not have been possible.

This case illustrates the essence of voluntary integrated basinwide water management. State government took no initiative nor made any of the decisions involved. Computer model MODSIM (described in Chapter VII of this report) was used by Fort Collins to test the plan's operation over a representative historical period (including significant droughts) before deciding to implement it. The cooperating water right owners benefited significantly and the municipal-agricultural-industrial partnership was strengthened for further cooperation in the future.

While water exchanges have been practiced for several decades, they are largely confined to relatively local areas. Exchanges involving widely separated users offer too many uncertainties to be resolved by trial and error. Fortunately, new technology for computer simulation of the hydrologic system is making possible the testing of more complex and far-reaching exchange schemes. The computer will test all possible options and find the most efficient way to operate the storage and diversion system. When computer simulation has been proven to be reliable and accepted by water right owners, the door will be open to significant improvements in voluntary basinwide water management.

4.5 Conjunctive Surface-Groundwater Management

During geologic time the South Platte River laid down a body of reworked sands and gravels creating the present-day alluvial aquifer underlying a major portion of irrigated area in the basin. This aquifer is, in effect, a giant reservoir or a series of more or less interconnected reservoirs.

Students of the South Platte River generally agree that the river's

character has changed considerably since man began to withdraw water for irrigation. It was previously a stream which carried a large flow for a relatively short time during early spring. By mid-summer the river was reduced to a trickle by the time it reached Greeley or perhaps even before that. While river flow was substantial near the foothills, the streamflow largely disappeared into the ground as it proceeded down the basin.

As ditches were constructed to withdraw water from the river in the upper basin, the condition of the river began to change. More and more the almost dry streambed in the lower basin began to contain water throughout summer and fall seasons.

The result of man's development of irrigation was the filling up of the underground reservoir. Irrigation water not consumed by growing crops entered this reservoir and became a supply source for surface flow in the downstream river channel. Each season, as irrigation added to the underground reservoir, its surface level rose and forced groundwater to flow into the streambed stream channel feeding the river flow.

Groundwater records show that the water table level toward the outer edge of the aquifer rose as much as 50 feet in the first 20 years of irrigation. Instead of a "losing" stream, the South Platte became a "gaining" stream due to groundwater return flow. This tended to make additional water available in the lower river during late summer and fall (compared to pre-irrigation times). Measurements of return flow were estimated as early as 1889 by L.G. Carpenter, a civil engineer at Colorado State University (later Colorado State Engineer). By 1930 the groundwater build-up throughout the alluvial aquifer reached an "equi-

librium" position in which the average annual return flow to the river from groundwater was about 1 million acre-feet.

Nevertheless, irrigators in the lower basin could not get enough water for their crops from the river flow available. By 1950 they were beginning to construct wells for supplementary water. An estimate of pumping in 1980 is 1 million acre-feet from over 5000 wells.

Although the surface water in the river and groundwater in the alluvial aquifer are intimately (hydraulically) connected, they have been developed at separate times under entirely different laws. Initially, groups of farmers joined together in cooperative mutual associations (later to become incorporated mutual irrigation companies) to finance and construct surface water diversion projects. At a later time, groundwater was developed by individual initiative and financing. No law regulating groundwater withdrawal existed when this development began. Most well owners assumed they owned all the water underneath their property.

When surface water flows are affected by groundwater pumping, under the priority system, pumps can be stopped by order of the State Engineer. By the late 1960's, the pressure from surface water right owners to have pumping stopped in the early summer was intense. The ingenuity of water users led to a partial solution to this problem. Recognizing that shutting off pumps in mid-season would legally satisfy surface water right owners but would at the same time prevent productive use of the large volume of water stored in the aquifer, a river augmentation strategy was adopted.

The Water Right Determination and Administration Act of 1969 allowed a groundwater user to continue pumping, provided he would make

available to the State Engineer sufficient water to be added into the river to compensate for the flow reduction caused by his well. The determination of how much water must be available is made in an "augmentation plan" proposed by the well owner and submitted to the State Engineer for approval.

The determination of how much each well reduces the flow rate (cfs) in the river at any place along the river and at any time during the season is a complex scientific problem. It is a problem that was partially solved by Professor Robert E. Glover of Colorado State University. He applied wellknown principles of heat flow to groundwater flow and, with certain necessary idealizations, he succeeded in developing a computational method which was sufficiently near to reality to be acceptable for augmentation plans.

However, the application of this analytical computation to each individual well proved to be time-consuming and expensive. The expediency of replacing 5 percent of the annual volume of pumpage was then adopted. For each 100 acre-feet withdrawn from groundwater the well-owner must make available 5 acre-feet to the State Engineer to be introduced into the South Platte River at any time it is needed to prevent injury to priority water rights.

While the 5 percent rule facilitated the augmentation plans, still administration by the State Engineer on individual wells was far too expensive to be practical. The solution to this problem was for well owners to form cooperative associations for the purpose of supplying augmentation water. The result is that groundwater pumpers' associations supply surface water into the river from storage at various points

or they pump additional groundwater into the river or directly into canals affected by pumping.

While this solution is working reasonably well, there are many surface water right owners who still claim inequity and many lawsuits pending over alleged injury to surface water supply by groundwater pumping.

Thus, the ingenuity of water users combined with technology developed at Colorado State University produced the first step toward voluntary basinwide management of the surface-groundwater resources. Although this was a large step, it is only the first toward full conjunctive operation of the two sources of supply.

While an augmentation plan is a sound basis for conjunctive management of the surface-groundwater system, other technological developments are yet needed. In particular, efficient recharge facilities are needed to supplement recharge now occurring by canal and reservoir seepage and deep percolation from irrigation. New facilities should be located to maximize the effectiveness of plans of augmentation taking into account the timing and location of return flow. While several recharge sites have been placed in operation during recent years, the total volume of artificial recharge is still small.

Groundwater recharge during the period of high spring runoff must be greatly increased if the full potentialities of conjunctive use are to be realized. Comprehensive recharge investigations should be a high priority for both surface and groundwater right owners.

The extent to which recharge strategy can substitute for upstream surface reservoir storage cannot be evaluated without such investigations. However, the possibility exists that a recharge system can reduce the need for some upstream storage. Use of the groundwater

storage capacity has some advantages over upstream reservoirs. Evaporative losses are very small from groundwater storage compared to surface reservoirs. Flexibility in delivering water at needed locations on an optimal time schedule can be better.

The recycling factor that results from the combination of surface diversions and groundwater pumping may also be a significant advantage of an improved groundwater recharge system. Under present conditions, the annual native supply in the South Platte, as previously noted, is approximately 1.44 MAF. Yet the total of surface water diversions is about 2.5 times that amount indicating the importance of groundwater return flow into the river. While the factor 2.5 is an impressive number, it is quite likely that an expanded recharge system could increase that number substantially.

The expedient rule of 5 percent augmentation can be substantially refined with modern computer simulation technology now available. With the new computer model SAMSON, the timing and the location of stream withdrawals into groundwater and groundwater return flow into the stream can be determined. Furthermore, these determinations can be done on a day-to-day basis. The exact effect on surface flow for any one well or for any group of wells can be calculated. With this information the appropriate augmentation plan for an individual well or groups of wells can be formulated. Further, the amount, timing and location of augmentation due the river can be calculated on a day-to-day basis.

Development of SAMSON, together with MODSIM, are two significant steps which have been taken at CSU in the development of advanced technologies leading toward voluntary integrated basinwide water management. With reliable quantitative daily information on pumping

impact on streamflow readily available to the State Engineer by means of the SAMSON simulation model, the daily delivery of augmentation water to each canal can be ordered by the State Engineer to be met by the appropriate groundwater organizations composed of junior appropriators within the Basin.

4.6 Water Markets

A water market is, in effect, a management tool of increasing importance in Colorado. Water right owners who no longer need the water or who have excess water are free to rent temporarily or sell the right. The only legal limitation is that changes associated with the transfer of a right not injure other water right owners. In the economic sense, a water market tends to increase economic efficiency of water use, because it gradually results in transfer of water from low-return to high-return uses.

4.6.1 Emerging Specialty Brokerages

Prior to the 1970's there were few sales of water rights separate from land in the South Platte Basin. Those which occurred were a result of private negotiation. Today, however, brokers handling farm real estate find that farm sales frequently involve a separate transaction for part of the water rights. These brokers, by necessity, had to become knowledgeable about the process of selling a water right. A few of them became sufficiently experienced that others looked to them for guidance and assistance. Out of this process a few speciality brokerages for water rights have emerged. One such specialist estimates, however, that in the basin there are only four brokerages in which 80

percent of the business is water sales.

At the present time there is no public supervision specifically designed for water right brokerages and transactions. Negotiations between buyer and seller are essentially private, and require no legal documentation beyond that to satisfy each party. Water rights are often recorded in the deed to land, but not necessarily so. The absence of a public record means that the State Engineer does not have an accurate record of current water right owners. Transfer of ownership occurs without any official notification to the State Engineer. There have been recent unsuccessful efforts in the General Assembly to require a public record of water transfers by sale.

4.6.2 Value of Water Rights

The market price of a water right depends on a number of factors, including the dependability of the water represented and the value of water to the buyer. Municipal and industrial water users are the principal buyers. Agriculture, on the other hand, is the principal seller. Highest prices are paid for rights which are easily transferable to the place of new use, and which are not subject to complicating legal action. Water rights upstream from the new point of use or rights in upstream storage are easily transferred downstream while upstream transfer may present problems. Rights in imported storage water such as Colorado Big Thompson Project (CBT) water, can be transferred without court action and are therefore preferred over appropriated direct flow rights which may be challenged in court by other right owners.

Municipalities generally require water rights to be supplied by developers to the city at the time of subdivision. This requirement

generates the major water market in the South Platte Basin. The amount of water required currently ranges between 3.0 and 4.0 acre-feet per acre of land developed for housing and commercial use.

4.6.3 Water Prices

The Colorado Big Thompson Project water represents a good example of trends in water prices because it is a preferred supply with great flexibility and reliability for use within the boundaries of the Northern Colorado Conservancy District. In 1962 the purchase price on the market was \$40 per acre-foot. By 1982 the market price was above \$2,500 per acre-foot at the same time direct flow water rights were selling for around \$1,500 for a right producing an average of one acre-foot annually.

By 1986, the market prices had dropped substantially. Water in the CBT project was being offered at around \$750 per acre-foot. A drop of this magnitude is quite likely the result of high speculation in water rights during the previous five to ten years coupled with the high interest costs of the past several years. Also, with drop off in residential growth, the demand for municipal use is down and the supply for agricultural sources was up substantially due to difficult times for farmers.

4.6.4 City of Thornton Transfer

Utilizing water brokers, the City of Thornton, a suburb of Denver, secretly purchased options and then completed purchase of 283 shares of Water Supply and Storage Company (WSSC), a mutual ditch company, with canal headgate on the Cache La Poudre River at the mouth of Poudre

Canyon, north and west of Fort Collins. This purchase involves over 30,000 acre-feet and represents almost fifty (50) percent of WSSC's supply. Thornton's preliminary plans for use of this purchased water and for additional water involving first-use rights it expects to purchase, call for construction of a pipeline to transfer the water to Thornton some 50 miles south. Many issues have arisen as a result of this market transaction. Some of them have been settled by an agreement between Thornton and Water Supply and Storage Company. Others, involving interests who will claim potential adverse effects to them of Thornton's plans, will have to be settled by the Water Court and various regulatory processes. Resolution of some of these issues may be greatly facilitated by the computer-based models that are now available. Thornton's basic legal right, however, to make this market transfer has not been questioned.

4.7 River Administration

The State Engineer supervises the day-to-day distribution of the surface waters of the State in accordance with statutory directives, court decisions, and interstate compacts. The Water Right Determination and Administration Act of 1969 provided for the creation of seven water divisions in the State with boundaries conforming to the major watersheds. Each division is headed up by a Division Engineer who is responsible to the State Engineer.

Water is withdrawn from streams under the supervision of a water commissioner assigned by the Division Engineer to a definite section of the stream. The duty of the commissioner is to monitor withdrawals in conformity with water right priorities in the stream section.

The commissioner is responsible for determination of where available water is to be allocated and for maintenance of records on water availability and its allocation. In order to be effective, the commissioner must have an intricate knowledge of the functioning of the system under his responsibility. Such knowledge includes cognizance of all types of water decrees in effect, physical layout of the entire system, capacities and conditions of all components such as pipelines, ditches and reservoirs, system response times, characteristics such as rates of return flow to the river and loss rates from the river, and the characteristics of the watershed supplying the system.

Each commissioner makes daily measurements of the water available from the river, and from that measurement determines eligibility of users to divert water. Allowable diversions may be modified by deferral of water by some users, exchanges between users, availability of imported water belonging to specific users, and availability of stored water belonging to specific users. Within the limits of his authority, the water commissioner enforces the priority system and at the same time seeks to maximize the number of users satisfied, while holding losses from the system to the smallest possible amount.

The water commissioner also has "unofficial" functions. He ensures that water users maintain the physical integrity of their systems. He provides the first point of contact for water right owners in administrative functions related to proposed changes in the use of water or in points of diversion. The commissioner really acts as the river-system "operator."

Scheduling of diversions requires close communication between the water commissioner and canal operators. Generally, canal headgates are

set by the operator on a daily basis at flow rates ordered by the commissioner. If any user desires to make a change he is required to notify the commissioner by noon of the day prior to the change. If the change is to reduce withdrawal, the commissioner notifies other users of additional water available in the order of their priority entitlement.

The water commissioner's function assumes more importance by mid-summer when native flows are lowest, when imported waters are being used more, and when exchange of water among right owners is at a peak.

Water users are permitted to use the natural stream channels for transport of water which they may obtain by import from outside the basin, by exchange with other water right owners, or from storage. The commissioner's responsibility is to ensure that use of the stream as a common carrier does not cause injury to any water right owner. This involves computing the transit loss of the imported and storage water, so only the diminished amount is withdrawn from the stream.

Reservoirs in the system consist of some which are active in the exchange system and some which are not. The latter are operated at the convenience of their owners, but again, the commissioner is responsible for assessing conveyance losses if the stream system is used for conveyance of these stored waters.

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V. MANAGEMENT PROBLEMS AND ISSUES

Chapter IV discussed current management practices which have evolved over a long period of time. These represent an answer to the question: how are all of the competing demands on the river currently met? Now must be asked: how are emerging problems on the river likely to be faced in the future?

The problems of managing the South Platte have been increasing ever since water users first began to bump against the limits of water availability. Early problems resulted in a system of laws and water rights administration which have served the State well. Now additional problems loom ahead: increases in litigation and conflict, growing urban demands, water quality issues and finding ways to utilize and conserve the deep bedrock aquifers. These issues will be discussed in this chapter in relation to the South Platte River Basin in Colorado.

5.1 Increasing Litigation and Water Use Conflicts

An issue that is apparently most serious is increasing litigation and water use conflicts. An ideal system of water law and administration would provide ready mechanisms for security of water rights and for exchanges between water users, without the expense of constant legal battles to defend water rights. While increasing competition for water naturally leads to conflict, an improved mechanism is needed to resolve the conflicts in a way such that water users avoid heavy penalties.

The issue of increasing litigation needs further research to identify more precisely why litigation is increasing, to determine its

social costs, as well as costs being borne by water users. It would seem possible, however, that institutional arrangements that would facilitate voluntary basinwide management could help to reduce litigation.

5.2 Growing Urban Demands

The South Platte Basin in Colorado contains both the major population of the state and its most productive irrigated agricultural lands. Yet in terms of water availability the basin has only 12 percent of the state's supply; and of this, 84 percent is withdrawn for agriculture. This means that municipal and industrial (M&I) water withdrawals are only 16 percent of the basin's total water supply.

This apparent insignificant role that urban water plays in the basin's water supply picture is undergoing major change because of the growth in population that the basin is expected to experience. The change in water use within the basin initiated by Thornton, and discussed above, is only the beginning of major transfers that can be expected. Agricultural usage is expected to increase very little, if at all, but domestic, commercial and industrial water demand will increase proportionately with the population. In addition, major new water imports into the basin will all be urban-based. By the year 2000 it is projected that more than 20 percent of the water withdrawals in the basin will be for municipal and industrial purposes. Increased cooperation and mutually advantageous management by municipal, industrial and agricultural water users are foreseen as mitigating the impact of growth on the basin's water supplies.

5.2.1 Population Projections by Counties

The growth in urban water demand can be linked directly to the projected population growth in the basin. Percentage growth rates from 1980 to the year 2010 for selected counties in the Basin show substantial variations (1).

In the Metro Area, Denver County is anticipated to gain about 81,000 persons, 16% over the thirty year reference period. But Jefferson County will increase by 49%, Adams County by 91%, and Arapahoe County by 75.6%, for a total population increase of 715,745, or 51%, to a total of 2,129,000 by the year 2010.

Reflecting the anticipated growth in Boulder and Longmont, Boulder County is projected to increase from 190,000 in 1980 to 326,000 in 2010. Similarly, substantial growth in Fort Collins and Loveland is anticipated. Population forecasts for Larimer County show an increase from 150,000 to 311,000. Weld County is projected to increase in population by nearly 67%. By contrast Morgan County is projected to gain less than 100 persons.

In all, the Basin counties containing the five large cities outside of the Denver Metro area Boulder, Longmont, Loveland, Fort Collins and Greeley will increase in population by 82% to 844,000. The total population anticipated for the six growth counties of Metropolitan Denver and North to the Wyoming border is 3,206,000, which is more than 95% of the total basin population projected for the year 2010.

5.2.2 Urban Water Management Options

The impact on agricultural water use within the South Platte Basin from the projected urban water demands can be mitigated by several voluntary urban water-management options.

The first of these is the implementation by municipal water utilities of increased efficiencies-in-use through water conservation. Such programs could include universal metering, increasing price structures, requirement of water-saving devices and plumbing fixtures in households, and perhaps, limiting landscaped areas for new homes. Reductions in urban withdrawals from, say, 215 gallons per capita per day (gpcd) to 185 gpcd or even less could result from such programs (2). Implementation of demand-reducing programs, piecemeal or as a whole, is dependent on current water supplies available to the utility and the anticipated growth rate for the service areas supplied. Some cities with ample supplies either owned or readily available will, of course, consider these options in a quite different manner than a rapidly growing city where the supply is already inadequate.

Secondly, much of the supply to meet new urban water demand has come from transbasin diversions. The Windy Gap project can now import about 48,000 acre-feet per year from the Colorado River through the CBT facilities. The Denver Metropolitan Area is currently assessing the importation of additional Western Slope water as part of its metropolitan Areawide plan. Import of water from the Arkansas River basin for urban use in the Metro area is being accomplished by purchasing agricultural water rights.

The third mitigating circumstance is that return flows from imports will be available for additional use and reuse within the basin. For those new demands that are met by transfers from agricultural use to urban use the quantity of consumptive use by the urban user is likely to be less than in the former agricultural usage, thus resulting in more water available to remaining agricultural users.

Unexpected impacts of these conservation measures is illustrated by a recent study comparing drought reserve requirements of a conserving with a non-conserving city. The conserving city, even with restrictions imposed, required nearly 40 percent more reserve storage than the non-conserving city during droughts of one to three years duration (3).

In contrast with the trend toward decreasing per capita demand in the future is the pronounced trend toward increased densities of household units, and the resulting increase in household use when measured on a unit area basis. Fort Collins has reported increases of housing unit densities from 4 to 6 units per acre to 10 units per acre and as high as 60 units per acre. This trend is illustrated in part by the difference in water demand per unit area in Westminster of 1.7 acre-feet per acre with Denver's 5 acre-feet per acre.

Sequential reuse projects where municipalities first use the water and then the return flow is used for agricultural purposes have been advocated as a viable management strategy. Despite the Northglenn reuse project history, which has been fraught with difficulties, the extension of such schemes to other locations--as Thornton plans to do--offers a viable option. Similarly, the recently evolved basinwide water management plan for the Clear Creek sub-basin can serve as a model despite the problems in its implementation. Water quality restrictions will increasingly be an important element in any plans for municipal/agricultural cooperation in sequential water reuse.

Management difficulties in implementing better plans for use and reuse can arise from legal and other institutional constraints. However, increased cooperation of municipal and industrial water entities

with agricultural interests could overcome many of these constraints when mutual benefits are identified through the modeling/planning techniques described later in this report.

Perhaps because of the difficulties with two-party agreements, pressure is building within the Basin for increased regionalization of water supplies. The Denver area is currently in the midst of a major areawide supply study. Fort Collins is discussing the possibilities with surrounding special service districts, Greeley and Loveland, of future jointly-managed, treated and pooled water supplies for their mutual advantage. But it is anticipated that integrated management cooperation can go much further than these efforts.

Solutions to interjurisdictional problems between cities and water service districts could be enhanced by formation of regional water districts, even though the current state law authorizing such districts is not acceptable to most cities. The Northern Colorado Water Conservancy District might be able to provide an institutional home for these regional functions within its much larger area of jurisdiction.

Improved water management through voluntary integrated approaches might suggest the need for increased joint agricultural/municipal storage and exchange projects which currently are limited by the inability of agriculture to finance its proportionate share of such projects. Alternative financial arrangements are needed, perhaps with State assistance, to improve the possibilities for such joint projects.

Perhaps privatization of a public water utility, with private financing, management and operation, could facilitate realization of such projects.

A regional basinwide strategic plan could be advantageous in seeking optimum utilization of available supplies and optimum use and reuse. But related detailed action plans are not now needed. Detailed action plans can be formulated as opportunities and needs arise. Strategic planning now requires use of high technology capabilities of computer-based simulation and design so that mutual benefits to urban and industrial users and agriculture can be identified and demonstrated. The use of computer hydrologic simulation technologies has already demonstrated their usefulness to water managers in achieving better water management in the case of GASP and the City of Fort Collins, as noted elsewhere in this report.

Computer-based methods and techniques are discussed in detail in Chapter VIII. Some uses that relate to the problems described in this chapter are as follows:

- (a) Impacts of water exchanges and transfers upon third party interests;
- (b) Drought contingency plans for coping with unexpected deficiencies in water supply, i.e. cooperative agreements with farmers to provide water for a contract price to cities during droughts rather than the city building expensive and little-used drought reserve storage;
- (c) Water utility rate designs which consider economic efficiency and equity as well as revenue sufficiency and year-to-year stability;
- (d) Effective and efficient water supply and conservation programs that balance new supply acquisition with implementation of increased efficiency-in-use programs.

5.3 Water Quality

In the South Platte River Basin water quality problems have gained public recognition. Most prominent are: problems of locating suitable hazardous waste disposal sites and clean-up of the groundwater contamination from the Lowry Landfill and the Rocky Mountain Arsenal. Other problems include:

(a) nitrates, organics, and high TDS (i.e. total dissolved solids) in alluvial aquifers which provide drinking water to towns along the South Platte from Denver to Julesburg,

(b) nitrates from individual sewage disposal systems contaminating groundwater,

(c) salt balance in the lower South Platte,

(d) prevalence of *Giardia lamblia* cysts in mountain streams used for drinking water and development of effective treatment techniques,

(e) random spills from various sources,

(f) pollution due to urban stormwater runoff.

(g) oil field brine water disposal presently in Weld County,

(h) high cost of tertiary treatment for municipal wastewater,

(i) effective water and wastewater treatment for small systems.

A panel of experts met at Colorado State University on January 18, 1984 to discuss present and future water quality problems of the South Platte River Basin. The following paragraphs describe some of their observations.

Concerning the South Platte alluvium as a water source, the drinking water quality problem in the Brighton-Fort Lupton area is acute and

is causing a search for new sources of water. These communities are growing, and they have explored the idea of obtaining Windy Gap water from the NCWCD. The nitrate-TDS problem may extend to all communities withdrawing water from the South Platte shallow aquifer, extending from Brighton to Julesburg.

Great strides have been made in pollution abatement by municipal and industrial dischargers. Aquatic habitat is a limiting factor in fish propagation now, and the remaining problems are spotty, including heavy metals, ammonia and random spills. A great deal of information is available in the permit program, and to interpret the information available offers an opportunity for research. There will be renewed interest in control of non-point pollution sources and urban runoff in the future. Problems of trace organics, pesticides, and other carcinogenic substances are of current interest.

Oil field brine disposal in Weld County is a major problem at this time. The Oil and Gas Commission has accepted regulatory control, and EPA has held hearings on this problem. However, it is questionable whether state level regulation is adequate at this time. Midnight dumping of brines has been and still is practiced.

The Water Quality Control Commission has set up a system to classify state water. The classifications developed should reflect a balanced view of water quality, but the Commission may be attaching too much significance to aquatic life in plains streams, especially in reaches where aquatic life is limited by flow and habitat. The mountain streams

and the off-stream reservoirs have the highest ecological and recreational values and should have the greatest attention. The water quality values of the mountain streams could be threatened by development pressures and are more sensitive to water quality impacts, especially from an esthetic point of view. Research in this area could provide a rationale for the Commission to weigh the values in mountain streams more heavily.

Because of continuing growth and regulatory pressures, water quality models will be needed in the future. Where we have adequate data, as in the Cache La Poudre system, we can do a great deal with these models.

Appraisal of data needs and of the need for a statewide data depository and/or central coordinating agency is necessary. Water quality data should be collected along with flow data.

In the lower South Platte the major water quality issue is salinity. It will increase in the future, especially as the cities use and reuse more imported water, and as additional water exchanges are worked out.

Since water quality is connected to water use, water plans and management must involve water qualities managers. Computer-based models available in the Basin increasingly include water quality parameters as well as quantity parameters.

5.4 Use of the Deep Denver Basin Bedrock

The issue of how to use the deep bedrock aquifer is important since the aquifer represents, in effect, an independent off-line large reservoir available to the South Platte Basin water users. Some of the technical and economic aspects of the issue are pertinent to this study.

The Denver basin bedrock aquifer is a north-south trending aquifer bounded on the west by the Front Range and on the east by the High Plains (Figure 5-1). The portion of the basin of interest in this report extends northward to Greeley, Colorado and southward to somewhat beyond Colorado Springs and underlies approximately 6000 square miles of land surface. The basin consists of a number of sedimentary geologic layers overlying rock that forms the basement. Several sedimentary formations within this sequence constitute aquifers and are commonly referred to as the bedrock aquifers of the Denver Basin (Figure 5-2).

Large quantities of water, suitable in quality for almost any purpose, are stored in these aquifers, and it is being used to meet the increasing demands for water caused by the population growth along the Front Range. As an apparent result some areas (e.g. the South Platte River corridor and the Strasburg-Byers-Deer Trail area) have experienced precipitous declines in water levels over the last decade.

The prudent management of these groundwaters depends on the relation between the drawdown of water levels and the volume of water recovered. Except near the outcrop areas along the edges of the basin, the bedrock aquifers are artesian (confined). Under artesian conditions, the relationship between drawdown of water levels and the volume of water recovered is governed by the slight expansion of water and the compression of the aquifer that results from a reduction of pore-water pressure. Because both water and rocks are only slightly compressible, large and extensive drawdowns are associated with water removal from artesian aquifers.

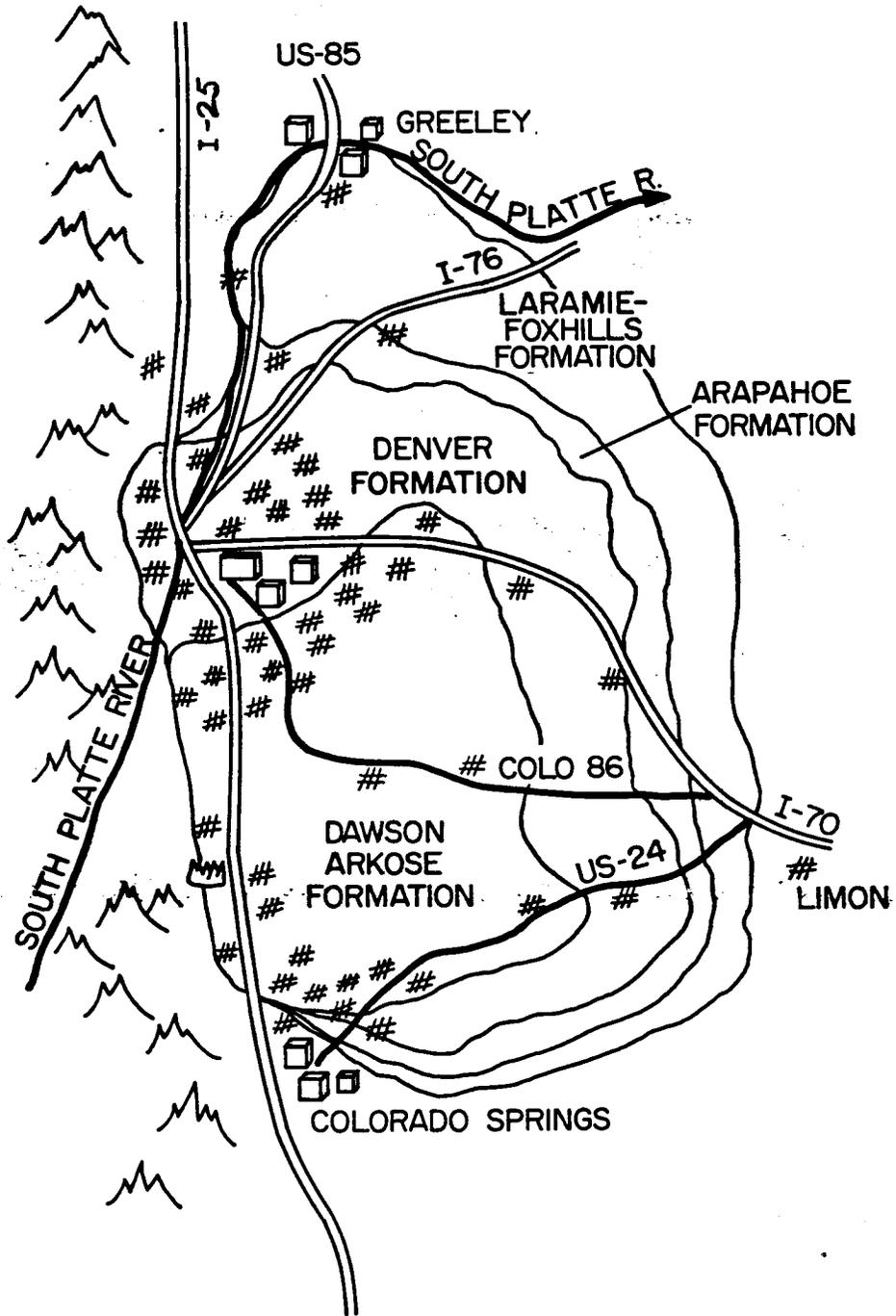


Figure 5-1. Surface Outcropping of Denver Basin Aquifers

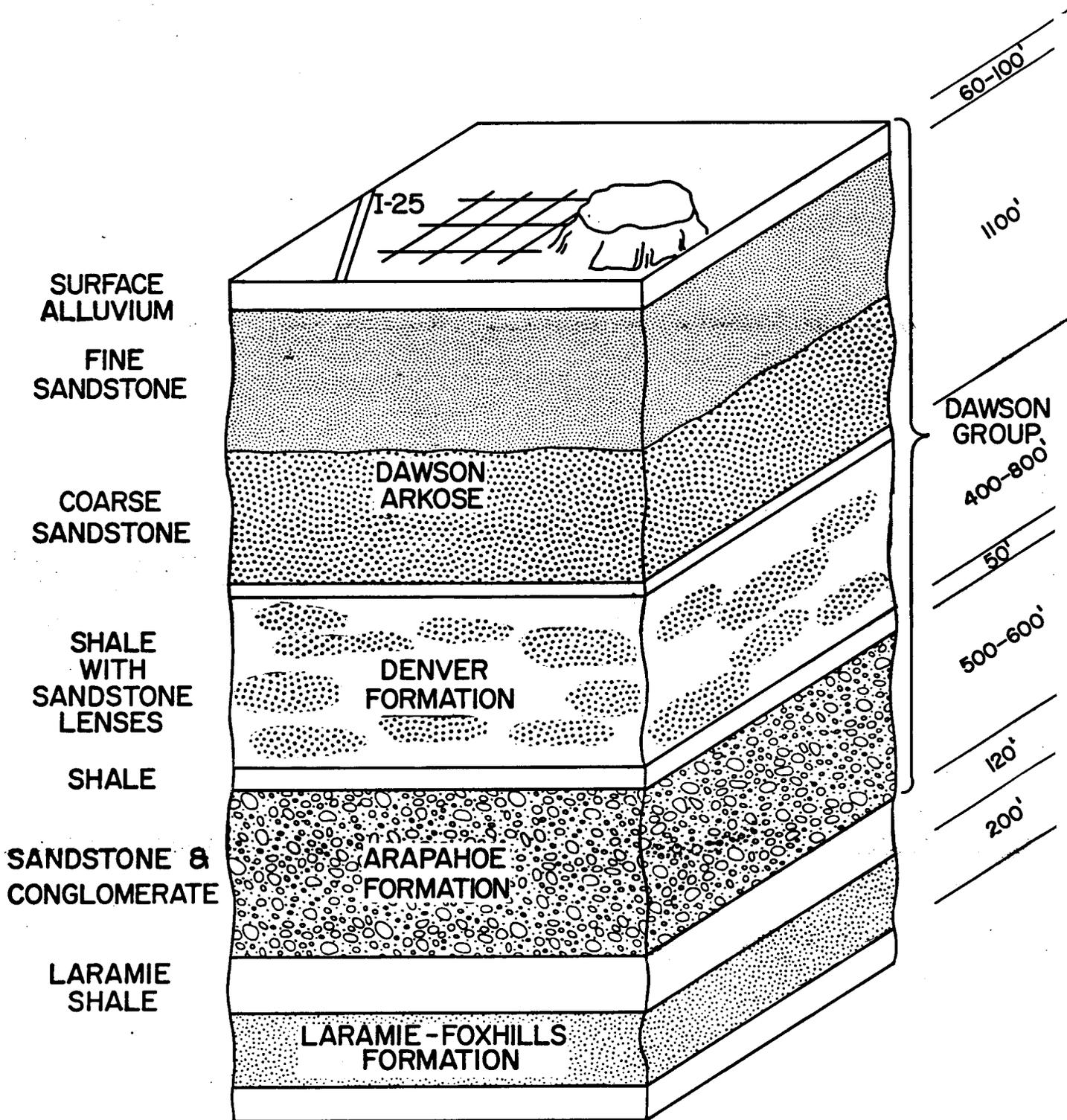


Figure 5-2. Aquifers of the Denver Basin: Vertical Profile

Continued removal of water from an artesian aquifer eventually causes the water levels to fall to the elevation of the top of the aquifer and the aquifer becomes unconfined. At this point, the relationship between the volume removed and the change in water level is modified dramatically.

Typically, the total volume of water recoverable under artesian conditions is less than 0.1 percent of the volume of water stored in the aquifer. In contrast, the volume recoverable once the aquifer becomes unconfined typically ranges from 10 to perhaps 50 percent of stored volume. That is, more than 99 percent of the recoverable water will come after the aquifer becomes unconfined. The salient difference between the artesian and unconfined condition is the physical drainage of pores and consequent replacement by air that occurs once the aquifer becomes unconfined. The recoverable volume of water in the Denver Basin is estimated to be 150 million acre-feet (4).

The relation between the volume of water removed and the associated drawdown is quantified by the storage coefficient in the case of artesian conditions and by the specific yield in the case of unconfined conditions. Field aquifer tests, performed by pumping and observing the corresponding drawdown, are the most reliable methods for estimation of these two important hydrologic parameters. However, field aquifer tests for the estimation of specific yield are applicable only if the aquifer is unconfined. Thus, if one seeks to estimate the total quantity of water ultimately recoverable from an aquifer which is initially confined (as in the Denver Basin) but ultimately will be unconfined, methods

other than the traditional pumping tests must be utilized to estimate the specific yield. Because the total volume of recoverable water is comprised almost entirely of water recovered under unconfined conditions, any uncertainty in the estimate of specific yield is directly reflected as a corresponding uncertainty in the estimated recoverable volume. Even a small difference between independent estimates of specific yield can represent large differences in estimated recoverable volume since pumping permits allow withdrawal of one percent of the recoverable volume per year, an accurate estimate of the specific yield has significant economic consequences to the permittee.

The important bedrock aquifers of the Denver Basin are, in descending order; the Dawson, Denver, and Arapahoe formations of the Dawson Group; the Laramie-Fox Hills formations; and the Dakota, Lyons, and Fountain formations (Figure 5-2). The Dawson Arkose is the uppermost of the aquifers in the Upper Cretaceous Dawson Group. It consists of interbedded sandstone, conglomerate, shale, and clay comprising a total thickness of as much as 1100 ft. The lowest member of the Dawson Group is the Arapahoe formation which ranges in thickness from 500 to 600 ft. The Laramie-Fox Hills aquifer is the next significant aquifer below the Arapahoe. It includes the Milliken sandstone of the Fox Hills formation and the A and B sandstones of the overlying Laramie. The average thickness of the Laramie-Fox Hills aquifer is 200 ft but ranges upward to about 400 ft. The Dakota aquifer consists of the upper 100 ft of the South Platte and Lytle formations of the Dakota Group. Groundwaters of usable quality are only found in the Dakota near the west boundary of the basin where the Dakota outcrops. Like the Dakota aquifer, the

Fountain formation and the Lyons sandstone are useful aquifers only near the outcrop on the western side of the basin. Except near the outcrop areas, all of these aquifers are artesian. Confining beds are clay and shale strata, but are not believed to preclude vertical communication between the Dawson Arkose, the Denver, the Arapahoe, and the Laramie-Fox Hills. The piezometric head is generally greatest in the upper most aquifer (i.e., the Dawson Arkose) and decreases with depth to the Laramie-Fox Hills, at least in the undisturbed, pre-development state. This downward gradient is thought to result in some small downward movement of water from aquifer to aquifer.

The three aquifers of the Dawson Group are the most significant from a regional perspective. It is believed that these aquifers receive recharge from precipitation on outcrop and subcrop areas, along fault zones near the Front Range, and from stream seepage in the Black Forest area. Total recharge to the Dawson Group aquifers has been estimated in the past to be about 110,000 acre-feet/year (4).

A recent study by the USGS, however, suggests that natural recharge to the Dawson Group aquifer may total only about 35,000 acre-feet/yr (4). Most of this recharge occurs in the uppermost aquifer, the Dawson Arkose, and the lower two aquifers are supplied mainly through vertical leakance. This study also suggests that the Dawson Group aquifers have the potential for discharging to streams within the basin. Under conditions prevailing prior to development, Robson suggests that all the annual recharge (35,000 acre-feet/yr) is eventually discharged to streams (4). From the Dawson Arkose, the major recipient streams are Plum, Cherry, Box Elder, Kiowa, and Monument-Fountain. Robson indicates that

the Denver and Arapahoe formations discharged, under pre-development conditions, a total of about 11,000 acre-feet/yr. Most of the discharge from these two lower aquifers in the Dawson Group was received by Plum and Bijou Creeks and by the South Platte River.

Robson indicates recharge to the Laramie-Fox Hills aquifer at about 4,000 acre-feet/yr (4). Again, under pre-development conditions, it is suggested that this quantity of water is discharged to surface streams, the major recipients being Bijou, San Arroya, and Badger Creeks. A small discharge (less than 400 acre-feet/yr) to the South Platte from the Laramie-Fox Hills is indicated.

While these issues relating to the deep aquifer pose independent problems and opportunities for water right owners, it would seem that the availability of this large groundwater reservoir could offer management advantages on a basinwide basis.

5.5 General Problems and Issues

The management problems and issues discussed in this chapter are believed to be particularly pertinent to the focus of this report on voluntary basinwide water management in the South Platte River Basin in Colorado. During the research leading to this report other problems and issues were identified that could be related to the South Platte Basin or to the State more generally. These are listed in Appendix B.

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VI. ACHIEVING VOLUNTARY BASINWIDE WATER MANAGEMENT IN THE SOUTH PLATTE RIVER BASIN

The principal objective of this report is to encourage voluntary changes in water management that are mutually beneficial, or at least not adverse, to water right owners who are affected. The pursuit of this objective stems from the belief that new advances in computer-based modeling of conjunctive use of ground and surface waters can identify and evaluate water exchange and transfer possibilities within the basin that will benefit the water right owners involved. In addition such exchanges and transfers would tend to optimize use of the water resources of the State within the framework of existing water law. Thus they would be in the public interest.

Application of new computer-based modeling developed in the last 20 years has proven to be difficult, not only because of the great complexity of the problems addressed but also because their useful application depends upon acceptance by persons whose vital interests are involved. It is essential that those persons believe the new knowledge to be valid. This means bridging the gap of understanding between university researchers and resource practitioners. In general, bridging this gap has not been found to be easy (1). But much thought has been given by university researchers around the world to design of their modeling efforts in such a way as to be practical for use by practitioners and yet rigorously take account of essential complexity (2).

On the basis of these worldwide and U.S. developments, scientists and engineers at the University of Nebraska have already addressed water problems of the Platte River Basin in Nebraska. They have utilized

computer-based models and have worked with various water interests in the basin. Together they have examined alternative water plans for better water use within the basin in Nebraska (3).

What types of water exchange and transfer possibilities could be identified and evaluated that might encourage voluntary changes? A few general types are described below. Water right owners and other water practitioners in the basin, no doubt, could suggest others. Also they could identify specific situations within the basin that might be profitably analyzed and evaluated. Below also are identified types of voluntary exchanges or transfers that appear to require changes in formal institutional arrangements. These changes are not now recommended. Instead they are identified to determine whether they are worthy of detailed study by basin water interests. Such study, of course, might then lead to proposals for formal institutional change with the support of basin water interest.

6.1. Types of Voluntary Changes

Types of voluntary exchanges and transfers within the context of present formal institutional arrangements that might be identified and evaluated within the basin are:

- (a) Water rights related to pumping in the South Platte Basin are generally junior to surface water rights. When this situation faced members of the Groundwater Association of the South Platte (GASP) they proposed an augmentation plan that would provide pumped water downstream for senior surface rights so that the GASP members could continue pumping. Presumably there are other opportunities for such constructive cooperative action within the basin. Noted in Chapter VII is the con-

tribution of computer-based technology through use of SAMSON in gaining acceptance of the GASP plan by all concerned.

- (b) Diversion of senior water rights upstream and outside the available area for groundwater in trade for pumping to supply water downstream is another type of voluntary change. To effect this voluntary arrangement, of course, the upstream water user would have to compensate the downstream user for pumping and any other associated costs. SAMSON is capable of indicating the feasibility and impacts of such a trade. Such study would be essential in obtaining permits for any required new wells or enlarging the capacity of old wells.
- (c) Often the total yield of a group of reservoirs can be increased by coordination of their releases. Studies of this possibility have led to a multi-agency plan on the Potomac River in Metropolitan Washington that now provides more water for the total area than was previously provided by uncoordinated operations. MODSIM, as discussed in Chapter VII, could be used in such studies.
- (d) Consolidation, relocation or betterment of canals could be studied with a view to transferring operation, maintenance and rehabilitation responsibilities, yet maintaining all traditional water deliveries to farms. SAMSON could indicate the physical feasibility of such changes on surface and groundwaters.
- (e) Much concern has been expressed on the need for greater agricultural water conservation through lining of canals and other physical measures. Water practitioners and other Western

water experts have doubted their feasibility as "water-saving measures" and have seen them generally as inhibiting the multiple use of water as it goes downstream both on the surface and in the ground. Both SAMSON and CONSIM could study this issue by indicating the impacts of such water conservation measures and help develop understanding of their utility or lack thereof.

- (f) Another type of potential voluntary change could involve the exchange rights to surface water for the right to pump with downstream water users who would give up their rights to pump. SAMSON could indicate the physical feasibility and impacts of such an exchange.
- (g) A voluntary exchange system during drought might facilitate a plan whereby a junior water-right holder would compensate a senior water-right holder when a junior-right holder could not meet his requirements by pumping and a senior-right holder could pump but at greater cost than surface water diversion. Under these circumstances both the junior and senior-right holders would be benefited and efficiency of water use would be enhanced as evidenced by greater agricultural production. Impact analyses by SAMSON could help in obtaining necessary well permit changes.
- (h) If encouragement throughout the South Platte River Basin were given to water reuse schemes providing for first use of water by Front Range urban communities and reuse by downstream agricultural interests, the overall efficiency of water use could be increased. In other words, the reuse schemes of Northglenn

and Farmers Reservoir and Irrigation Company as well as Westminster and Farmers Highline Canal and Reservoir Company could be adopted elsewhere in the basin where feasible. The preliminary overall plans of Thornton for use of Cache la Poudre water, as noted above, include a reuse component. Both CONSIM and SAMSON could be helpful in testing feasibility and identifying impacts.

- (i) Finally, computer-based models could provide an analytical basis for identifying the several types of positive as well as adverse effects of transferring storage in plains reservoirs to upstream consolidated storage facilities.

6.2 Possible Formal Institutional Changes

- (a) Consideration within the Basin could be given to modifying the normal water-right administration during years of severe drought. This strategy appears to be feasible because of the very substantial volumes of groundwater in storage within the basin. The shallow South Platte alluvial aquifer contains about 8 million acre-feet. The river tributaries also are underlain in part with tributary groundwater storage. The Denver Basin bedrock aquifers contain even greater quantities. It should be possible to take advantage of this large storage volume during severe droughts by allowing greater than normal withdrawals to supplement the surface supply.

The alluvial aquifer is now used partially in this way on a routine annual basis. However, large withdrawals on an emergency basis cannot now legally be made. A provision to

suspend the normal operating rules could be tested with the new computer simulation model, SAMSON, to determine the feasibility of such a contingency plan. The model could be used to test groundwater storage recovery time under the current system as well as under modifications which would increase artificial recharge.

Provisions for declaration of a severe drought could be made in the water law to make such a management change legally possible if it should prove to be physically feasible. Public policy also could be developed which would reserve some fraction of the water stored in the Denver Basin for drought emergency use. However, that storage is very slowly rechargeable under present conditions. Whether or not recharge to the aquifers could be accelerated is a good question for future investigation.

- (b) Flow rights, as indicated above, are measured in cubic feet-per-second flowing constantly. Failure to divert the full right could raise doubts about the "reasonableness and appropriateness" of the amount of the right. To prevent this question being raised, a diverter is encouraged by the present law to "use it or lose it," as is commonly said. On the other hand, water rights from stream diversions could be expressed in acre-feet, as are reservoir rights. If such rights could be claimed to the maximum duty of water efficiently needed over the long term for agricultural production, and if water saved through improved conservation practices could be sold, then the interests of water-right holders in agricultural

production would be preserved. In addition, they would be encouraged in their own interest to sell water rights in excess of their long-term needs. Also, the public interest in maximum efficiency in use of the state's water resources would be furthered. However, each water-right holder under such an arrangement would only utilize his water rights when water was actually needed for his crops. Thus, to make practicable such demand rights, it might be necessary to provide more reservoir storage for surface waters and pumping capacity for use of groundwater.

The general feasibility of this scheme should be studied in real life situations and estimates made of increased reservoir storage requirements, if necessary, before it is given definitive legislative consideration.

- (c) Transaction costs for water rights determination and administration are believed by many to be excessive. David Getches, formerly Director, Colorado Department of Natural Resources and now a Professor of Law at the University of Colorado, has suggested a modest means for reducing these costs (4). Legislation could be enacted, he has suggested, that "gives a presumption of correctness and regularity to State Engineer's determinations." Such presumption could be challenged, of course, in a Water Court proceeding by any of the parties at interest.

While this change in method of measuring water rights has been advocated for years, the difficulty in measuring the

duty of water in acre-feet along with the hydrologic uncertainty of variable flows has prevented adoption of this suggestion.

The South Platte Research Team believes that those three ideas for formal institutional change should be studied further in the context of the realistic and practical circumstance of the South Platte Basin. Unless they can be justified within this context, and gain widespread support of knowledgeable water practitioners, they should be abandoned.

Beyond these possible institutional changes, an arrangement for cooperation could go a long way toward improving efficiency and reducing conflict among water right owners in the basin.

The remainder of this chapter describes this cooperative management. In effect, the suggestion that follows constitutes the research team's primary idea for improving water management in the South Platte. This idea the team believes, should be tested in the future through experience.

6.3 Current Status of Cooperation

Historically speaking, water right owners have not cooperated very fully. Each local entity, whether an individual, district, a city or a farmers' irrigation company, focused on its own need without much regard for others who used the same water supply. There are many reasons. One is the uncertainty of weather; another is the fugitive nature of water. The water right system itself is difficult to understand. Everyone knows that paper water rights do not put water into the stream and the harsh realities of the prior appropriation system can put water right owners in a tenuous position. This is particularly true during dry

years, especially since the South Platte is overappropriated. Water right owners find that it is very difficult to keep track of what is happening on the entire river, and there is always a suspicion that some remote change in river operations may adversely affect individual water rights.

According to one water judge, the water court necessarily moves very slowly in handling changes such as augmentation plans, changes of use and point of diversion, conditional decrees and the accompanying protests. The Water Resources Division is hard pressed to keep up with all of the changes so it can effectively administer the water rights. One division engineer pointed out that there is not enough staff to handle the workload efficiently. A common complaint from water right owners is that they must spend a great deal of money for engineers and attorneys just to protect their water rights. Protection is a prevalent theme that brings out suspicion of anybody, including the state or federal government, which "tinkers" with the river. There are even stronger feelings against a so-called "water czar" or a central authority managing the river. This idea appears to water right owners as a threat to their property rights.

This background presents a great challenge to those who would promote voluntary basinwide water management. Even though some water users and managers may say they approve of the concept of basinwide water management, the foremost thought is still: "I must protect my water right." Therefore, any scheme for basinwide water management must strongly embrace the idea of protecting and improving the status of all water rights in the basin.

Even with the parochial, antagonistic and protectionist attitudes on the surface there is an underlying sense developing that says, "We must cooperate and work together to manage the common water supply." A division engineer recently said, "There is more talk about cooperation than ever before." The question is, how can this be done? What are the incentives to do so?

6.4 South Platte Federation: A Proposed Experiment

If all water right owners in the South Platte River Basin would participate in a voluntary, integrated basinwide management scheme, then each one of them might gain increased benefit from the water supply according to their individual need. This assumption would have to be tested and proven by water right owners themselves, based upon their willingness to work together and the degree of confidence they can develop in the new computer simulation technology now available to help them.

The following suggestion of an approach to cooperation and a method to test is presented for discussion purposes only. The centerpiece of the suggestion is the formation of a voluntary federation or local association of water right owners. It could be called the "South Platte Federation." Some of the basic principles could be:

- (a) The purpose of the organization would be to exchange information and facilitate consumation of water exchange and transfer contracts between legal water entities (i.e. individual water right owners, districts, cities, etc).
- (b) The mechanism would be developed so as to protect individual

water rights without great expense to owners.

- (c) There would be little "non-water right owner" interference in the process.
- (d) "Grassroots" involvement would be maintained so that each water right owner could develop confidence in the system.
- (e) The process would be strictly informal without legal status or authority.

The contracts between legal water entities, as noted above, would relate to water exchanges and water transfers. An exchange means making a flow or quantity of water available to another party at a particular time and place in trade for a flow or quantity of water at another time or place. A transfer means the sale or lease of a flow or quantity of water in trade for a monetary or other valuable consideration.

The membership of the organization could be made up of elected representatives from local water user associations organized for each major tributary, i.e., Clear Creek, Boulder Creek, St. Vrain, Big Thompson, Cache La Poudre, etc., and representatives from designated sections of the mainstem of the South Platte, i.e., possibly Sterling to state line, Fort Morgan to Sterling, Greeley to Fort Morgan, Greeley to Denver, etc.

As shown on Figure 6-1, each year each local association could meet to discuss local water supply problems and develop exchanges if needed. Each local association might elect, say, three representatives to the South Platte Federation. These three representatives could be bound to develop one position on each issue. The division engineer might be a non-voting moderator of the Federation.

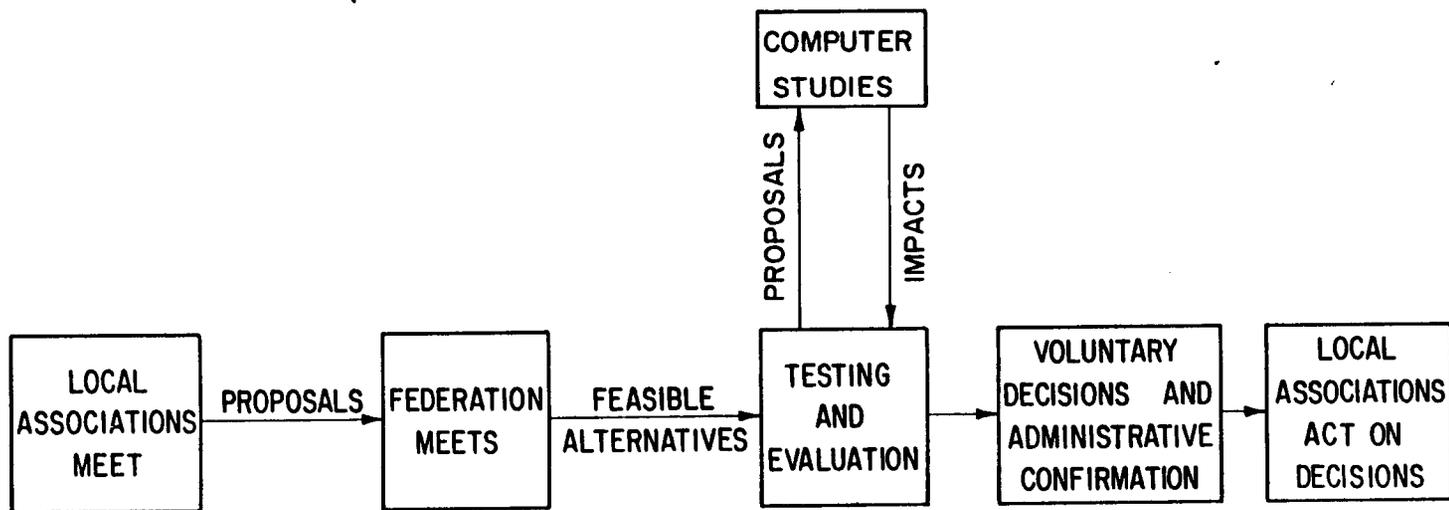


Figure 6-1. Sequence of Decisionmaking for a "South Platte Federation".

The Federation might work out proposed exchanges or transfers between legal water entities. These proposed changes could then be studied on a basinwide computer model to predict their effects on all water rights in the river sections and tributaries represented. The three local association representatives would take the results back to their respective local associations for discussion. The three representatives would then return to a meeting of the South Platte Federation for discussion. Any water right owner who preferred not to be part of any exchange could withdraw. The burden of proof that no injury would result to junior appropriators would be placed upon the legal parties to the exchange or transfer contract backed up by the results of computer-based basin modelling.

Operation of the actual exchanges would be closely monitored by the Division of Water Resources. Each local water commissioner would play a key role in implementing cooperative management programs which may go beyond routine duties to encompass efficient water use. All exchanges could be developed on a yearly basis and could be modified each year to meet changing needs.

The idea of the voluntary approach is to get some cooperation started, even informal cooperation in the beginning. As more and more water right owners became involved, they would change and modify the process.

Fundamentally, the research team believes that voluntary basinwide water management could be operated within existing law. However, there may be some legal problems which would require legislation or change in regulations. If the water right owners supported changes that through careful and complete examination proved to be necessary and desirable, then the political problems would be minimized.

Successful voluntary basinwide water management would focus upon specific problems. One type of problem might be: how to use a tributary aquifer for storage. Solution could require exchanges to store water in reservoirs so that releases could augment pumping. Other types of problems that could be tackled in a specific context were set forth earlier in this chapter.

Everyone must be winners, with no losers. Otherwise the process will break down and result in more problems, not less. The research team believes that there are many specific situations in which exchanges would benefit all participants and junior appropriators would not be harmed.

Experience has shown that some water right owners oppose just about any proposal. The key will be to facilitate negotiations skillfully between opponents and proponents. Every concern must be carefully and fully dealt with. Compassion, patience, diplomacy and tenacity will be required. The development of the process may take many years. Complete perfection, of course, will never be achieved. However, the alternative to voluntary water management is intensified and costly bickering over a very limited water supply.

The real test for voluntary integrated water management will be political. Could a South Platte Federation work if some large, powerful water right owners chose to fight it rather than join? This eventuality could happen, since large water right owners might choose to take advantage of their power to gain advantage. By the same token, outside financial interests might choose to fight the Federation for profitmaking purposes. Both of these problems are possible, and must be anticipated by any Federation. The correct answer, it seems, would be

for the Federation to also gain power through organization, and through legal and engineering expertise.

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VII. COMPUTER-BASED MODELS: NEW WAYS TO PROVIDE BETTER DECISION INFORMATION

7.1 Models and Decision Information

A major premise of this report is that computer-based models to improve water decisions can benefit water right owners. The models can produce information and knowledge that will allow an examination of multiple factors at the same time, including: complex exchanges, water quality changes, storage opportunities, and management plans. In this section the ways by which models can be used is elaborated, and the capabilities of two specific new models developed under the sponsorship of the CWRI are described.

The models do not replace the experience of the persons who already have knowledge about river management possibilities, such as the Water Commissioners. They can extend the capabilities of these people. The end result of using a model is added information, or knowledge.

A hydrologic model simulates how an actual situation, like flow in a river reach, will respond under given conditions. An economic model might predict how farm income would respond to changes in water cost, availability and demand. The models are a resource that has value because they indicate how to get maximum economic use out of water. For example, the information they produce can be used to demonstrate to the State Engineer and the water courts that planned exchanges are desirable.

The vehicle to produce information or knowledge for decisions is a study. The models are tools to be used in studies to produce informa-

tion and knowledge for the purpose of good decisionmaking. Today's studies must be far more complex than previous studies because the water supply system and its administration have become extremely complex. Also the demands upon water supplies have become numerous and complex. Research has provided advanced technology for better models with which to make these studies.

Private or public water decisions result in economic outcomes that have important impacts on groups of people. These groups affect decisionmaking through the channels available to them, both informal and formal. This is illustrated in Figure 7-1 as shown. The water decision-making impact process is continuing because it goes on continually.

On the South Platte, and in other Colorado river basins, the channels for decisionmaking are not always well-defined. However, the economic outcomes from water decisions are clear: they determine whether farming or other enterprises can be successful or not. With so many water right holders on the South Platte, there exist many formal and informal ways to make decisions, but many potentially useful channels are blocked for lack of information and knowledge.

Information and knowledge for decisionmaking can be viewed as a "decision support system", as illustrated in Figure 7-2. In the figure, a number of groups are shown inside a "decisionmaking space." These are groups such as water right owners, cities, water regulatory bodies and interest groups. The decisions are made by various means depending on the conditions at hand, and groups are involved according to their relative influence in a given situation. The most involved group will

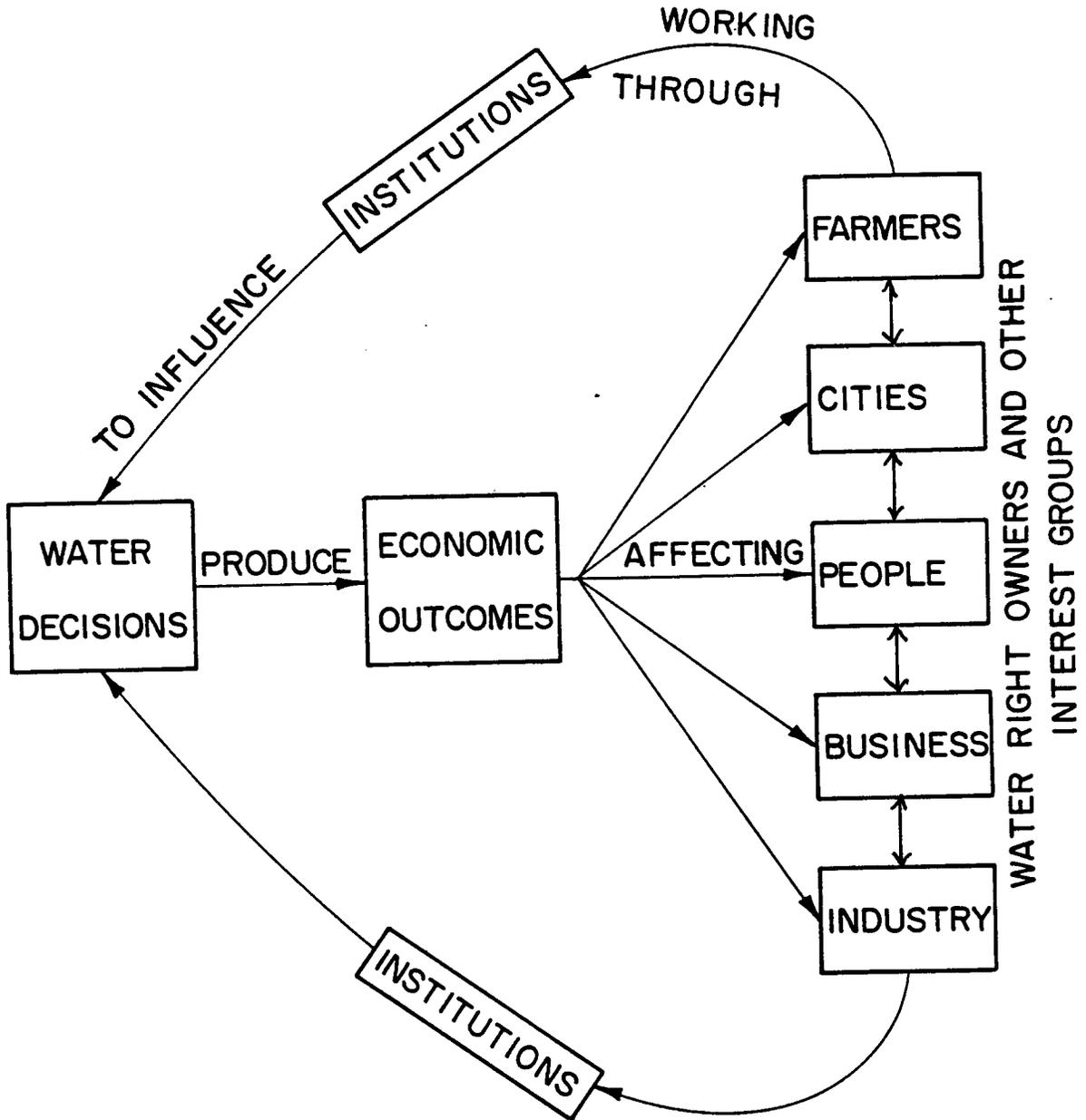


Figure 7-1. How water decisions affect economic outcomes.

DECISION MAKING

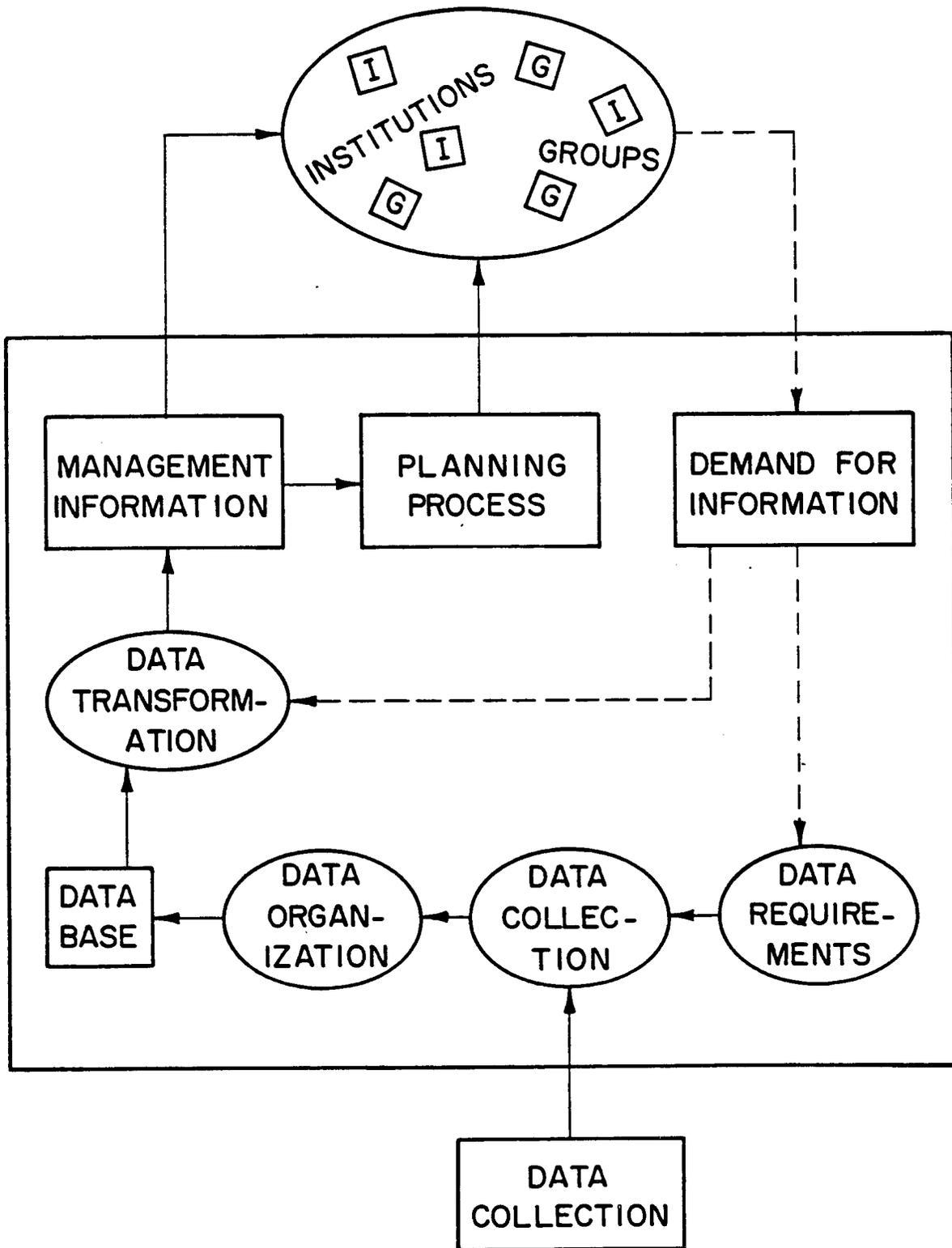


Figure 7-2. The decision support system.

be water right owners. The important point here is that whatever the decisionmaking arrangement information about the consequence will be needed, and Figure 7-2 illustrates the information support system needed for a voluntary association such as the one described in Chapter VI. The figure shows how a management information system, including data, studies and models, can provide useful decision information for whatever groups are involved in the decisionmaking process. As described in this report, the need in the South Platte Basin is to provide information about exchange and transfer opportunities, water supply forecasts, water demands and other data which can assist water right owners in making exchanges and transfers, as well as improved management arrangements through a voluntary association.

In the decision support system, the planning process (one of the blocks in Figure 7-2) is a familiar place to use models. The planning process in this situation can be, for example, an annual planning meeting for an association of water right owners, as described in Chapter VI. Here, models are used for several purposes: to formulate solutions to problems, to evaluate how different proposals will work, and to determine optimum policies. The diagram shows how the models might fit into the planning process. Here it is very clear that the models are transforming raw data into more concrete knowledge and information that can help the process. In the same way, information and data from other sources may be useful.

Models can be used in a number of ways to support decisions. It is easy to visualize how better information leads to better decisions, as shown in Figure 7-2, but the information has to be processed and trans-

formed before it is useful. This is "value added" to the information. As shown on Figure 7-2, the models could be used in the "data transformation" activity to produce management information directly, or they could be used as part of the planning or problem solving process itself. In water management, an excellent way to use models is in the operational phase, to show how to make good detailed operating decisions.

The general use of models for management is as shown in Figure 7-3. The models are for the purpose of making predictions about outcomes, whether the focus is hydrologic or economic. The inputs are in the form of controllable variables and non-controllable variables, and the output is predictions of results, based on stated objectives. As an example, consider that one wants to know the consequences in a given year of a relaxation on well-pumping restrictions. The non-controllable variable might be the precipitation of that year, and the controllable variables might be the amount of pumping allowed. The prediction of results, or goal achievement, might be whether the amount of crops desired can be produced. This kind of model run could be used by a water right owners association to demonstrate preferred policies to the Division of Water Resources.

This kind of modeling approach can also be used by individual farmers or associations to learn about increased water supply and income possibilities resulting from water exchanges.

There is a general use for the information produced by models in the overall decisionmaking process, whether the stage involved is planning, design or operation, and whether the group involved is the water

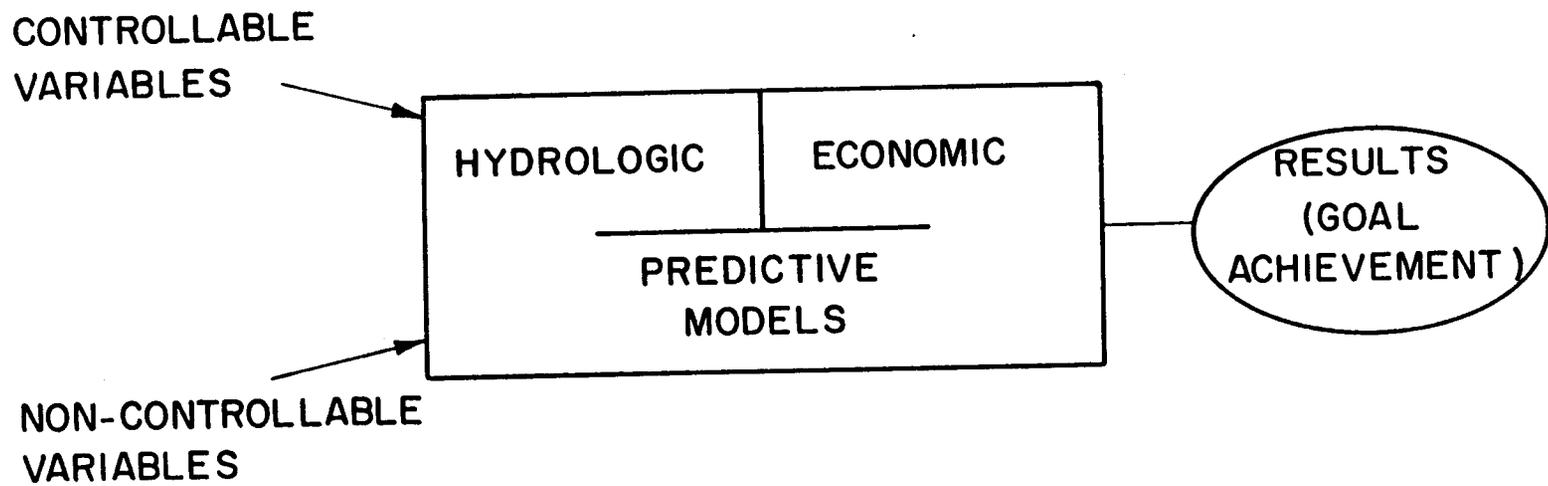


Figure 7-3. General Model Formulation and Use.

right owners, the state government or another planning entity. The Planning Process supports decisions as part of the "decision support system," and the models support the planning process, as well as produce management information for direct use.

7.2 Two Specific Types of Models

Two specific types of models will now be discussed to show how they can provide useful decision information and knowledge. They are CONSIM and SAMSON. The names, developed by Drs. John Labadie and Hubert Morel-Seytoux respectively, are acronyms and refer to two different types of models which were developed for different purposes. They have the common characteristic that they are both computer-based hydrologic models capable of simulating connected stream-aquifer systems, but each has a different focus. Both, however, have the capabilities of incorporating economic variables and legal constraints.

The primary differences are that:

- (a) CONSIM is a model designed for screening preliminary plans for an entire basin water system or parts thereof. It is a capacitated flow network in which the components of the system are represented as nodes (reservoirs, diversion points, points of inflow, demand locations, etc.) and links having specified direction of flow and maximum capacities (canals, pipelines, river reaches). Volume balance is always satisfied throughout the network. This model is not intended for use in day-to-day decisions on system operation, but rather as a means of examining and evaluating alternative management strategies or

developments in order to find those most favorable for further, more intensive, analysis.

The model is designed in such a way that operational rules and constraints may be imposed on the various sources of supply allowing demands to select water from any of the available sources. The model selects the optimum combination of sources by an adaptation of a cost-optimizing program. This program also indirectly accounts for water right priorities, thus preserving the priority of rights in the model operation. Similarly, exchanges of water rights can be accounted for if they are specifically identified as model inputs. This quasi-optimization feature eliminates the usual trial-and-error procedure of similar models and thus reduces cost of model operation.

CONSIM is a very cost-effective generalized model that can be applied to any river basin water system. It is ideal as a screening tool to examine options in both management and development. With a preliminary estimate of the optimum approach from CONSIM, a model such as SAMSON can be used to establish the details and confirm its physical feasibility. The model has been designed to be "user-friendly." It has been adopted for planning purposes by a substantial number of firms and organizations in Colorado and elsewhere.

- (b) SAMSON is a computer simulation model representing the state-of-the-art in advanced computer simulation technology. The model enables the user to predict the responses to differ-

ent water resources management strategies (water right exchanges, alternate points of diversion, reservoir storage, etc.) throughout the entire basin water system. It is ideally suited to evaluate the effectiveness and legality of augmentation plans and to test tributariness of groundwater. The decision processes of the agencies or individuals that oversee the operation of the system are inputs to the model. Proposed management decisions can be tested regarding all withdrawals at all withdrawal points in the entire basin for every day. Long-term impacts of management changes or of proposed new developments can be found with confidence.

The model divides the basin into a grid of one-mile squares. Proposed management decisions are computed for each grid cell based on the known physical laws that govern the movement of water both above and below ground. The model computes in each cell the drawdown of the water table due to pumping, the aquifer return flow to each one-mile reach of the river, the amount of aquifer recharge due to excess irrigation, the flows in each one-mile reach of the rivers and in the canals, the amounts of seepage from reservoirs and canals, etc. It simulates the water system day-by-day for each plan or action proposed within the basin.

These models are discussed in more detail in the following sections, followed by a discussion of economic and legal modeling.

7.2 CONSIM, A Network Optimization Model

CONSIM is a capacitated flow "network model" which not only simulates the conjunctive operation of ground and surface water facilities in a river basin, but also provides an optimizing capability. The name "CONSIM" comes from the terms "conjunctive use simulation." The precursor to CONSIM is MODSIM which is similar, but without stream-aquifer interaction.

MODSIM or CONSIM are not intended for use in day-to-day decisions in systems operations, but rather as a means of obtaining potential monthly or weekly management options over, ultimately, the entire South Platte basin. The model is capable of generating optimal operational plans while satisfying formal water right constraints and informal water exchange mechanisms. Allocation of streamflows in strict accordance with water right priorities can result in waste of valuable water supplies, so exchanges of water have become a useful expediency. CONSIM and MODSIM have been designed to account for water exchanges. Water exchanges provide a flexible means of meeting water demands from a variety of water sources while protecting the rights of senior water right holders in the basin.

To understand what CONSIM or MODSIM are, visualize a river basin with facilities in place. They might consist of stream sections, reservoirs, wells, municipal and industrial demands, irrigation ditches and other facilities. All of these working together would constitute the river basin operation. Figure 7-4 shows a small-scale example selected from an area near Fort Collins, Colorado, on the Cache La Poudre River, a tributary of the South Platte. These facilities can be

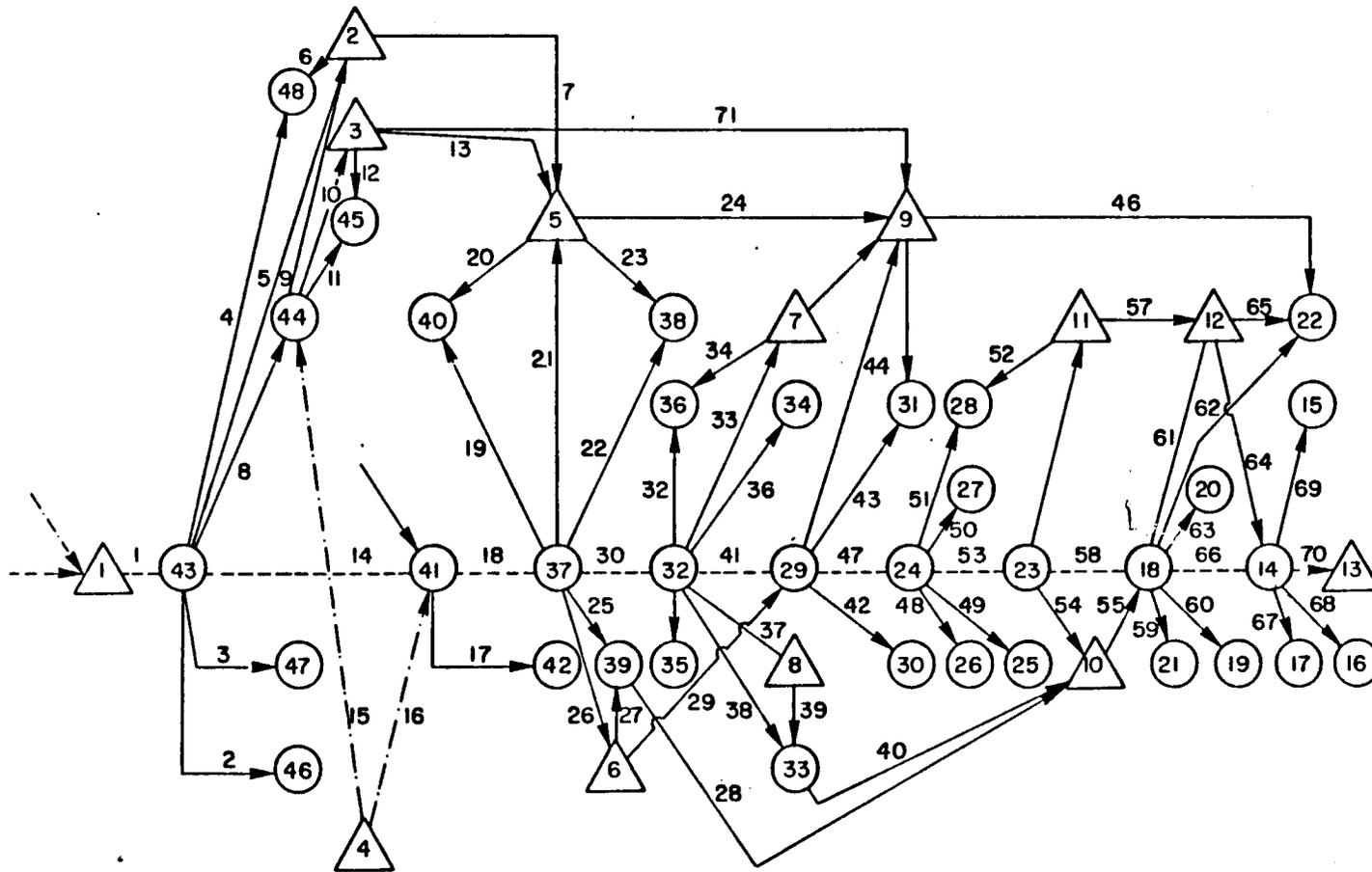


Figure 7-4. The Network Representation of the Cache La Poudre River Basin's Physical Features.

simulated by a series of "links and nodes" as shown on Figure 7-4 and they provide the computer with a way to keep up with where the water is going at the times of interest, and the volume that is transferred during each month or week. In this way the model is a fast "accounting model," able to keep track of water wherever it is.

CONSIM, or variations thereof, can be applied to large river basins such as the entire South Platte. Applying it to such a large area at once has not been done yet, but the availability of large capacity computer facilities such as the CYBER 205 "super computer" at Colorado State University provides that capability. The problem then becomes one of handling all of the large quantities of information available and needed at one time. This case is a good example of the use of a computer to solve complex problems involving the handling of large amounts of information at once.

A Municipal Example. MODSIM3, a third generation version of MODSIM, has been applied to the Fort Collins water supply system. This application was developed through joint work with the City of Fort Collins which has now adopted this model for water supply management planning.

The Fort Collins water supply system contains elements such that water may be drawn from a variety of physical sources. Coupled with this are the exchanges of water rights which increase the management complexity of the supply system. It is this complexity that makes planning difficult because of the myriad of possible alternatives and their impacts.

MODSIM3 was used to find the safe annual yield of the City supply in the following manner. The model was run over the six year simulation period using a trial average annual demand level. If the available carryover storage reservoirs indicated surplus water available at the end of the critical period, the run was repeated with an increased demand. This iterative procedure was continued until the carryover storage reached a predefined level with minimum water shortage occurring at Fort Collins. This procedure was repeated with varying amounts of reservoir storage and configurations of water rights.

The particular focus of this case study was to determine the safe annual yield that could be realized under given hydrologic conditions. MODSIM3 was used to determine the safe annual yield for the City's existing water rights as of 1983 and the projected future water rights which the City expects to acquire by the year 2000.

The major components of the Fort Collins water supply system are shown in Figure 7-5. This map represents the geographical location of existing facilities available to the City. Although the Fort Collins supply facilities interact directly with the Cache La Poudre river system, modeling of the entire basin was thought to be unnecessary for this study. A network was designed to isolate the Fort Collins water supply system to simplify the required inputs to the model without substantially detracting from reality.

Figure 7-6 demonstrates the complex structure associated with the City's water supply system. The numerous links in the diagram are necessary in order to account for the individual water transfers that can occur.

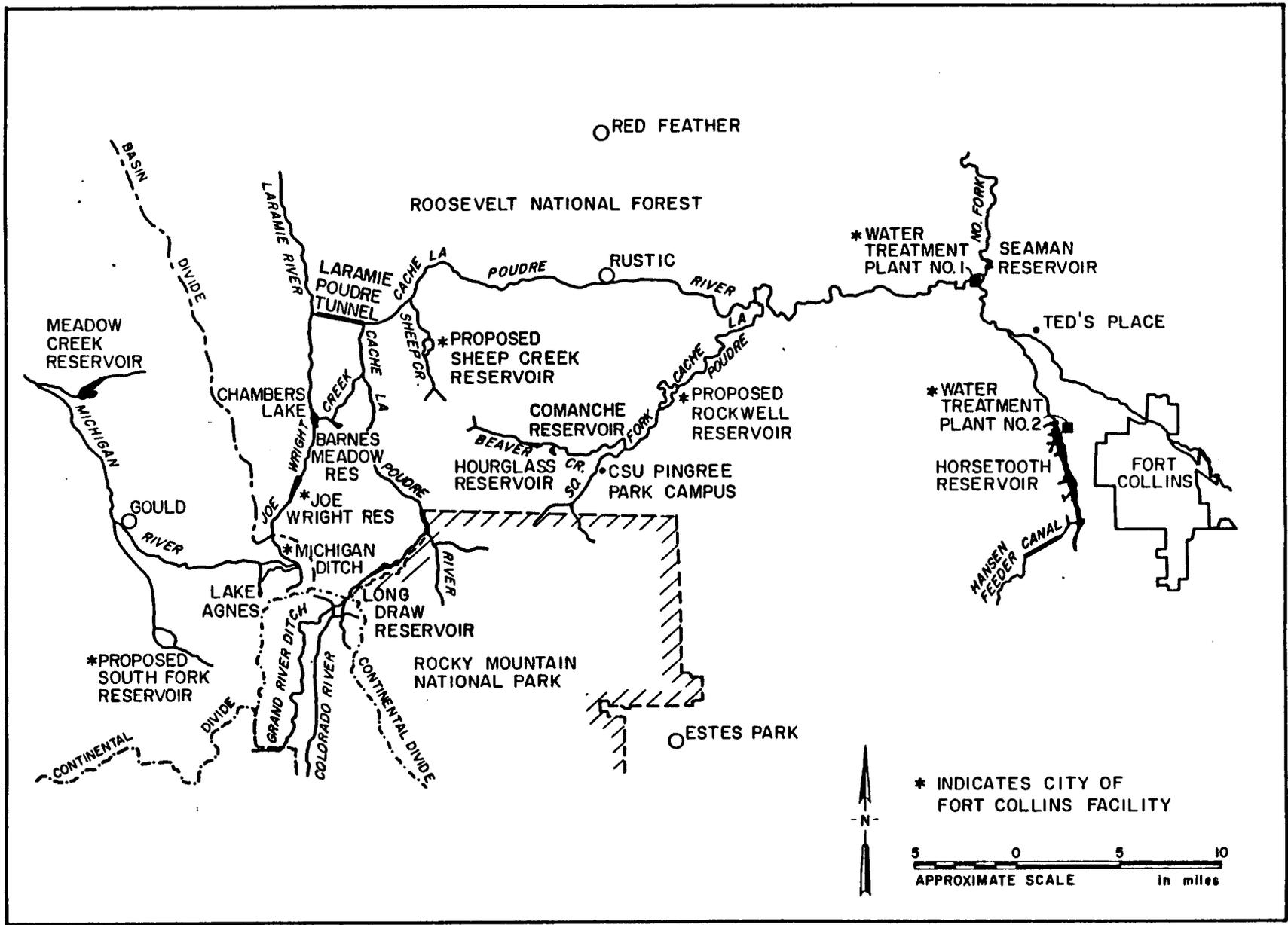


Figure 7-5. City of Fort Collins Water Supply System.

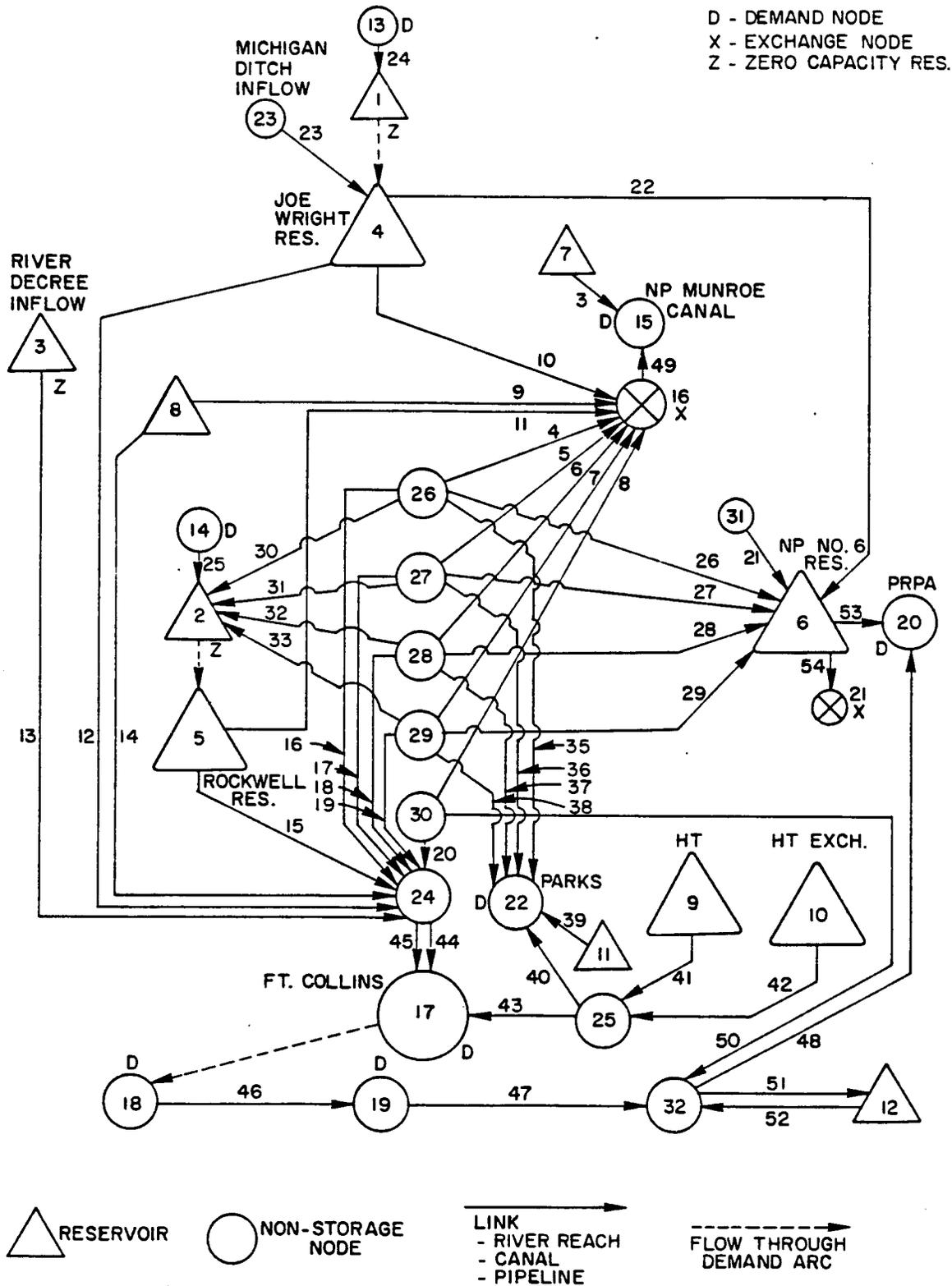


Figure 7-6. Link-Node Configuration for Fort Collins Case Studies.

A River Example. The following discussion describes a river application that can be used to develop management policies for a river reach.

Figure 7-7 shows the disaggregation of the lower South Platte study reach and Figure 7-8 shows the link-mode configuration. For this example, each subarea is associated with one diversion canal or one releasing canal, though a finer resolution is possible.

The detailed calibration and operation of the model is described in Labadie et al. (1). Management situations that could be examined include: exchange arrangements, artificial recharge, new surface reservoirs, new demands, compact change alternatives and changes in regulations. The following describes a hypothetical case of artificial recharge.

In the artificial recharge simulation a number of assumptions about pumping and water use are made. A hydrologic period ranging from April 1953 to March 1957 was chosen for study. It includes drought years (1953-55) and an average year (1956). Computer runs were made for the period with no artificial recharge and then with the unregulated inflow assumed available for artificial recharge.

Figure 7-9 shows the result of the simulation. With artificial recharge, subsurface storage can be maintained; without it, subsurface storage, and groundwater levels, decline. The magnitudes shown on Figure 7-9 are hypothetical, but it is clear that an analysis of this type can be used to develop management policies. Figure 7-10 shows an example for a particular demand area (node 32, Figure 7-8) how the model would suggest that surface water and groundwater use be apportioned over

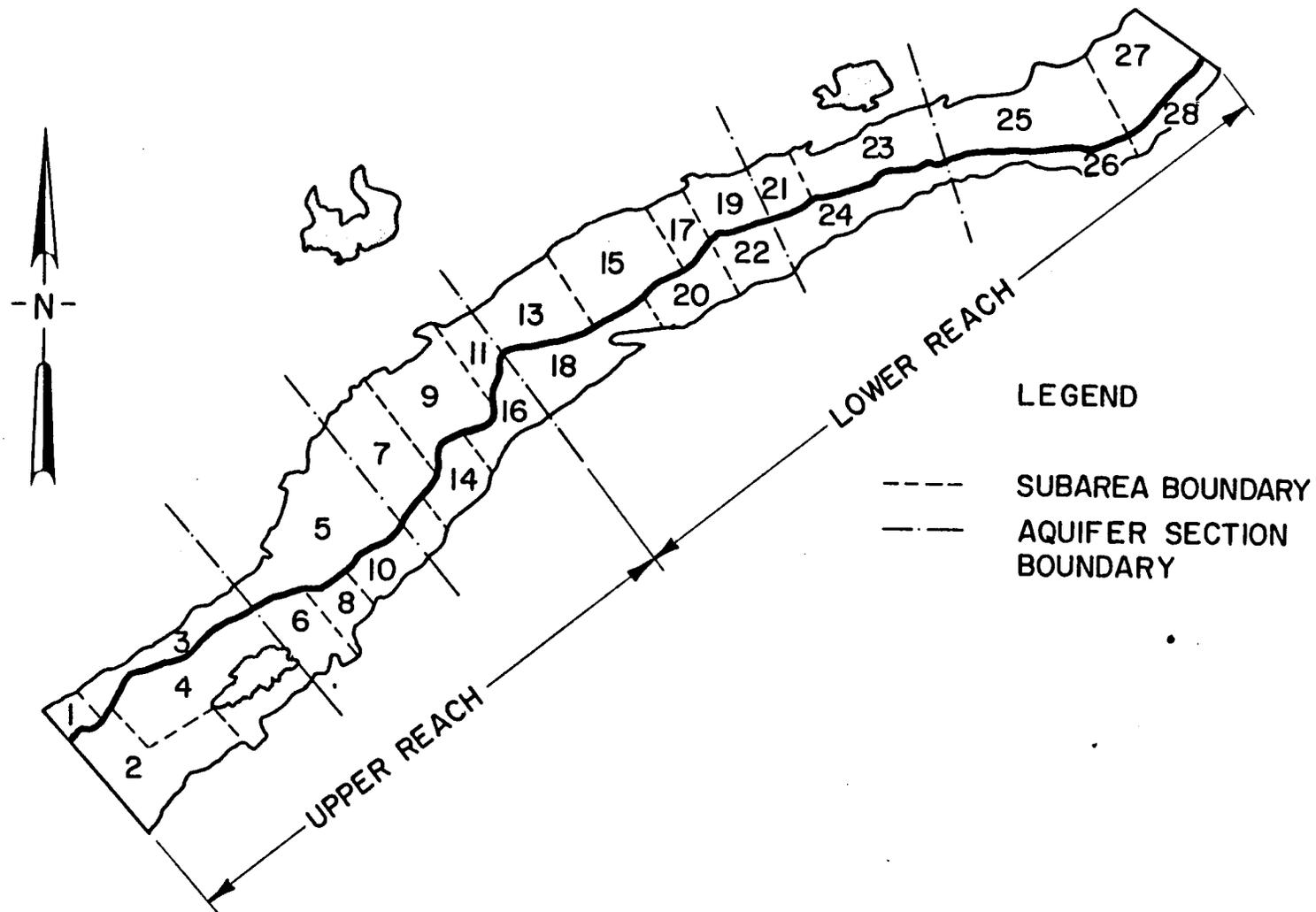


Figure 7-7. Approximate Spatial Decomposition of the Case Study Area.

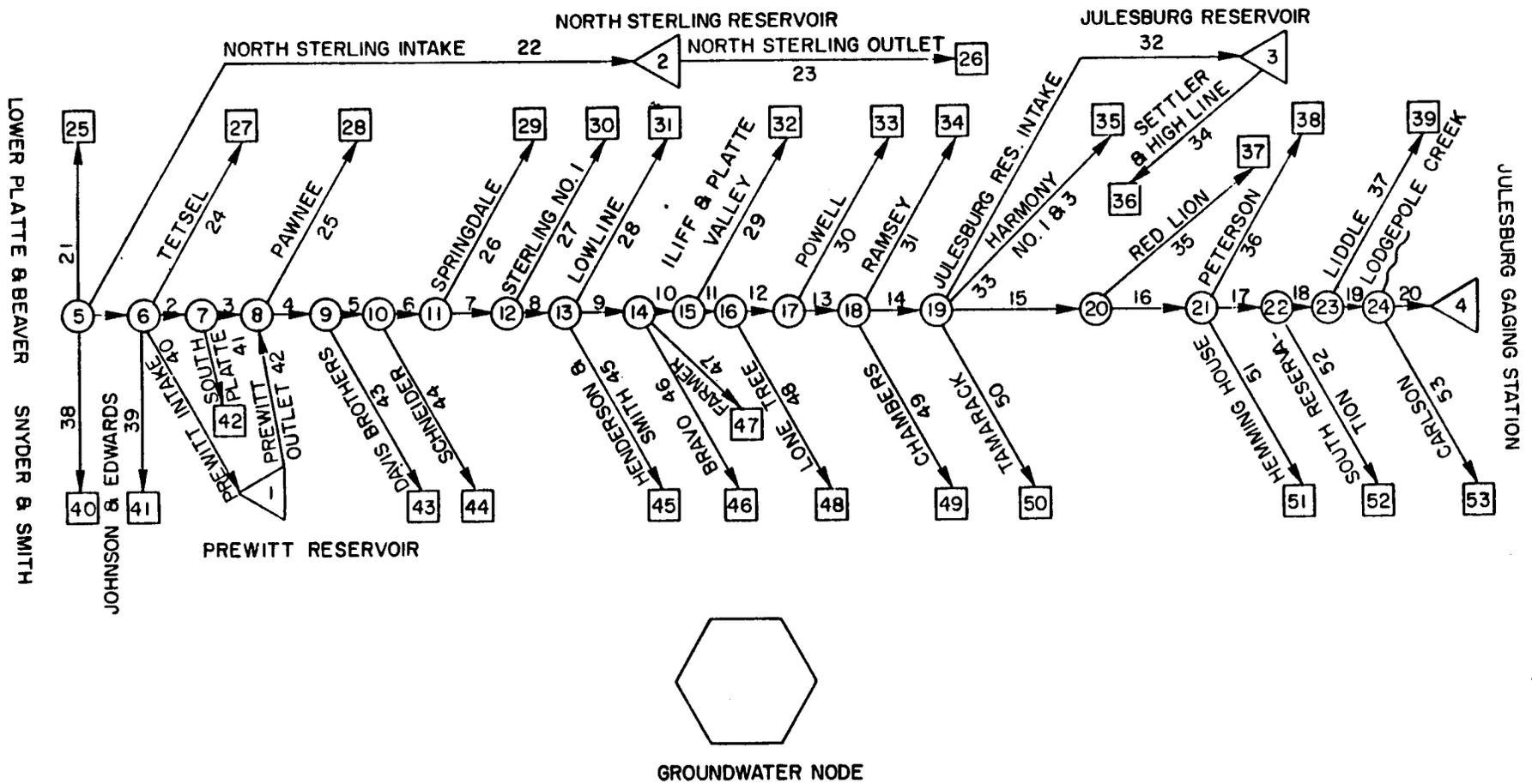


Figure 7-8. Network Representation of the Case Study Area.

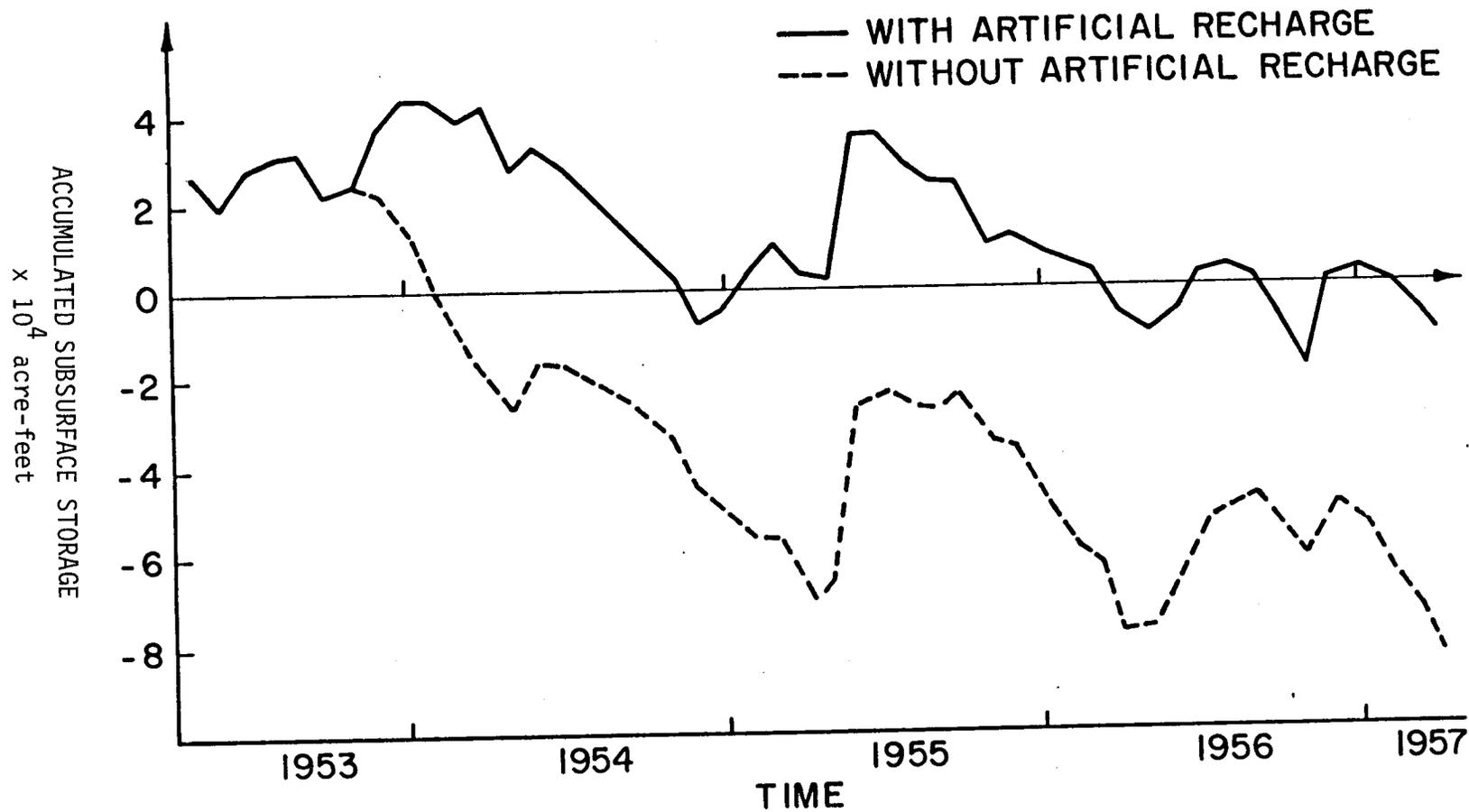


Figure 7-9. Change in Subsurface Storage with Artificial Recharge and Without Artificial Recharge.

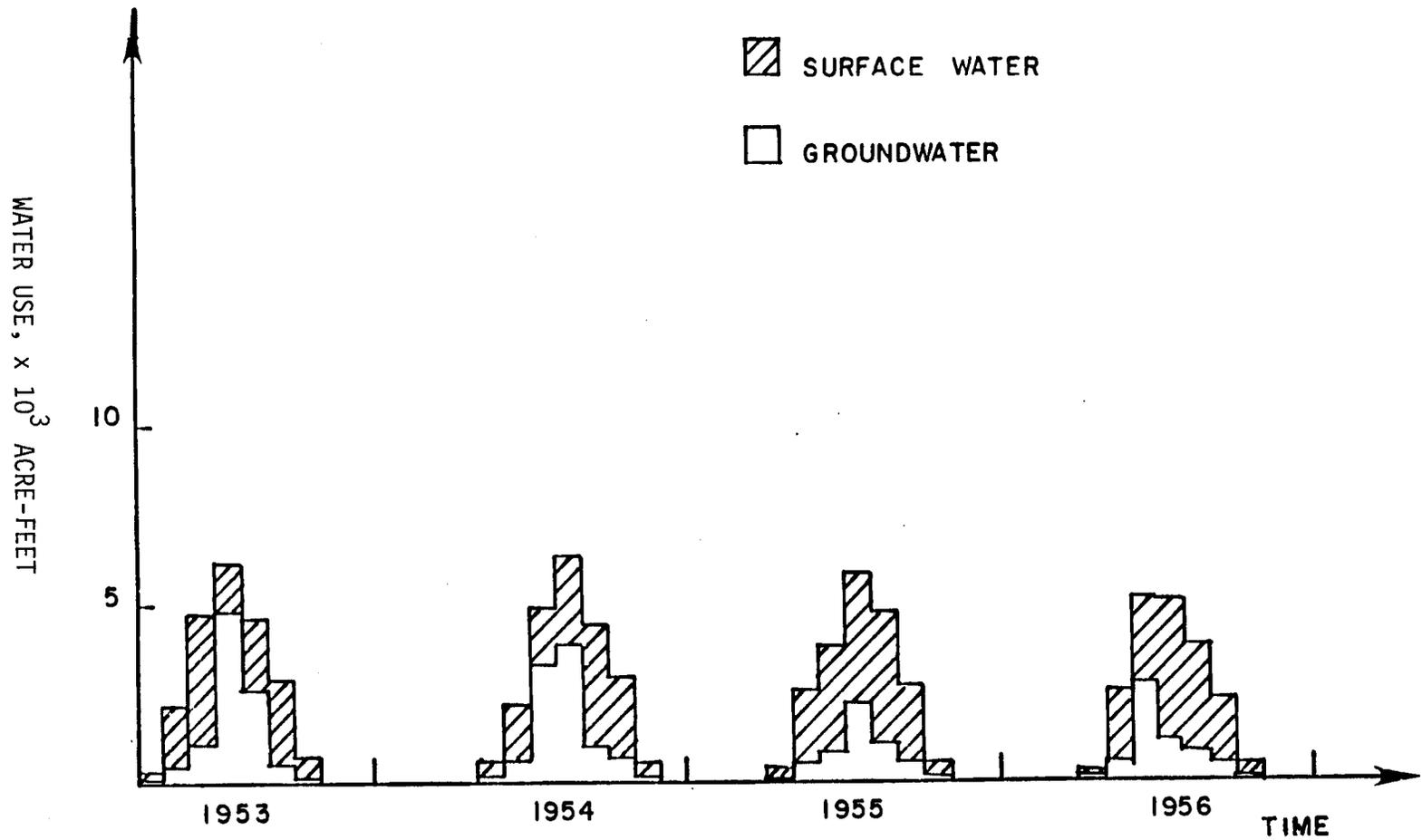


Figure 7-10. Example of Demand Satisfaction for Node 32, Iliff and Platte Valley.

the season in order to maximize efficiency and minimize shortages. The model is capable of producing more detailed information on a weekly basis for this area if appropriate data are available for input.

It is clear from these illustrations that MODSIM and CONSIM introduce new possibilities for management and development planning studies, such as:

- (a) Screening various alternative proposed storage projects for cost-effectiveness.
- (b) Determining how much and where additional storage is needed in a river basin to meet new water demands and reservations.
- (c) Predicting the effects of new water demands for energy development and its (possible adverse) impacts on other uses, particularly irrigated agriculture.
- (d) Reevaluating accepted water policy on a comprehensive basis at the river basin level, including prediction of impacts of policies to enhance hydropower production.
- (e) Analyzing the feasibility of new transbasin diversion schemes.
- (f) Predicting water quality impacts of alternative policies.
- (g) Determining innovative, integrated reservoir operation plans that maximize water use efficiency and minimize wasted outflows from the basin.
- (h) Planning real-time operations during drought periods (the model could be used to continually generate plans over a season as additional data become available).
- (i) Helping to document the experience of an administrator. This

is particularly useful if an experienced river basin commissioner leaves his position for any reason. New, untrained-personnel would find such a model available.

7.3 SAMSON A Stream-Aquifer Model

Another model, SAMSON, a stream-aquifer model, provides the capability to look more closely than CONSIM at operational impacts everywhere in the basin. It is a comprehensive model on a river basin scale, and can simulate daily surface or groundwater responses making it suitable for aspects of real-time management, as well as for water project planning. It has been developed over a period of about ten years at Colorado State University and carefully adapted to the complexities of Colorado water law and administration. In other words, SAMSON is state of the art technology applied to the realities of Colorado practices ^{4/}.

At the present time SAMSON has been constructed for the South Platte River, its tributaries and associated lands from Denver downstream to the state line. The model simulates hydrologic processes on a daily basis including flows in streams, flows in the alluvial groundwater aquifer, aquifer recharge from irrigated lands, evapotranspiration from irrigated lands, moisture storage and movement in the unsaturated zone above the water table and canal seepage.

^{4/}The mathematical basis for SAMSON is reported in a series of Institute publications produced during its development between 1973 to 1981. See references (2), (3), (4), and (5). An application to a study to evaluate drought emergency options for the South Platte Basin is (6). Another application for GASP, Inc. to evaluate augmentation plans was done by contract. The report was furnished to GASP, Inc. but not published by the Institute.

Figure 7-11 shows the dimensions of the portion of the South Platte River from Balzac to Julesburg, originally covered by SAMSON. The grid in Figure 7-12 shows a detail of a region near Balzac. The SAMSON computer program stores hydrologic information for each of the grid squares. Thus the "areal resolution" depicted by SAMSON is one square mile. For each of the grid squares in Figure 7-12 the program stores all of the physical components shown by the map: river reaches, canal reaches, reservoirs, irrigated land and groundwater aquifer. In addition, the square stores the hydrologic data necessary to depict surface and groundwater flows within it.

In operation, all flows to and from each grid square, plus or minus changes in surface storage and groundwater storage must balance. Since the flows from one grid square must equal the flows to the one adjacent, a water volume balance is necessary for the system as a whole, as well as for each grid square.

Figure 7-13 shows the kinds of structural features contained within SAMSON, but more important, it depicts the idea of operation. The actual daily flows of water shown in Figure 7-13 are determined by two things: (1) the amount of water available; and (2) the rules for its allocation. The water available in the system is determined by the weather pattern for a given year, while the rules for water allocation are determined by the water rights system comprised of the basic legislative doctrine, the 1969 Water Rights and Administration Act, court decrees, and administrative rules by the State Engineer.

Figure 7-14 illustrates how SAMSON works. The portion of SAMSON's instructions containing the water rights rules, practices, and procedures is called the "water allocator." It determines whether water can

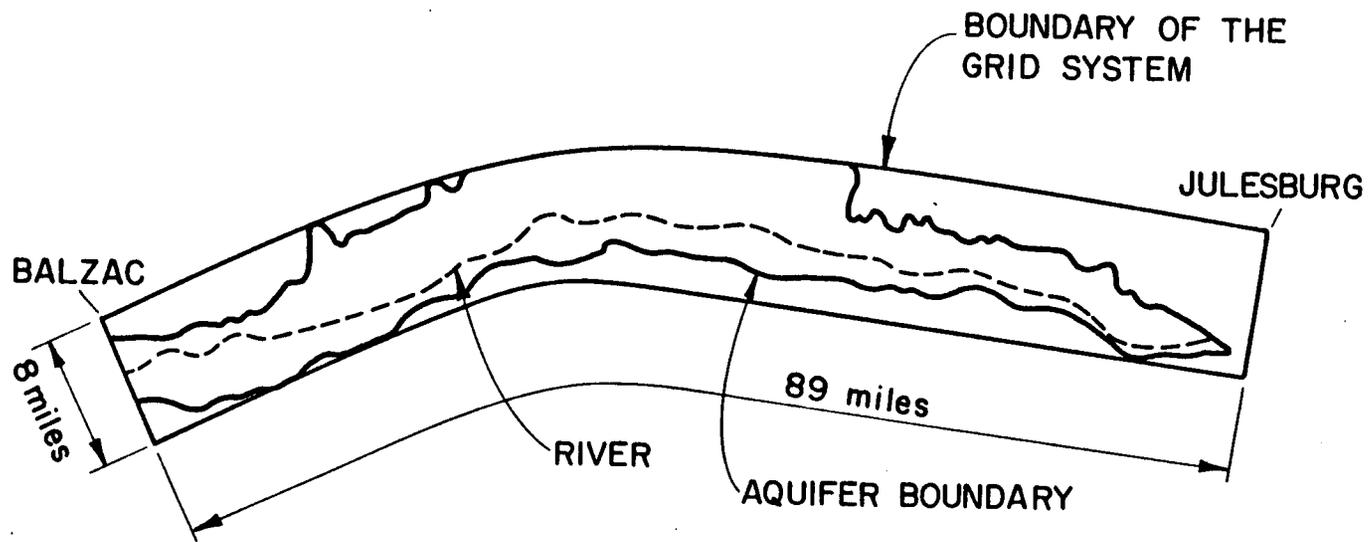


Figure 7-11. General Boundaries of the Grid System.

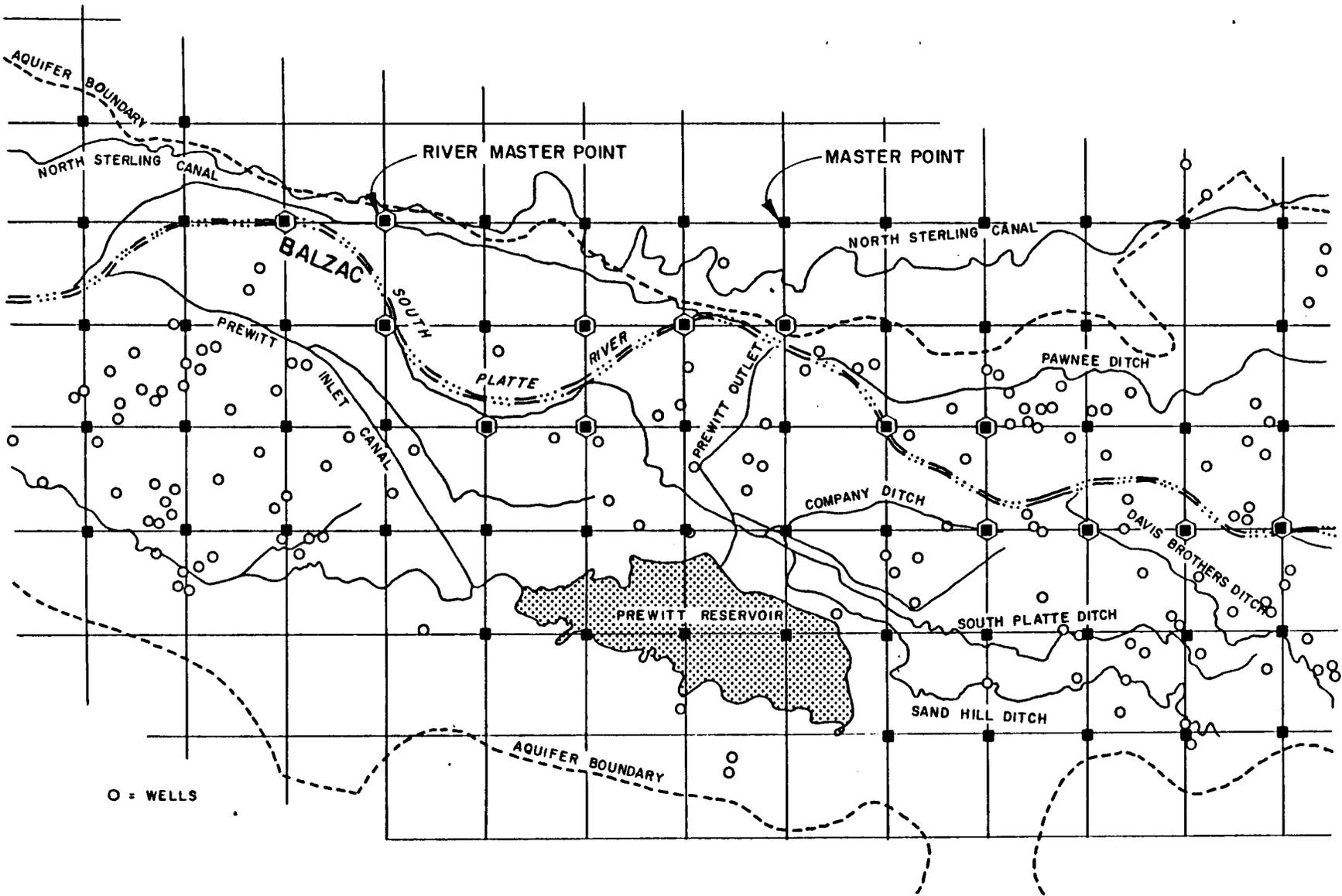


Figure 7-12. Detail of Discretized Physical Systems Near Balzac.

Table 1. Correspondence between a Physical (Hydrologic, Engineered) Excitation and the Numerical Code Shown on Figure 2.

No.	Description
1	Precipitation
2	Canal seepage (canal not in hydraulic connection with water table)
3	Reservoir evaporation
4	Reservoir seepage
5	Evapotranspiration from irrigated plots
6	Deep percolation from irrigated plots
7	Aquifer withdrawal by pumping
8	Tributary seepage (stream not in hydraulic connection with water table)
9	Phreatophyte losses
10	Aquifer return flow to stream
11	Surface return flow to stream
12	Effective deep percolation from precipitation
13	Upstream inflow
14	Diversion from stream to reservoirs
15	Reservoir releases
16	Diversion to ditches supplying irrigated land
17	Tributary inflows to stream
18	Downstream outflow
19	Canal seepage (canal in hydraulic connection with water table)
20	Aquifer return flow to tributary

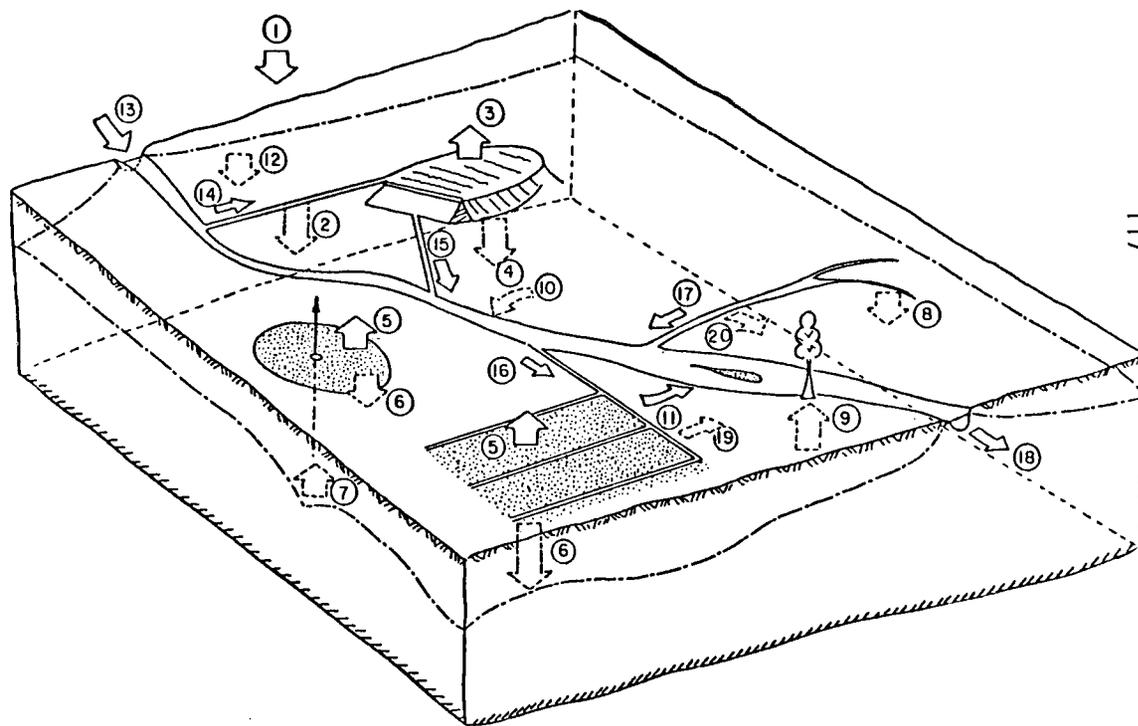


Figure 7-13. Structural Features and Operation of SAMSON.

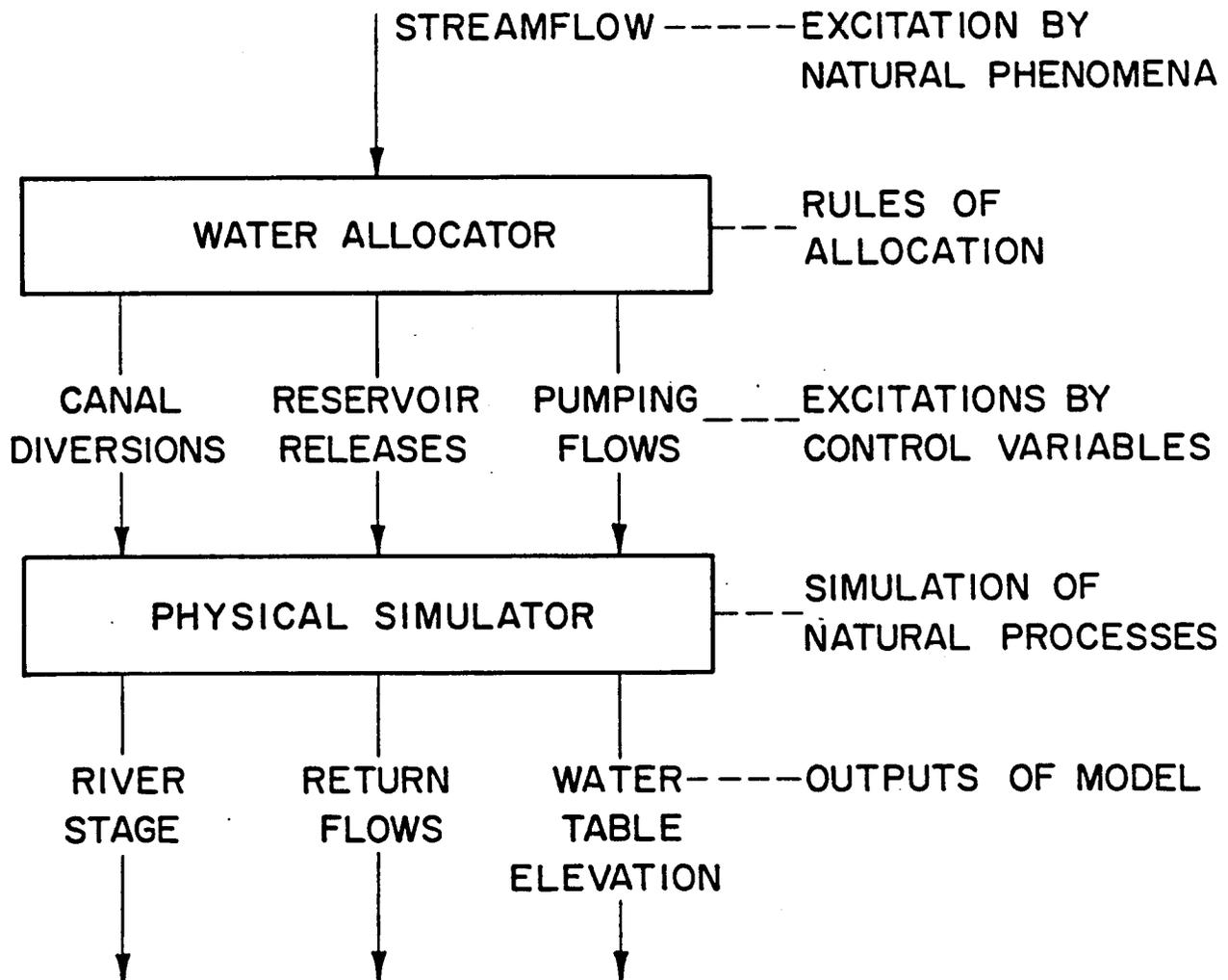


Figure 7-14. How SAMSON Works, a Conceptual Depiction

reach a particular component, such as a canal or an irrigated field, at a given day. The water reaching a given component is called an "excitation" (i.e. input) to it.

Once water reaches a component the "physical simulator" portion of the model simulates the flows by mathematical representation of natural phenomena (e.g., river flow velocities, daily evapotranspiration, seepage, groundwater flows, etc.). Most of these simulations (e.g. ground-water flows) require application of advanced mathematics, but the underlying themes are very simple and can be explained easily.

Other "excitations" of SAMSON include: pumping from the aquifer, diversions from the river, climatic conditions causing varying rates of evapotranspiration and precipitation. The water management rules, or the "water allocator," control some of these external excitations, and regulate the controllable variables, such as reservoir releases, diversions from the river, and pumping from wells.

The idea of modeling the water system of an entire river basin with enough detail on a daily basis is only just now becoming feasible. The SAMSON model is new technology. As noted above, SAMSON was developed initially for the South Platte system between Balzac and Julesburg. By request of the Colorado Legislature, SAMSON has been revised and extended to include the water system for a greater part of the South Platte River basin, from Henderson to Julesburg.

The results of operating the model and computing predicted flows at several gaging stations below Henderson and comparing these flows with the actual historic flows is indicated in Figures 7-15, 7-16, 7-17 and 7-18. Except for certain high flows, the model simulation compares

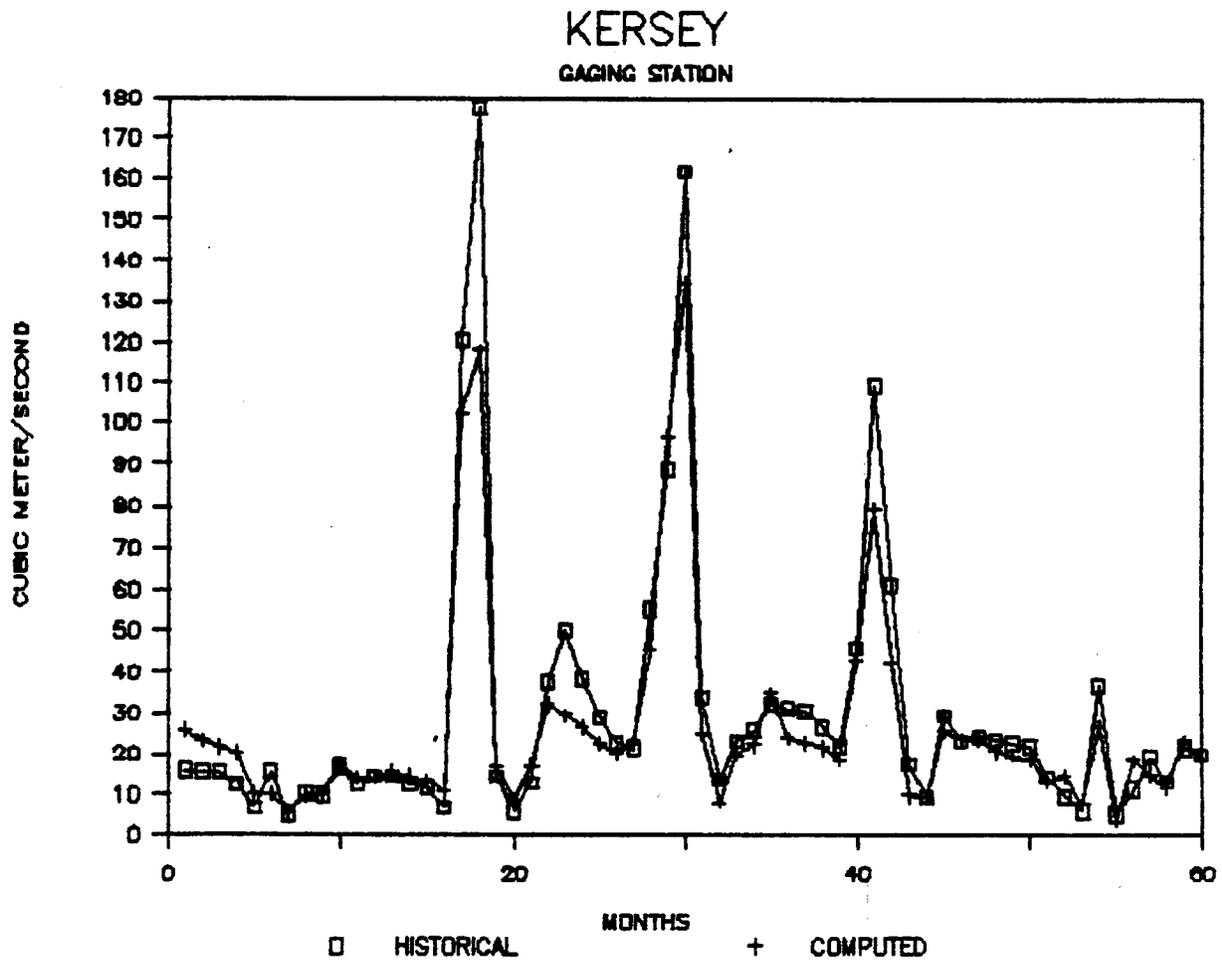


Figure 7-15. Comparison of Historical and Computed Monthly Values at Kersey

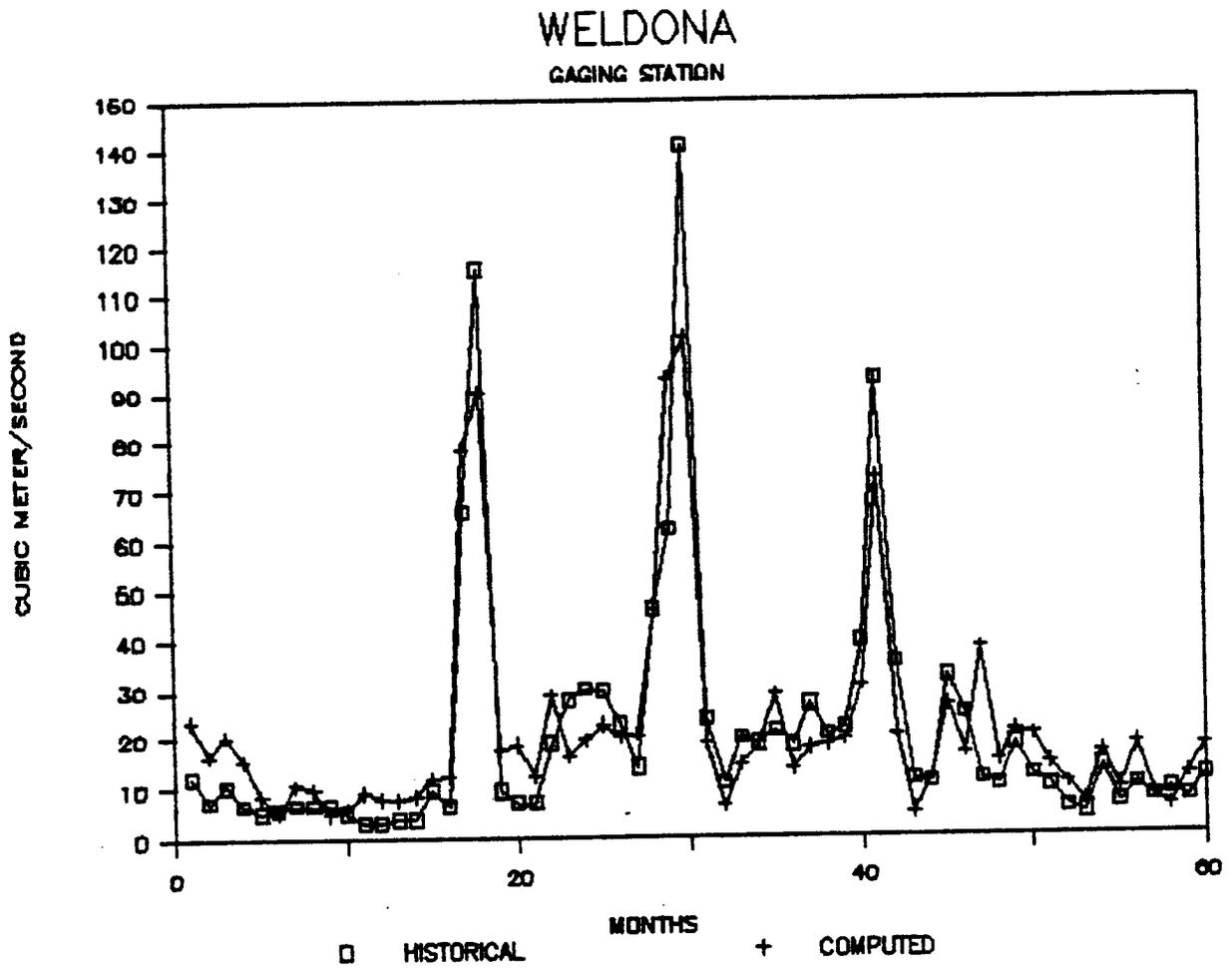


Figure 7-16. Comparison of Historical and Computed Monthly Values at Weldon

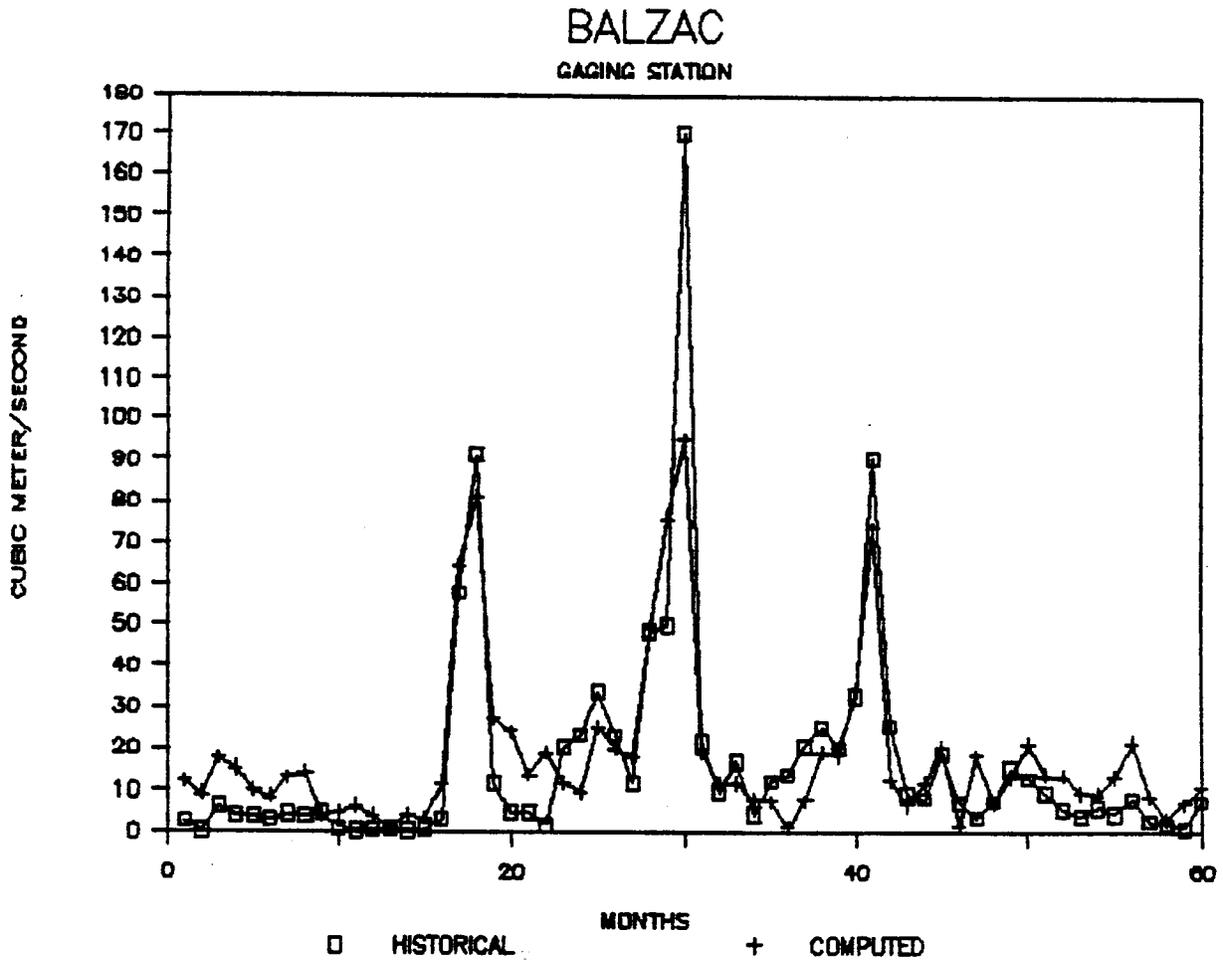


Figure 7-17. Comparison of Historical and Computed Monthly Values at Balzac

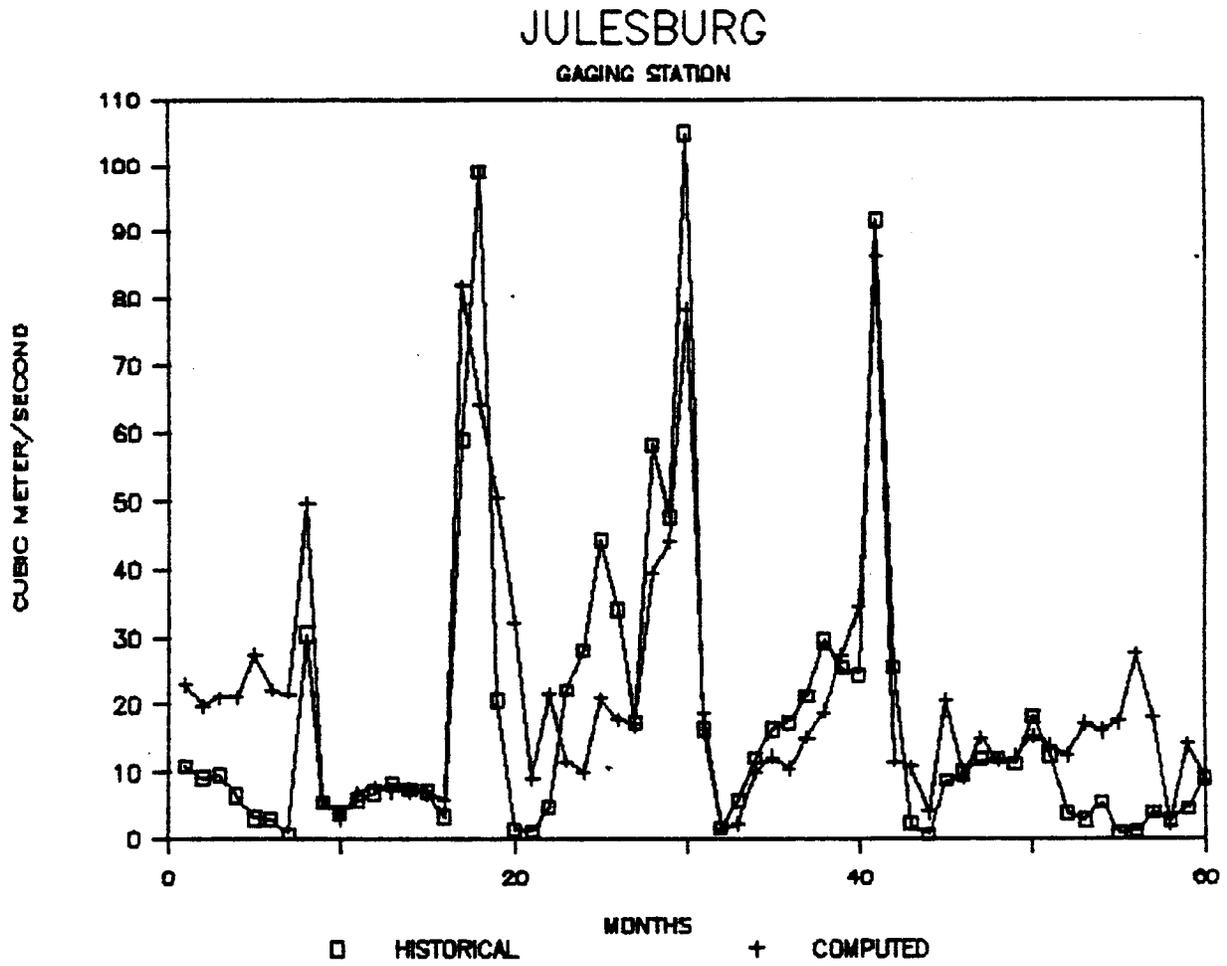


Figure 7-18. Comparison of Historical and Computed Monthly Values at Julesburg

quite favorably with the actual historic flows. Thus the initial calibration on the model can be said to be good.

7.4 Economic Modeling

Figure 7-3 illustrated two types of decision variables: hydrologic and economic. While hydrologic modeling is widely understood by Colorado water engineers, lawyers and managers, the contribution of economic modeling to decision information has been limited, mostly because decisionmaking has been based primarily on engineering and legal factors. Economic modeling needs to be applied more widely in order that the benefits of water decisionmaking can be understood by the individual water right owners.

Figure 7-3 also shows the general process of economic modeling. The models predict goal achievement as a result of controllable and non-controllable variables. Examples of non-controllable variables might be crop prices, rainfall and growing season length. Controllable variables could include water allocations and exchanges, crop decisions and agricultural policy shifts.

Economic models are like hydrologic models in the sense that they range from the simplest concepts and calculations all the way to elaborate computer-based simulation models. One category of economic model is the "input-output" scheme for demonstrating the interrelationships of economic outputs to the factors of production, one of which is water. Models of this type can be used to predict, for any defined area, the economic results of water exchanges or other decisions. Another type of economic model is the interdisciplinary management model which fits many decision problems.

Robert Young, a member of the team preparing this report, has investigated the applicability of economic modeling to the South Platte Basin (7). One study examined the use of an economic-hydrologic-legal approach to finding the best management policies for the river. In essence, the hydrologic component (and to a certain extent the legal component) could be represented by SAMSON or CONSIM. The remainder of the model represents the economic actions of the individuals and institutions involved.

Young has formulated a model specifically to analyze management policies in the Lower South Platte (8). He utilizes an economic objective function which maximizes net economic yield, the difference between annual gross value of crop sales and the sum of fixed and variable costs of crop production and public costs. This use of the model provides an analysis based on a regional public point of view. It would not necessarily represent the point of view of the individual farmer who will always act in his own best interest. But the farmer's viewpoint also can be represented by economic modeling. The model contains three components: the hydrologic, economic and legal submodels, and has the capacity to examine two levels, the farmer's viewpoint, and that of the institutions involved in regulating the river.

The hydrologic sub-model is like that of SAMSON. It simulates the response of the system to the controllable and non-controllable variables involved. The economic sub-model simulates farm decisions in the intermediate-run (season) such as planting choices and amount of irrigated land to farm, as well as short run decisions such as when and how much irrigation water to apply to crops. It computes the economic benefits and costs accruing to both surface and ground water users.

Both the intermediate-run and short-run models incorporate linear programming decision approaches. The legal sub-model, like in SAMSON, incorporates the queue of senior and junior water right owners.

The model has been operated to study a number of alternative policy proposals and water supply situations, and could be adapted to provide information to a cooperative association of water users.

A demand project model for urban water utilities in the basin was developed by Ellinghouse and McCoy under the supervision of team member J. Ernest Flack (8). This model included an assessment of current demand by municipal water users in the basin and then made projections of future demand based on population projections and various water conservation programs. The costs of implementing these conservation programs and the value of the water saved was compared over time with the costs of acquiring new water supplies, both from transfers and new storage, without conservation of any kind. A benefit-cost analysis demonstrated that water conservation is cost effective, based on the assumed future costs of new water supply (9). It was also demonstrated that a water utility practicing water conservation, as contrasted with one that did not, would need a considerably larger drought reserve water supply to get through a drought sequence of several years for the basin.

The operation of this, or similar, models can be particularly effective in assisting urban waters managers in deciding when and to what degree to adopt various water conservation methods. It also permits development of drought contingency plans for coping with unforeseen but certain-to-occur deficiencies in supply.

The monetary value of water rights exchanges, reuse schemes and similar management proposals are readily analyzed by economic analysis

and models. These can be formulated in such a way as to illustrate to the individual water rights owner--an individual farmer, a city, a water district or an association--the appropriately discounted value of the net benefits that will result from implementing various management options. Economic models, when coupled with hydrologic models within the institutional setting of the basin, can serve as powerful tools in helping select among the options that can lead to improved water utilization and economic returns.

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VIII. Conclusions and Implementation Plan

The principal conclusion in Chapter VII is still an assumption: that managing the water of the South Platte Basin for the benefit of water right owners and the public at large can be improved by utilizing computer-based models to provide information of potential improvement strategies. A related conclusion in Chapter VI is that a South Platte Federation of water right owners and associations of such owners could be organized and operated to provide voluntary, integrated water management for the basin utilizing inputs from the computer-based models. Underlying both of the major conclusions is the assumption that a substantial number of significant water management, exchange or transfer strategies could be identified which, if carried out, would be mutually beneficial or not adverse for the participants involved and would improve the efficiency of basin water use.

The preceding analyses of the hydrologic setting in Chapter II, the formal state and local water management institutions in Chapter III, the current water management practices in Chapter IV and the current management problems and issues in Chapter V provide background and context consistent with the major conclusions.

The South Platte Research Team that prepared this report believes that the major conclusions and their underlying assumptions are valid. But critical to implementation are the opinions of the basin's water right owners. Without a broad consensus among water right owners that a substantial number of possibly beneficial water exchange or transfer strategies exist within the basin and that computer-based technology is capable of demonstrating the feasibility of such changes, the report is to no avail.

Accordingly, a proposed plan for implementation of the report must start with one or more workshops attended by water right owners, or representatives of their associations. The workshop(s) would be aimed at identifying potentially beneficial exchange or transfer strategies, demonstrating in very practical terms the validity of the output of computer-based models, the evaluation of those strategies and showing how a South Platte Federation could approach basinwide management utilizing such computer-based information.

The upshot of such workshop(s), hopefully, would be basic acceptance of the need for and validity of the computer-based models and of the practicability of a South Platte Federation for voluntary, integrated basinwide water management. Acceptance, to be useful, must then lead to leadership arising from within the basin among water right owners and their associations: (a) to form a South Platte Federation; and (b) to find the financial support for the federation and the computer-based inputs. The South Platte Research Team is willing to assist to the extent practicable in both of these tasks.

Also, a plan would need to be developed and carried out to transfer the current CSU research modeling effort as applied to the South Platte (probably in stages), to a regularly-staffed operating unit and to train staff in its operation. SAMSON would be used to test all management or development proposals as well as to find and test feasible options by daily simulation. It will require a highly qualified and trained professional staff to perform and perfect its operation, including the supply of data inputs. Similarly, CONSIM would be used to provide preliminary planning studies and would also require capable professional staff.

Although implementation of the report's proposals would rest primarily upon the basin's water right owners and a professional staff, acceptance and assistance by others would also be essential. Participation by the Division Engineer as well as the Water Commissioners would be essential. More generally, acceptance and support by the Colorado Legislature, the Director, Department of Natural Resources, State Engineer, the Colorado Water Conservation Board and other state officials would be necessary. The legislative and executive branches, together ultimately with the judicial branch, must see the report's proposals as effective and efficient means of furthering basic state policy of maximizing the utility of Colorado's waters. The leadership arising in the basin, together with representatives of the university community, will need to be active in gaining this acceptance.

Specific changes in water laws and regulations, particularly with respect to effective conjunctive use of ground and surface waters, may prove useful in the future. The report suggests no such changes at this time, believing that changes, if desirable, arising out of specific planning and exchange or transfer proposals will be most likely to be accepted.

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APPENDIX B

5.5 General Problems and Issues

In addition to the general issues already discussed, there are a number of specific issues that need to be faced by the State and the water right owners. Some of them are policy issues and some are research questions. A partial list is given below both to flag particular management issues and to provide future topics for research. These are the issues:

- (a) Protection of individual water rights against damage from distant actions is a heavy burden of cost and vigilance for the individual or small organization. Groundwater pumping impacts are typical. How can these be better handled?
- (b) Policy alternatives for managing, developing and administering the total water supply should be identified, along with benefits, constraints and impacts of each alternative.
- (c) State Engineer's authority is limited in evaluating water right changes (and other actions) for basinwide impact. Technical solutions yield to "legal" solutions. Can this situation be improved?
- (d) A possible state role and state-of-art technology to protect individual water rights as a part of or alternative to the current litigation systems needs to be explored.
- (e) Water rights transfers may either help or damage basinwide efficiency. Is state surveillance needed?
- (f) Is a state managed "water market" an option that should be considered (rental market, sale market)?

- (g) Relationships of exchange schemes in Colorado River basin to water supply/management options for South Platte basin should be explored (e.g. Green Mountain exchange as alternative to Homestake II).
- (h) Augmentation plans are not decreed; hence not protected. They depend on annual approvals of the State Engineer. What move should be done to protect them?
- (i) The filing of conditional water right applications locks-up a place in priority and forecloses other alternative possibilities for development. Are greater limits on conditional decrees needed and desirable?
- (j) The urgency of water problems is mobilizing local-level managers to leadership in search for comprehensive planning, evaluation of options, and general initiatives in improving management. How can this movement be encouraged?
- (k) Sewage effluent treatment and disposal by land treatment creates recycling advantages but introduces water rights problems. How can these be better handled?
- (l) Can development projects be prioritized with respect to immediate action in order to satisfy political heat without risk of "wrong" decisions?
- (m) Joint management of supplies by urban water suppliers could solve some supply shortages and have other mutual advantages (e.g. Fort Collins and surrounding special service districts). How could it be accomplished?
- (n) Can agricultural water supply be augmented by conservation? What is the potential for use/management of water "saved," i.e., physical and legal availability?

- (o) What if all domestic withdrawal in South Platte were curtailed to 80, 130 or 180 gpcd by some means (meter, pricing, restriction, appeal)? What would be the impact on (1) municipal supply, (2) agriculture supply, (3) municipal investment, and (4) environmental quality?
- (p) The storage of water has two purposes: to store water otherwise lost downstream; and to enable better management of the basinwide supply. How can these purposes be coordinated for the benefit of water right owners?
- (q) The Central South Platte Conservancy District rents Aurora sewage effluent, yet may need only a fraction of the water for augmentation in a wet year. What would be a better solution for arrangements of this kind?
- (r) Recharge sites are now in operation at several places in the basin (e.g. Kiowa near Wiggins; Bijou near Hudson). Augmentation credit is given to return flow at the time it occurs. Determination of time and amount is a potential issue.
- (s) Instream flow objectives of fish/wildlife interests need to be addressed. An example is the interagency planning for lower South Platte and Platte Rivers. This includes "channel flushing," habitat preservation and recreation.
- (t) What are the benefits and costs of plains reservoir rehabilitation/betterment versus new main stem storage in the mountains? The feasibility may depend on impacts of existing groundwater recharge recycle systems and associated basin efficiency. New water management procedures would be needed (maybe new institutions), exchange plans would be affected.

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