MANAGING AN INTERRELATED STREAM-AQUIFER SYSTEM: ECONOMICS, INSTITUTIONS, HYDROLOGY

by

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FOREWORD

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ABSTRACT

In many river basins in the arid west, groundwater bodies ("aquifers") are interconnected with the river. Policies permitting unrestricted groundwater withdrawal for irrigation, common in early development stages, ignore the hydrologic and economic interdependence between users of surface flows and well owners. Large withdrawals lower the aquifer water table, indirectly reducing the stream flow that would satisfy the owners of property rights to surface flows. In economic jargon, this impact of groundwater users on surface right holders is called a "depletable external diseconomy," and causes a sub-optimal water management regime. Colorado several years ago adopted a unique non-structural solution to this type of interdependency problem between conjunctive ground and surface water users. The new management policy, termed the "augmentation plans" approach, was designed as a decentralized approach to correcting the depletable externality caused by groundwater withdrawals.

This report attempts to forecast the ground and surface water allocation and the corresponding net economic benefits to water users so as to evaluate three alternative policy approaches. One is an augmentation plan, the second is an unrestricted pumping policy, and the third is a system of pumping quotas, the extreme. Any change from the historical open access policy generates a gain to surface water right owners, a loss to those who must curtail their pumping, and an administrative cost. The goal is to determine the water resource policy that maximizes the net economic benefits.

A computer simulation model comprising of three sub-models incorporating the legal, hydrologic, and economic characteristics of the lower South Platte River Basin in Colorado evaluates the different water policies. In the legal sub-model,surface water allocations must comply with the prior appropriation doctrine. The hydrologic sub-model represents the physical interrelationships between a stream and aquifer. The economic sub-models represent the intermediate and short-run farm decision making process. An intermediate-run model uses an expected income-variance model to determine the planted acreage of each crop. The short-run model allocates available surface and groundwater between crops according to a profit maximizing motive. The simulation combines all sub-models to predict the net income for each alternative conjunctive water use policy.

Comparing the simulation results of a policy that completely prohibits pumping with a policy of non-regulation indicates that groundwater withdrawals are responsible for much of the area net income. Unrestricted groundwater use increases the predicted short run net income from $33.1 million from the only $11.3 million for a surface water only regime. However, during a year where river flows are below average, pumping causes a significant depletable externality. Pumping, by reducing surface flows, causes the income of farmers that use only surface water rights to decrease by 39 percent.

The most efficient simulated conjunctive use water policy are augmentation plans that generate the largest area net benefits, $36.4 million, and eliminate any losses to senior surface users. The solution recognizes the prior rights of senior surface users while permitting farmers to withdraw groundwater but at an appropriate price. For this solution to be effective, however, there must be (a) adequate upstream reservoir storage and (b) a market system for water such that groundwater users can purchase or rent water rights for augmentation purposes. Both conditions exist in the study area.

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CHAPTER 1

INTRODUCTION

Farmers in many river basins of the semi-arid Western United States divert surface stream flows or pump from groundwater systems (aquifers) to satisfy crop water needs. Irrigation enables farmers to produce a much higher output of crops and substantially increases farm income. However, in river basins with a tributary aquifer (an aquifer that is directly connected to a river) a detrimental interdependency may exist between ground and surface water irrigators. Unrestricted, large scale pumping eventually diverts surface flow from the stream into the aquifer, thereby reducing water supplies that would satisfy downstream surface water irrigator's crop requirements. This economic spillover, causing the social pumping cost to exceed individual pumping costs, may lessen surface irrigator's farm income. An efficient management strategy must account for the physical and economic interdependencies associated with conjunctive water use.

This report analyzes a recent innovation that uses a market approach, rather than the conventional regulatory methods, to solve the spillover problems in an interrelated ground and surface water system. The water allocation system, termed a "plan of augmentation," emerged in Colorado as an alternative following numerous court battles between groundwater users and surface water irrigators. This non-structural water policy allows groundwater users to pump throughout the growing season only if they can augment surface water supplies. The groundwater users association rents or purchases supplemental surface water, usually from reservoir storage. State water managers use the supplemented surface water to supply surface water right owners who would otherwise be injured by extensive groundwater withdrawals.

Objectives

This study reports the assumptions, procedures, and results of our interdisciplinary analysis of the economic and hydrologic impact of alternative water management policies on conjunctive water use allocations and the related externality problem. The model analyzes the problem in the lower South Platte River Basin in northeastern Colorado,but the general methodology is applicable to any interrelated stream-aquifer system with excess groundwater demand. We compare the study area's net farm income under each of several policies: (a) a complete prohibition of groundwater use, (b) an open access groundwater institutional structure, and (c) with Colorado's recently adopted conjunctive use regulation procedure, "the plan of augmentation." We define the optimal water policy as one that maximizes net direct economic benefit to water users, given any surface water supply condition.

Procedures

A digital computer model was developed, which compares the alternative water institutions. The simulation is comprised of: (1) a hydrologic model that predicts the temporal and spatial relationships between pumping and stream flows; (2) an economic model that captures the groundwater externalities, and includes the intermediate and short-run response of irrigators to alternative water supplies and costs; and (3) an institutional structure specifying the legal conditions of ground and surface water use in Colorado. Since we studied a small part of the South Platte River Basin and simulated just a few of many potential water policies, the results can only approximate a true optimum.

The Hydrologic Model. The hydrologic subsystem models the physical interaction between a river and an alluvial aquifer. Excessive pumping creates a cone of depression, which lowers the aquifer water table near the well, altering the natural stream-aquifer balance. This depression intercepts underground water flows moving toward the river. If the aquifer water table declines far enough, water will even move from the river into the aquifer. The water flow direction and volume moving between the river and aquifer varies with the location and timing of the withdrawals. The nearer a well is to the river the larger and more immediate are its effects on stream flow. In the hydrologic model, the stream flow is a function of pumping rates, pumping locations, surface diversions, and surface flows into the study area.

The Legal Subsystem. Colorado's constitution provides the broad pattern of property rights in water. The basic framework, the doctrine of prior appropriation, is a queuing system where the date on the irrigator's application of diversion establishes his relative right to divert water flows. The common phrase, "first in time—first in right," means the earlier the water appropriation date, the better the irrigator's position for water diversion, provided he can beneficially—which includes most uses—apply his water right. The earliest water rights, known as senior surface water rights, have appropriation dates between 1880 and 1890. These early rights insure that the irrigator has sufficient irrigation supplies even in extremely dry conditions. Junior surface water right owners having appropriation dates between 1890-1910, divert water only if runoff is above average. Even then, most divert return flows from upstream senior right owner's irrigation and not virgin stream runoff. Well owners have the latest water appropriation dates, after 1930, giving them junior and legally insecure water rights.

The actual water management regime may not conform to legal specifications.Well owners have had an implicit first right to water supplies. For many years, imperfect knowledge about underground water movement and the small scale of pumping activities resulted in a common property groundwater management policy. This practice produced overdevelopment in wells, excessive withdrawals, and significant impacts on surface flows.The legal model has the flexibility to represent the situation that existed prior to 1930 when groundwater was insignificant, an open access policy, and the current plan of augmentation procedure.

The Economic Representation. The economic model predicts the response of irrigators as they face crop prices and surface water supplies, and captures the external diseconomy (negative spillover) imposed by groundwater withdrawals on senior surface water users. Each spring, each irrigator must make difficult choices about his summer crop mixture. The model assumes this choice depends primarily on expected profits, conditioned be the individual farmer's preference toward risk and his subjective judgments about the future summer water supplies. The intermediate-run economic subsystem represents this decision making process. After planting, the irrigator must decide at each of several points in time how much water should be applied to each of the crops he planted. The short-run economic subsystem models these latter choices.

The interdependence between ground and surface water users is, in the terminology of Baumol and Oates (1975), a "depletable externality." According to Baumol and Oates an externality exists whenever an individual's utility or production relationships include real variables whose amounts are chosen by others without attention to the effects on the first individual's welfare. The ground-surface water externality is "depletable" since the increase in use of the external product, fewer surface flows, by one farmer reduces the amount remaining for other surface right owners.

Most depletable externalities have characteristics that make them what economists have termed "common property" resources. Private firms using common property resources will eliminate or internalize the externality as long as the potential return exceeds the cost of elimination or internalization. Why then didn't irrigators themselves correct the ground-surface water problems? The answer is that the fugitive nature of groundwater resources implies high transaction costs for establishing conventional property rights systems. Failure to correctly assign property rights to groundwater resources hindered any normal market exclusion of private pricing systems.

Background: The Physical Setting

The South Platte River originates on the eastern slope of the Rocky Mountains in central Colorado. It flows northeasterly through Denver and northeastern Colorado toward its meeting with the North Platte in western Nebraska. The 90-mile reach of the South Platte River in northwestern Colorado from the Balzac gaging station near the town of Balzacto, the Colorado border with Nebraska, is the study area. Four small intermittent flowing creeks, Pawnee, Cedar, Moore's, and Lodge Pole provide additional surface water to the South Platte River. Under this reach of the South Platte is valley-fill alluvium and dune sand aquifer, which lies under the South Platte River. The average aquifer width is about six miles, but it varies between ten miles and two miles. This unconfined aquifer has a generally impermeable base of clay, silt stone, shale, and sandstone. The average depth to water-bearing formations is between 30 and 40 feet (see Hurr, et al., 1975, p. 9, for further details).

Farmers use surface irrigation procedures extensively throughout the river valley. However, surface water sources and precipitation together do not provide a dependably adequate irrigation supply, making supplemental groundwater an economical choice. Conklin (1974) reported that 78 out of 89 farms he surveyed used well water as an additional source, but only eight used the aquifer as the only water source. Even though the annual surface water supply is about equal to the irrigation requirements, the distribution of the water supply does not correspond to the monthly crop needs. The average flow of the South Platte River at Balzac is the lowest during the high irrigation demand periods in July and August. The annual rainfall is between 12 to 18 inches but also varies greatly between years and during the growing season. Table 1 shows the annual precipitation and Table 2 shows the rainfall in the irrigation season.

The two most common soil associations found in the study area are heavier alluvial loams and the sandy soils. Occupying the bottom lands, the loams are flooded frequently, and causing drainage to be slow forcing the water table to rise . At the valley edges are the sandy soils, which provide excellent seed beds but require more irrigation applications than loamy soils and are subject to wind and water erosion without the proper preventive care.

Table 1 Annual Precipitation at Three Weather Stations in the Study Area.

	Average Precipitation				Range 1961-1975			
	1931-1960		1961-1975		Wettest		Driest	
	inches	cm	inches	cm	inches	cm	inches	cm
Sterling	14.10	35.81	15.40	39.12	20.56	52.22	7.59	19.28
Sedgwick	n.a.	n.a.	18.24	46.33	22.52	57.20	10.24	26.01
Julesburg	16.32	41.45	17.16	43.59	25.25	61.14	12.65	32.13

Source: Environmental Data Services, U.S. Department of Commerce, Climatological Data.

Table 2 Growing Season Precipitation.

	1971		1972		1973		1974		1975	
	inches	cm	inches	cm	inches	cm	inches	cm	inches	cm
Sterling	9.08	23.06	11.14	28.30	11.09	28.17	5.46	13.87	9.76	24.79
Sedgwick	13.03	33.10	12.42	31.55	12.83	32.59	7.60	19.30	11.99	30.23
Julesburg	10.46	26.57	10.82	27.48	11.15	28.32	5.74	14.58	12.02	30.53

The most common irrigated crops are corn, alfalfa, sugar beets, pinto beans, and other small grains. Table 3 shows the changing cropping patterns over a 22-year period. Conklin found that farmers planted 60 percent of their land in corn with about two-thirds harvested as grain and one-third as silage. The remaining crops and the planted percentage were: alfalfa—20 percent, sugar beets—8 percent, pinto beans—7 percent and small grains—5 percent.

Historical Development of Agriculture in the Study Area

Irrigation was as important to the early farmers as it is today. To survive, settlers accustomed to the wet summers of the eastern U.S. had to learn unfamiliar irrigation practices. They had to construct river and farm headgates, closely watch the soil and crop moisture so they would know when to irrigate and how much to apply, and determine what crops benefitted the most from irrigation and what crops they could ignore when water was scarce. Advertisements to attract settlers to Colorado pictured these irrigation methods as easy to learn and that the "certain" supply of irrigation water was vastly superior to relying on nature's rainstorms (Abbott, 1976; p. 44).

Table 3 Crop Acreage Distribution (Morgan-Logan-Sedgwick Counties).

Percent of Cropland				
	1952	1962	1972	1974
Corn	25			
Grain		22	32	44
Silage		11	18	16
Alfalfa	28	31	25	21
Sugar Beets	16	20	12	10
Pinto Beans	8	7	8	6
Other Small Grains	23	9	5	3
	100	100	100	100

Source: Colorado Agriculture Statistics, 1974-75, Bul. 1-76.

In the 1860's, private companies began building irrigation canals to provide water to farmers not bordering the river banks. Before long, the application of the riparian rights doctrine created problems. (The riparian doctrine was brought as common law from the East and provided that where the right to the water belongs to the adjacent landowner as long as the stream flow remains unaltered.) Colorado soon changed from the riparian system, since the objective of the canals, diversion of water away from the stream, violates the very basis of that doctrine. They established the system of prior appropriation where the earliest dated claim on the water has the first right to beneficial water use. This system over the years has been helpful in avoiding many potential disputes.

The South Platte canal, built in 1872, has the earliest and one of the largest water rights in the study area. The ditch's senior right provides water through the summer to its member farmers. Three other senior, although relatively small ditches, were also built in the 1870's. Located in Logan County; the Sterling, the Buffalo (now the Pawnee), and the Schneider remained unimportant diversion points until the Union Pacific Railroad constructed a trunk line into the area in 1881-82 providing an outlet for agricultural products. By the 1870's, the ditch companies had fully appropriated the stream flow. Many junior rights already were diverting the return flow from upstream irrigation.

Farmers recognized the need to supplement surface water supplies soon after the construction of the irrigation canals. Smiley (1913) reports that E. F. Hurdle completed the first irrigation well in 1889 in the Lone Tree Creek bottom near Eaton, Colorado. But, groundwater as a source of additional irrigation water was slow to develop. In 1909, there were 79 irrigation wells in the whole South Platte Valley and only 334 in 1929 (Hafen, 1948). Costly and unreliable steam tractor engines drove these early pumps. The 1930's brought a major drought and the demand for groundwater dramatically increased. During that decade, gasoline, slow-speed oil-burning engines, and electric motors replaced steam as the power source. The high cost and uncertainty of energy supplies still limited any widespread use. In the 1950's, a major change occurred; the growth and speed of cooperative electrical associations substantially lowered electricity costs. For the first time, farmers had access to a cheap and stable energy source. Pump and well-drilling technology greatly improved. Lower energy costs, another drought, and the absence of any prohibitive regulations were the incentives behind large farm investments in supplemental groundwater observed since 1950.

The Condition in the 1970's

About half of irrigated production in the South Platte Basin relies on groundwater. Almost all irrigators, both those who own junior surface water rights and many senior right owners, use supplemental groundwater in the crucial growing months of July and August. The Colorado State Engineer's water use tabulation in 1975 reported about 750 wells yielding at least 100 gal/min with the majority yielding over 1,000 gal/min in the study area.

Well use in the 1970's had progressed to the point where it affects other water users. Well owners were beginning to notice declines in the water table in their wells resulting in lower well yields. Surface water right owners came to recognize the groundwater withdrawals intercept return flows to the river that should have satisfy their own rights. The burden of these external costs falls primarily on farmers with surface rights as their only irrigation water source. Many have inadequate surface water supplies except in years when stream flows are above average. These same users have prior appropriative rights that would be senior to groundwater use if the doctrine were applied equally to all water sources.

Up until the late 1960's, the lack of any actual groundwater regulations permitted farmers to develop the subsurface reservoir with almost complete disregard to surface interrelationships. Only recently has Colorado made attempts to bring current scientific understanding of stream-aquifer hydrology to bear to create a rational basis for development and use of groundwater.

Plan of the Report

The order of presentation is as follows: Chapter 2 reviews the economic theory of efficiency as it generally applies to resource allocations and specifically as it relates to groundwater use. Chapter 3 specifies the evolution and current status of the legal and institutional constraints on groundwater use in Colorado. Chapter 4 develops an economic model that reflects both short and long-run farm operating decisions. This step involves formulating a planning model, which incorporates uncertainty in the decision on which crops to plant. The short-run model in turn allocates the available water supplies to the crops, given the effect of water on the respective plant growth, in a way maximizes net returns. In Chapter 5, we combine all the economic, legal, and hydrologic factors into one simplified but representative computer simulation model. Chapter 6 presents the simulation results from each different water management policy, and Chapter 7 summarizes the major points and makes recommendations for further research.

CHAPTER 2

ECONOMIC CONCEPTS FOR OPTIMAL ALLOCATIONS IN CONJUNCTIVE GROUND AND SURFACE WATER SYSTEMS

This chapter discusses the questions of the optimal allocation of ground and surface water supplies and reviews previous research on the topic. Optimality is interpreted in terms of economic efficiency. An economically efficient conjunctive water policy allocates water supplies so that the study area's welfare—measured as net producer income is maximized.

Economic Optimization

Economic welfare maximization has long been a major objective employed in the water resource planning literature (Marglin, 1962, p. 17-86). Federal government water planning also recognizes economic welfare theory. National guidelines for project approval require analysis of national economic development (economic efficiency), in addition to environmental quality, income distribution, and regional development as measures of society's welfare.

An economically efficient allocation must satisfy the condition known as Pareto optimality. Water allocations are optimal or efficient if no reallocations exist that would make any individual or firm better off without making others worse off. Conversely, an allocation is inefficient if someone can be made better off by changing consumption and production patterns without harming others.

The perfectly competitive market system without market failures automatically satisfies the conditions necessary for economic efficiency. The interaction between supply and demand for a homogenous commodity establishes a market price. Rationality, meaning if the consumer prefers good A to B and good B to C, then A is preferred to C, is assumed to be the normal behavior. Given the prices of goods and a budget constraint, the individual will adjust his consumption patterns to maximize satisfaction. Similarly, producers operate within their budget to maximize profits. All members of this system must have complete information and perfect knowledge about the choices open to them.

Economic Efficiency As a Social Objective for Evaluating Alternative Institutional Changes. Economic efficiency, with its ability to maximize the benefits to an economic system, is a desirable goal, but it is not the only major criterion nor is it more or less value-laden than other objectives. Also, situations where the strict definition of Pareto optimality holds are especially infrequent. Very few water policy changes can make someone better off without making others worse off. Most projects benefit some users while causing others to lose. As Ciriacy-Wantrup (1965) and others have shown, even if there are projects that meet the efficiency requirements, this criterion may be insufficient for decision making since it lacks any method for choosing between more than one such policy and the status quo.

The concept of "compensating side payments" expands the traditional definition of Pareto optimality to cover situations where there are both gainers and losers. Compensation must be an amount sufficient to persuade the losers into accepting the change and still leave those who gain better off than they were without the project. A policy is efficient if it is impossible for the gainers to bribe the losers to accept the reallocations or for the losers to bribe the gainers to reject the change (J. de V. Graaff, 1971). Even though the Pareto criterion with compensation is not conceptually identical with welfare increases, it is a close approximation, providing the projects do not appreciably increase the inequality of the present income distribution. The compensation principle makes it possible to compare water reallocations where some users benefit while others lose.

Efficiency, even extended by the compensation principle, rests upon two basic assumptions that may make it a less than optimal single objective to use in evaluating alternative projects. Efficiency assumes that each additional dollar of income a project produces is equal in social value regardless of who receives it. In other words, the marginal utility of income of all individuals the project affects is equal. For this assumption to be correct an extra dollar of income must be equally desirable, for example, to a corporation president or to a migrant worker. Ranking projects only in terms of efficiency creates problems because there can be numerous alternatives all satisfying the Pareto optimality conditions while ignoring the effect they have on income distribution with the best project depending upon the equity preferences of society.

The second major assumption of economic efficiency is its reliance on individual preferences determined through market prices. Many analysts feel that responses made in the market reflect largely the individual's own self-interest, which may not correspond to community goals. Maass (1965) argues that if the federal government is to serve the total community, some criterion other than efficiency is needed to represent a measure of the community oriented goals. It is necessary, he believes, to determine all the needs of a community and to insure those socially desired goals are incorporated into the design of the project.

While recognizing the limitations implied by these assumptions, we feel they are not of overwhelming concern in the present case. Money income is a primary concern of agricultural producers, and wide divergences in income are not thought to be characteristic of the study area. Money income is a primary concern of agricultural producers, and wide divergences in income are not thought to be characteristic of the study area. Hence, maximization of net producer income is employed as our criterion for optimality.

Departures from the Competitive Norm. When examining real world resource allocations, several situations occur that violate the assumptions of the perfectly competitive model. The model assumes consumers and producers have complete and perfect information concerning prices. Participants then use those prices in their decision making process switching resources from one activity to another to attain the highest satisfaction or production possible. Independence, where individual decisions don't affect others, must exist between all participants (Eckstein, 1958). Failure to satisfy any of these assumptions can render the perfectly competitive equilibrium inefficient. Market prices generating the marginal conditions need for an efficient allocation of resources fail to value resources correctly. The departures, known as market failures, may justify governmental interference into the market in an attempt to move the economy toward an efficient resource allocation. While all market failures are important, conjunctive water use usually generates spillover or externality problems.

Externalities. Externalities arise from uncompensated impacts imposed upon individuals and firms as a result of consumptive or production choices made by others. In production, externalities cause the firm's private cost to differ from the social cost of producing the commodity. For example, if a firm during its production pollutes a nearby river, then the private marginal cost equal to the resource cost necessary to produce the good is less than the social marginal cost that includes the cost of resources and the additional cost of cleaning the river for downstream use. This external effect has a negative impact on society. The private marginal cost (PMC) is less than the social marginal cost (SMC) resulting in the over use or over production of the commodity. From society's point of view the firm's production is too large.

Most definitions include some statement that externalities are conditions required for non-optimal resource allocation. Baumol and Oates assert while this definition is operational, they would be happier if the violation of the marginal conditions could be deduced from the definition rather than having the violations define the externality. A Baumol and Oates externality exists whenever the utility or production of an individual includes nonmonetary variables whose values are determined by others without regards to effects on the individual's welfare (Baumol and Oates, p. 18). This definition is notable for its lack of an additional condition that compensation be paid to the affected party. Not requiring compensation has the advantage that "instead of postulating in advance the pricing arrangement that yield efficiency and Pareto optimality, we can deduce from it what prices and taxes are compatible with these goals and which are not" (p. 46). In addition, compensation is not always a complete solution. When a political agent levies an optimal tax on a polluting production activity, the firm will lower its emissions but not necessarily to zero. Compensation reduces the externality to an appropriate level but hasn't eliminated it altogether.

Baumol-Oates subclassify a production or consumption action that satisfies their externality definition into depletable or undepletable categories. An undepletable externality has the non-rival characteristic of a public good. Consumption by one individual doesn't affect the availability of that good for consumption by others. One person's breathing of air pollution doesn't reduce its availability to others.

Groundwater that diminishes surface river flows accessible to other irrigators is an example of a Baumol-Oates depletable externality. Any increase in surface water use by one farmer reduces the external product, reduced stream flows, available for all other irrigators. Water institutions incorrectly assigning property rights and preventing normal market exclusion operate where marginal private costs equals marginal private benefit causing conjunctive use externalities. Once the government corrects the property institutions, the market system can establish appropriate price structures.

The open access management of groundwater can be the source of inappropriate prices and inefficient conjunctive water use allocations. Groundwater management under the open access institution, implicitly giving pumpers rights over the surface users, do not reflect the social cost in terms of reduced stream flows. Regulations that redefine the relative property rights of ground and surface water users create conditions where a market could correctly set prices (i.e., where marginal social costs equal marginal private cost). However, physical situations exist where the continuation of the externality is efficient. The externality may be so insignificant relative to the transactions costs of enforcing an appropriate price that the social costs of eliminating the externality exceeds the potential gains.

Institutional Analysis

Wherever externalities occur, the potential for conflict between the possible winners and losers is present. Complex sets of rules and laws usually referred to as institutions develop to cope with the conflicts. The market system is only one example of an institution resolving resource allocation conflicts.

Institutions are especially important in the allocation of water resources where there are few markets, few price guidelines, and many externalities. Presently, production economists can predict the effect of additional water on crop yields and subsequently on farm income but little is said about the effect of alternative water institutions. Do alternative institutions make a difference on output or income?

According to Ciriacy-Wantrup (1967a), institutional analysis is important when evaluating water resource allocations.

> Water policy is less concerned with markets and prices and more with the laws, regulations, and administrative structures under which self-supporting individual firms and nonprofit organizations make decisions. This situation poses a challenge to scientific inquiry that must be faced squarely: institutional influences are so diverse, so pervasive, so widely distributed over time, so difficult to isolate and quantify, so resistant to controlled experiment, and so closely related to the social conditioning of the political preferences and the emotions of the investigator that the temptation is great to remain on the descriptive level instead of proceeding toward analysis.
>
> Over many years, the descriptive approach to water institutions has yielded much valuable material, contributed largely by non-economists. This material is now available to the social sciences for analysis focusing on the structure, the functioning, and the performance of water institutions. Water policy as a field of scientific inquiry is analytically oriented institutional economics. In such an economics, theoretical constructs and their testing are no less needed than in the economics of the market place.

The term "institution" has a wide variety of meanings. John R. Commons defined institutions as "collective action in restraint, liberation, and expansion of individual action." Ciriacy-Wantrup (1967b) defined it as ". . . a social decision system that provides decision rules for adjusting and accommodating. . . conflicting demands. . . from different interest groups in a society. An alternative view by Schmid (1972) defines institutions as ". . . ordered relationships among people, which define their rights, exposures to the rights of others, privileges, and responsibilities. All of these definitions imply that institutions structure the incentives and opportunities open to individuals by conveying the right to benefit or not from certain actions. These definitions are general and all inclusive but they are inadequate when looking at a specific resource like water. Exactly how do and what institutions effect the problem of conjunctive water use? To help with this problem, Ciriacy-Wantrup (1967b) proposed four levels of institutions. The first level is the constitutional level, which defines the broad basis for all social actions. The next level, policy level, specifies the constitutional guidelines in the form of explicit goals. Examples are the full employment act or the 1972 Clean Water Act. At the third level, organizational level, specific agencies carry out the goals. The final level, operational level, is the level where the specific rules of the organizational level impact private individuals.

At the constitutional level the major institution concerned with water resources is property rights. These rights define the possible actions of man regarding water use. Three types of property institutions, private, state, and common have developed to internalize the externality problem connected with water use. A private property right permits an individual to own and control a resource. The state prevents any interference of his control, provided his actions are not prohibited by the rules of the right. A rational owner maximizes the present value of the resource by comparing present and future benefits and costs from alternative uses. Owners may exchange private rights, and if the exchanges occur in a perfectly competitive market system, then resulting resource allocations are efficient.

The government may control the resource declaring the resource to be public property rights. Powers to exclude or allow individuals to use the resource rest with the state. Political procedures establishing the management of the resource determine the resulting allocation.

Common rights are the third type of property rights. These rights allow anyone to use the resource without hindrance or charge. For example, individuals commonly do not own the rights to use a city sidewalk. Common property rights may efficiently allocate resources when the cost of excluding individuals exceed the potential gain from such actions. These rights are usually connected to abundant or renewable resources where the demand for the resource is still small.

There are two problems when allocating a resource using common property rights. The resource owner in pursuing his own self-interest uses the resource as long as the extra benefit exceeds the extra cost from an additional unit. In the "Tragedy of the Commons," Hardin (1973) illustrated the problem when no property rights govern resource allocation. The extra gain accrues totally to the individual; the extra cost is spread over all the users. The potential gain will always be greater than the loss creating the incentive for the individual to increase his use without limit on a resource usually limited in supply. A second problem occurs when the demand on the resource eventually exceeds the supply. Each additional use will diminish the total amount available to all users causing the costs to rise rapidly. Continued unrestricted use in this situation generates destructive competition where the greater the individual effort to capture and use the resource the worse off society becomes.

The state can change these property institutions in an attempt to return to an efficient allocation. These institutional changes in turn affect the economic structure and performance, creating new external effects. The dynamic forces of technology altering the production process also generates new externalities complicating the problems from institutional change. In the presence of changing externalities and institutions, the problem becomes to compare alternative institutional arrangements and choose that particular institution that results in the best resource allocation.

Actual institutional analysis in this report is at the operational level. We simulate farmer reaction to the new groundwater augmentation rules proposed by the State Engineer. The performance criterion is economic efficiency. Comparing augmentation plans with the previous open access water policy, the institution maximizing the area net farm income will be identified as the best policy.

Groundwater Management

The optimal mining rate from a groundwater reservoir depends on the physical conditions, the existing institutions, distribution of rights, and the revenues and costs from development. For example, if the extraction rate is small in relation to the amount in storage, external costs representing declining water tables are minimal. At the same time, regulation to eliminate the externality that involves accurate measurement and continuous observation of the aquifer is expensive. These conditions usually prohibit any change in the governing water institution since the benefits from new regulations are less than the costs.

This situation was typical in Colorado in the 1930's and 1940's. Farmers were only beginning to develop the groundwater resources. An open access management policy regulated groundwater use. Groundwater rights were considered common property. The supply was available to any overlying land owner without hindrance or charge.

This allocation system combined with the "fugitive" nature of groundwater created the potential for an inefficient use of the aquifer (Hirshleifer, et al., 1960). Individuals recognize if they don't immediately capture the water for their own use then their neighbors will, thus eliminating part of the aquifer's supply for later use. As each individual increases his extraction rate to capture water supplies, uncertainty about the future life of the aquifer increases. Users concentrate withdrawals in the present ignoring any possible future benefits from deferred use (Ciriacy-Wantrup, 1963).

River basins characterized by arid or semi-arid climates intensify the problems of efficient groundwater use. In these areas, groundwater pumping intercepts water flows from the aquifer to the stream causing additional uncompensated external effects on surface water users (Young and Bredehoeft, 1972). Under the open access unrestricted institution, each individual groundwater user fails to consider the external costs his pumping imposes on other ground and surface water users. Water institutions must remedy these inherent interdependencies of groundwater use before private use can attain economic efficiency.

Hirshleifer, et al. (1960) proposed three alternative institutions to correct the problems of an open access resource. The first method is centralized control of water supplies. A monopoly or governmental agency trying to maximize social profit considers all benefits and costs from pumping, eliminating the discrepancy between private and social costs. The tendency of public policy to discourage large monopolistic organizations prevents basin monopolies from frequently appearing in reality.

A second solution is to introduce a use tax on groundwater withdrawals. A profit-maximizing irrigator pumps groundwater up to the quantity where the marginal cost, cost plus tax, equals the marginal return from irrigation. Applying a use tax equal to the loss imposed on other users theoretically produces a socially efficient allocation since pumpers will consider the marginal cost to society in addition to their own private pumping cost.

Assigning quotas, the third solution, is the method water planners generally use to regulate groundwater resources. Quotas eliminate open access allocation problems by replacing the commonality of rights with specific shares. The end result is similar to the use tax but it does not generate any revenues for compensation payment to those who suffer losses.

Using quotas does not insure an efficient or equitable allocation of groundwater. The goal of simply dividing up the supplies and protecting vested interests may not produce efficiency. An historical basis to determining quotas encourages an initial over-use of the resource in order for the individual to justify a large quota right. The major advantage of a quota system is its simplicity.

Whatever system is chosen, all must determine what is the correct quantity of water withdrawn over time. The question is complex since the optimum extraction rate varies with present and future costs and prices of the water resource, final goods produced using water, interest and pumping technology. First attempts to determine the optimum rate adopted the concept of safe-yield. The safe-yield rate is that rate at which the average amount pumped equals the average rate of recharge. This rate tries to maintain water levels in the aquifer at a steady level. The safe-yield concept supposedly eliminates undesired effects on water quality, water rights of others, and on the level required to insure economically feasible pumping.

In most situations, the safe-yield mining rate fails to maximize economic welfare. Mining oil at the safe-yield rate means that no oil can be extracted since the recharge rate is zero. Clearly where groundwater has accumulated into immense reserves, but the natural recharge rate is small, the economic optimum use rate will be different from the safe-yield rate. Where gainers from extracting above the safe-yield rate could compensate the losers and still increase profit, welfare also increases. The safe-yield management policy minimizes the external cost of extraction regardless of the size of the potential benefits possible from withdrawals above the safe-yield limit (Young, 1970).

A second problem using the safe-yield as an optimum mining rate is that it discounts future values of groundwater at a zero interest rate. Withdrawing groundwater at a rate equal to the recharge rate, maximizes the long-run physical yield of the aquifer resulting in future uses becoming equal in value to current uses. Interest rates allocate goods between current and future uses by discounting future income and costs to present values. Economists propose many interest rates for public policy but no support can be found for a zero interest and discount rate for relatively abundant renewable resources like water.

In a series of articles, Oscar Burt (1964a, 1964b), used dynamic programming to determine an optimum temporal allocation of groundwater. Burt compares the need for current mining with 1) diminishing returns to water users (in any period caused by rising pumping costs as groundwater stocks are depleted); and 2) the value of stock reserves as a guard against uncertainty, to formulate an optimal extraction rate. Stated simply, the decision rule is to establish the optimum rate where the marginal value of water in current use is equal to the marginal value of water as a groundwater stock. Using this rule any rise in the interest rate increases current use while decreasing the groundwater storage level. Similarly, a rise in product prices or fall in factor prices increases current use and lowers groundwater storage levels. This decision criterion generates an optimum rate of groundwater extraction gradually decreasing as the surplus storage capacity of the aquifer is depleted eventually falling to the rate of recharge.

Young and Bredehoeft (1970) employed a simulation model that analyzed various groundwater basins where variations in draw-down and water costs occurred. Assuming that the pumping depth rather than the level of physical exhaustion of the aquifer was the economic limit to water users, they calculated the effects of alternative management policies (taxes and quotas) on the temporal allocation of groundwater. They discovered that policies that diminish the rate of groundwater extraction increased the discounted net economic yield.

CHAPTER 3

ALTERNATIVE INSTITUTIONS FOR CONJUNCTIVE GROUND AND SURFACE WATER MANAGEMENT

This chapter examines the legal and institutional structure concerning conjunctive water use in Colorado. The interdependencies causing external effects between water users makes the coordination of ground and surface water use difficult but necessary to obtain the most valuable use of both resources. Early legal arrangements failed to consider the hydraulic and economic interdependencies of ground and surface water, regulating them as two separate entities. This chapter discusses the legal institutions allocating water, outlines the development of the institutional framework governing groundwater in Colorado and presents alternative methods of administering conjunctive water use.

Legal Institutions for Water Allocation

Water exists in differing quantity and quality throughout the United States. In each region, the particular characteristics of the water supplies have resulted in different property institutions. Each specific management system attempts to alleviate conflicts and uncertainties regarding the right to use the water resource. Areas with abundant water supplies need only certainty of tenure to establish workable water allocations. In arid and semi-arid regions, flexibility that permits trading or transfers of the resource rights is also important (Ciriacy-Wantrup, 1965). Only if water supplies coincide with quantity and quality demands of an area will institutional development be absent.

Three property rights systems have developed to cope with regional supply differences, the stochastic nature of runoff, and the externalities associated with water use: the riparian, correlative, and appropriation doctrines

Most western states use the doctrine of prior appropriation to allocate water. This doctrine states that a person who diverts the water and applies it to some beneficial use acquires the water right. A water right is a property right to the diversion and use of a specific quantity of water that may be flowing in the stream and not a right to the water itself. Non-use, or use other than reasonable beneficial use, may result in the water right being forfeited. The earliest water right on a given stream has a right to water use equal to the amount determined by his water right in priority over later rights. This rule is commonly described by the phrase "first in time, first in right." In each year, the stream flow goes first to senior or earliest rights with the remainder allocated to the junior or newer rights until supply is exhausted.

Other states, especially those in the East where water is abundant, use the riparian doctrine to allocate water. Land owners control the right to use water flowing in streams adjacent to their lands as long as the water is not unreasonably altered in quantity or quality and used only upon the owner's property. The land owner in some states can acquire a water right simply by securing a declaratory judgment of intent to use his water at some "reasonable" future time (Ellis and DeBraal, 1974). Some states alter the riparian doctrine by requiring a "reasonable" water use with the courts defining what reasonable means.

A third legal institution developed to allocate specifically underground water is the correlative rights doctrine. Similar to riparian rights, overlying land owners control the rights to the water stored in the aquifer. The differences being that correlative right holders do not have the same tenure certainty. Competing with other overlying owners, the individual must capture the water to obtain the right to its use.

All three property institutions eliminate some problems of open access resource allocation, but each suffers some uncertainty and inflexibility of water rights. The correlative doctrine imposes no constraint on withdrawals. The water right to future resources is uncertain creating an incentive to exploit the resource as fast as possible. Correlative rights are also inflexible since they prohibit use on lands other than the overlying lands. Riparian rights establish certainty of ownership, thus eliminating the need for immediate capture of the resource. Owners have an incentive to develop and invest in the resource because they will receive all future benefits. Where water is abundant, non-use means that the owner foresees the possibility for greater revenues from water in the future (Hirshleifer, et al., 1960). But if water happens to be scarce, riparian water allocations can be inefficient. Use may be more productive on non-riparian lands. The riparian doctrine prohibits water transfer to those lands.

The semi-arid west has avoided riparian water institutions because of the possible inefficiencies caused by the inability to change water allocations. Conceptually, under the appropriation doctrine, users evaluate both riparian and non-riparian water uses and allocate the supply of water where the net benefits are the greatest. In reality, however, transfers are infrequent because downstream users depend on the return flow from upstream users.

Any upstream water transfer may diminish the quantity of water available to users of the return flow. Water laws usually prohibit transfers that injure other users (Ditwiler, 1975).

Another problem exists when water becomes scarce and historical use determines the amount of the water right. The first appropriators have an incentive to over-irrigate their lands, in order to insure an adequate water supply while at the same time preventing other potential users right to the excess water. A strict priority system also forces the junior rights to absorb most of the losses while senior rights receive their historically determined prior rights. In some shortage periods, benefits to the community might increase if part of the stream flow could go to save crops of the junior appropriators.

Many states include in the appropriations doctrine the condition that the water use must be beneficial. This condition might eliminate wasteful uses of water if the courts could identify those uses that are wasteful and those that aren't. Beneficial uses range from irrigating corn to flooding pasture lands. The essential requirement is to divert some quantity of water and then spread it on the land (Radosevich, Hamburg and Swick, 1975).

Ground Water Legislation in Colorado

Early in its history, Colorado recognized the need for property institutions governing water use. Article XVI, Section 5 of the Colorado Constitution states that all water is public property:

> The water of every natural stream, not heretofore appropriated, within the State of Colorado, is hereby declared to be the property of the public, and the same is dedicated to the use of the people of the state, subject to appropriation as hereinafter provided.

Section 6 refines the appropriation doctrine with respect to water by indicating a priority system allocates water between users when water shortages occur. The priority date, the date when the first step to secure the appropriation took place provided work to complete the appropriation proceeded with reasonable diligence, defines the priority order of the water rights.

Specific property rights to the use of groundwater took more time to develop. Early case law divided groundwater into either tributary or non-tributary. The courts suggested that tributary groundwater, water which flows in well defined underground streams and eventually reaches a surface stream, was subject to appropriation as part of the stream flow. In reality, proving that groundwater is tributary was difficult, resulting in the non-regulation of groundwater. It wasn't until 1951, in the case Safranet vs. Limon, could the appropriation doctrine govern the use of tributary groundwater. In that case, the court stated that groundwater is assumed to be tributary with the burden of proof falling on the party asserting the opposite.

A major drought stimulated well use in the 1930's. Farmers with junior surface water rights sunk wells to provide them with the needed additional water. But, the external effects from pumping were still slight due to the high operating costs that effectively limited use.

During the 1950's, the setting changed drastically. Another drought encouraged more farmers to acquire supplemental ground water capacity. In addition, the REA program provided cheap abundant electricity and the pumping technology improved greatly. These changes substantially lowered the costs previously prohibiting major development. The increase in the number of wells and the reliance on groundwater to provide irrigation water continued into the 1960's. Groundwater use may now cause large external effects on surface flows and water tables.

Prior to the 1950's, case law implied the use of the appropriation doctrine for both ground and surface water in the South Platte River basin. But in reality, the state considered the two water resources separately. Neither the courts nor the legislature had determined the relative priorities between ground and surface water rights. As a result, Colorado had two water allocation systems: 1) the priority system regulating allocation of surface water, and 2) the unadjudicated, non-regulated well owners.

The expanding development of non-regulated groundwater resources led to first attempts to regulate well owners in 1953 by the Colorado legislature. This act authorized a study of the effect of pumping in certain areas and required new well owners to file well logs. Missing from the act were any provisions giving the State Engineer power to shut down wells to protect senior surface rights. In 1957, the legislature passed a second act that brought all groundwater use under the administration by the State Engineer. Again, any power to regulate use was missing. The only control given to the State Engineer was the requirement that new well owners must obtain drilling permits. Subsequently, groundwater development continued to expand rapidly. By 1965, the external effects from pumping had developed to the point where surface water appropriators became convinced that their rights were being infringed upon. There was a definite need for regulating well owners, but the power to shut down wells was absent.

During the late '50's and early '60's, a substantial part of the area's economy became dependent upon the additional ground water. Well owners spent considerable sums constructing wells and irrigation methods using groundwater. They pointed out that using the aquifer as a water source was more efficient than surface storage reservoirs. Similar to surface reservoirs, spring runoffs recharge the aquifer, but the aquifer needs no hydrostatic support and loses no water to evaporation. The well owners justifiably felt their rights ". . . had become vested even though they had never been adjudicated" (Morel-Seytoux, et al., 1975).

To cope with these problems, the legislature passed the 1965 Groundwater Management Act (see Colorado Revised Statutes Annotated, Section 148-18-1, et seq., 1965). The Act contained two important provisions designed to strengthen and clarify controls used to regulate the state's water. The first provision required new groundwater users to apply to the State Engineer for a permit to construct a new well. He would grant a permit only if the amount withdrawn would not injure vested water rights of other water users. The second provision provided for the control over the state's waters in accordance with the strict application of the appropriation doctrine. The Act forced the State Engineer to recognize the effect of a well on other users. He could now shut down any well materially injuring senior water rights. The Act was the first major attempt to regulate the conjunctive use of ground and surface water.

In 1966, the State Engineer made the first attempt to regulate the state's waters according to the 1965 Act. He ordered 39 wells causing injury to the surface flow in the Arkansas River to stop pumping. The well owners immediately sought an injunction against that pumping restriction. The case, known as Fellhauer vs. People, eventually went before the Colorado Supreme Court. The court ruled the State Engineer has authority to shut down wells if he followed the procedures set forth by the statue. After upholding the Act's constitutionality, the court also decided that the Water Division Engineer had acted incorrectly, shutting off only 39 wells out of approximately 1,700 affecting the stream in the area. His enforcement of the 1966 Act was held to be arbitrary and discriminatory, thus violating the equal protection clause of the Fourteenth Amendment in the United States Constitution.

The court set forth three requirements in order for groundwater regulation to be valid and constitutional (Ellis and DeBraal, 1974).

1. The regulation must be under and in compliance with reasonable rules and regulations, standards and a plan established by the State Engineer prior to the issuance of the regulative orders.
2. Reasonable lessening of the material injury to senior rights must be accomplished by the regulations of wells.
3. If by placing conditions upon the use of a well, or upon its owners, some or all of its water can be placed to a beneficial use by the owner without material injury to senior users, such conditions should be made.

The court realized that strict application of the appropriation doctrine might not efficiently allocate the water resources. It altered the doctrine, permitting groundwater uses not materially injuring senior rights. The court also proposed that any new regulation recognize "maximum beneficial use" of water. The concept known as "futile call" would also have an important role in accomplishing the new water allocation goals.

The "doctrine of futile call," recognizing the relatively long time lag between groundwater withdrawals and impact on the river, prohibits senior appropriators from claiming water that will not immediately benefit them from junior appropriators. Junior right well owners can continue to use groundwater knowing they won't be shut down until senior water users feel the effects caused by the withdrawals. Administrators can recognize the time lag effect of groundwater use on surface flows, thus permitting conjunctive water use.

The 1969 Water Rights Determination and Administration Act incorporates the changes made in the Fellhauer decision into statues. The Act, conceding the interrelationships between ground and surface water, states "it shall be the policy of this state to integrate the appropriation, use and administration of underground water tributary to a stream with the use of surface water to maximize the beneficial use of all the waters of this state" (Colorado Statutes, 167 Colo. 320, 447 p2d, 1969).

The new Act retains the priority system but attempts to efficiently use water resources. Four principles included in the Act allow the State Engineer to attain this goal (Radosevich and Sutton, 1972). The first principle states that any regulation must protect all previous vested rights. To apply this principle, the Act forces unadjudicated well owners to obtain a priority date. Well owners had until July 1, 1972, to apply for a priority determination with exact amount and data decided in the respective division water court. In times of shortage, wells because of junior rights, will be shut down first. To protect well owners, the second principle indicates that well use shall be given the fullest possible recognition. The third principle states that using wells as an alternative source of water for surface appropriation enhances optimal water use. Lastly, the senior appropriator cannot take water from junior rights unless the time lag has significantly diminished his surface supplies, consistent with the futile call concept.

The 1969 Act created the foundations that have enabled the State Engineer to administer water on an integrated basis. Based upon the Fellhauer case and 1969 Act, the State Engineer formulated regulations to carry out his function as water administrator. The state Engineer's goal was to formulate a flexible system maximizing beneficial water use and preserving the priority system. The State formally recognized the vested interests of both ground and surface water users for the first time. The specific objectives were: 1) to maximize the possible use of the state's waters, 2) protect vested rights, and 3) preserve the economy developed through the use of wells.

The actual rules, which were set forth, regulated unadjudicated wells as if they had the same priority date. A zoned map of depletion factors describing how pumping from different locations effects the surface flows would serve to integrate water use. Depending upon location and pumping rate, the State Engineer determined when and which wells to regulate to meet a senior appropriator's call on the river.

The zone depletion concept focuses on well location relative to the river and the individual characteristics of the aquifer. For example, a five percent stream depletion factor of 20 days means that a well would intercept five percent of the stream's total flow in 20 days. Lines drawn connecting points of equal stream depletion factors, similar to map contours, represent zones where groundwater pumping has equal impacts on the stream flow. Previously, using a strict priority system, the State Engineer might have to shut down junior wells distant from the stream. The actual increase in stream flow might not materialize until the growing season is over due to the slow movement of groundwater toward the river. Ignoring priority rights by treating all unadjudicated wells as having the same priority date and employing the zone depletion concept, the State Engineer could effectively integrate the use of groundwater as surface water. Recognizing that the current stream depletion factor might not be as precise as necessary, regulation of the individual wells could not exceed three days per week.

Any change of status quo water use generally upsets existing vested interests. Well owners attempting to protect the right to pump without interference sought and received a temporary injunction prohibiting the State Engineer from enforcing the 1969 rules and regulations. In the case, Kuiper vs. Wellowner, the Supreme Court decided in favor of the State Engineer allowing him to administer his regulations. The opinion of the court was

> . . .his regulations are presumed to be valid until shown otherwise by a preponderance of evidence. . . All that can be expected is that he exercise his best judgement, using information then available to attempt to reach the goal of maximum use, of course, without being arbitrary or capricious (Morel-Seytoux, et al., 1975).

In 1972, rules and regulations included the zone depletion concept, but omitted any statement about protecting the existing economy produced from well use. Instead, regulations would protect water rights and uses vested in any person by virtue of previous or existing laws. Following the new rules, the State Engineer prohibited the Weldon Valley Ditch Company from diverting from the Platte River to immediately satisfy a senior call on the river. The Ditch Company defended its right to the water on the assumption that if the State Engineer allocated the available water according to the Constitutional priority system, its right was senior to wells in the area. The company decided to continue diverting surface water as long as the wells in the area continued pumping.

In this case, Kuiper vs. Weldon Valley Ditch Company, the courts upheld the order to stop diversion but also stated that any future regulation of both water sources to be in accordance with the Colorado Constitution and Statues. The ruling eliminated any concept similar to zones of depletion thus requiring the State Engineer to allocate water on the basis of a strict priority system thus ignoring the hydrological and economic interdependencies of conjunctive water use.

Augmentation Plans

Presently, the only way a well owner in Colorado can continue pumping throughout the irrigation season is to be a party to a plan of augmentation. First proposed in the 1969 Groundwater Management Act, a plan of augmentation is a

> . . .detailed program to increase the supply of water available for beneficial use by the development of new or alternative means or points of diversion, by pooling of water resources, by water exchanges, by providing substitute supplies of water, by development of new sources of water or by any other appropriate means (Radosevich, Hamburg, and Swick, 1975).

The water users must design their own plans and submit them directly to the water clerk of the appropriate water district or the State Engineer whose approval or disapproval is persuasive evidence in the water court. For approval the plan must meet the following criteria: (Radosevich, et al., 1975).

1. That replacement water for stream depletion shall be made available to the Division Engineer in an amount equal to 5% of the projected annual volume of a groundwater

diversion, and may be used by him at a rate of flow sufficient to compensate for any adverse effect of such groundwater diversion on a lawful senior requirement, as evidenced by a valid senior call, but not exceeding 5% of the capacity of the diversion structure.

2. Such capacity shall be determined by court decree, . . ., by well permit or by registration. If none of these means of determination is available, the capacity will be the maximum pumping or delivery date.

3. The operation of the augmentation plan shall not be used to allow groundwater withdrawal which would deprive senior surface rights. . .they were entitled in the absence of such groundwater withdrawal, and groundwater diversions shall not be curtailed or required to replace water withdrawn. . ., assuming water would not have been available for diversion for senior appropriators under the priority system.

The last guideline means that there may be areas where the required five percent stream depletion requirement, if enforced, would provide more or less than the necessary water to insure no injury accrues to senior surface appropriators. As the physical conditions in aquifer and stream vary, the five percent depletion factor may be modified using one of the following criteria: 1) the method developed in The Pumped Well, by Robert F. Glover, "Technical Bulletin 100," Colorado State University, 2) the transmissivity value obtained from the U.S.G.S. open-file reports, "Hydrogeologic Characteristics of the Valley-fill Aquifer in the South Platte River Valley," 3) the specific yield will be assumed to be 20 percent, and 4) the consumptive use for irrigation purposes assumed to be 40 percent. In simple terms, augmentation plans must illustrate the ability to replace 5 percent of the annual water withdrawn, but the state can change that percentage to reflect changing conditions. The actual amount replaced into the stream in any particular year depends upon the demand and supply conditions. Groundwater users replaced approximately 1.5 percent of the annual ground water diversions in 1976 due to the relatively abundant water supplies in the South Platte River basin.

The largest augmentation plan approved and in use by well owners along the South Platte River is GASP (Groundwater Users Association of the South Platte). GASP provides augmentation water to the State Engineer by purchasing or leasing existing storage rights and from wells placed near certain senior surface rights. Membership fees generate the revenue used to acquire replacement water. GASP charges a one-time initiation fee and annual fees based on the quantity of water the member normally pumped for one irrigation season. The present fee is $0.25 for every acre foot withdrawn. The sources of GASP's 1976 replacement water supplies are shown below.

McClellan Reservoir (Rented)	2,000.00 acre-feet
Bacon Reservoir (Rented)	1,000.00
Bijou, Colorado Big Thompson (Rented)	800.00
Union Reservoir 58 3/4 sh @ 23 aF/sh (Rented)	1,351.25
Prewitt Reservoir (Rented)	180.00
Riverside CBT (Rented)	2,400.00
Sterling 'A' Wells 180 day X 66 aF/day (New development)	11,180.00
Sterling 'B' Wells 180 day X 44 aF/day	6,777.00
Total	25,688.25 acre-feet

GASP's association with the Sterling No. 1 Ditch typifies maximum conjunctive use of total water supplies. Under the strict appropriation doctrine, the Ditch's senior right and large water requirement would force junior well owners in Logan, Washington, and Morgan Counties to stop pumping to provide the water supplies when the Sterling Ditch makes a call on the river. The total call is equal to the ditch's water right and the substantial amount lost in transmission to the ditch from seepage and evaporation of the river. GASP has developed a well field along the ditch to supply the water when a call is made. The wells supply the water immediately without the extra loss from transmission. Upstream junior appropriators are able to use the water previously lost in transmission without harming downstream users because of the time lag effects of groundwater extractions.

Water augmentation plans promote maximum and efficient use of the available water supplies. Under these plans, junior well owners can continuously pump, taking advantage of water previously lost to seepage and evaporation and the delayed effects of groundwater pumping on surface flows. Colorado water laws force GASP and other augmentation plans to buy or rent water from existing supplies, creating a quasi-market system. The market price of water (equal to the value it has in additional crop production) becomes the allocative mechanism distributing both water sources to their most efficient uses. For example, well owners will find it to their advantage to continue to pump as long as the pumping variable cost plus the replacement fee for an additional unit of groundwater is less than purchasing or leasing a unit of surface water.

The recent development of the augmentation plan system in Colorado has been in the spirit of Randall's (1972) suggestions for creating a market solution to the externality. (Randall noted that an open access property system is equivalent to a zero liability rule on the source of an externality. A full liability rule transfers the responsibility for an external cost to the source, and facilitates a market solution to the problem.) The new Colorado groundwater institution invokes a full liability rule, allowing the external effects of mining groundwater to exist only if compensation is made to surface water users. Transaction costs are reduced by requiring groundwater users to join an augmentation plan in order to continue pumping. Under augmentation plans, a large number of individual pumpers are brought together in a collective body that collects revenues to acquire water for the farmers. Paying the fees, which GASP and similar organizations use to buy supplemental water, forces the ground water users to compensate for the external diseconomy they produce as they pump water from the aquifer. GASP members, in contrast with other individual users, must pay both the social and private groundwater costs. This institutional change allows the market to efficiently allocate all water resources. The full liability rule and appropriate pricing system should lead to reduction in the externality and promote production methods or crops that use less groundwater. This recent institutional change permitting conjunctive use of all water supplies using a quasi-market promises both an increase in efficiency and less institutional rigidity.

Ruttan (1978) has proposed a theory of institutional innovation, in which modifications of institutions are made in response to changes in benefits and costs of such innovations. The benefits must exceed the costs plus administrative (or transaction) costs for an innovation to occur. The plan of augmentation appears to provide an excellent example supporting Ruttan's hypothesis.

Following this review of legal alternatives, the next two chapters present the conceptual basis and the data sources for the simulation model employed in this study to evaluate management alternatives for the South Platte tributary aquifer-stream system.

CHAPTER 4

THE IRRIGATION WATER ALLOCATION SUB-MODELS

The traditional model of a firm's decision process assumes that the firm makes choices with complete and perfect knowledge. The real-world farmer plans in a more ambiguous setting. He makes decisions without complete information about prices, technology, weather, and other uncontrollable variables. In this uncertain environment, the decision maker can no longer expect an exact relationship between alternative actions and their outcomes. To accurately represent farm operator's reactions to different water management policies and stochastic water supplies, this chapter formulates a model predicting farmers' behavior in an uncertain environment.

The first section of this chapter reviews the theory concerning decision making under uncertainty. Next, we develop an intermediate-run planning model incorporating uncertainty considerations where farmers are assumed to make crop planting decisions at the beginning of each growing season. The planning model determines which crops and how many acres of each the farmer plants. Farm manager behavior toward uncertain conditions at this stage is a crucial factor in the determination of crop production, water allocation, and the total returns to the enterprise. We assume that the irrigator's choice between alternative crop strategies depends on the trade-off between the expected net income and variance of a crop plan.

Uncertainty also affects the farmer's short-run decisions about the care each crop receives during the growing season. Especially critical is the deviation of actual water supplies from expectations. The second section of this chapter presents the short-run operating model, which measures the net returns from various levels of uncertain water supplies. This model also determines how much surface, ground, or reservoir water the farmer uses under various potential water supply situations.

Decisions in the Presence of Imperfect Knowledge

Basic Concepts. Decision making is the central coordinating concept of any organization whether it is a family farm, a giant manufacturing firm, or a governmental agency (Halter and Dean, 1971). Farm operators make plans early in the spring for a product forthcoming in the future. Even though crop production involves repetitive activities, the process occurs over a time horizon and requires future predictions about nature, resource supplies, and market possibilities. Decision making under conditions of non-certainty truly characterizes agricultural enterprises.

Decision making under certainty or risk are two classifications of problems about planning for the future. Risk refers to measured variabilities of outcome. If the farm operator empirically or statistically estimates the probability distribution of an outcome, decision making is said to take place under conditions of "objective risk." If the farmer intuitively approximates the probability distributions, decision making is said to occur under "subjective risk." When the parameters of the probability distribution cannot be determined, uncertainty exists.

Bernoulli (1954), Friedman and Savage (1948), VonNeuman and Morgenstern (1947), to name only a few theorists, have developed models of decision making under risk. The models range from simple risk discounting or certainty equivalents to complex expected value and expected utility models. But, pure risk does not significantly alter the traditional static equilibrium theory. Risk can be incorporated directly into the cost structure of the firm. It is uncertainty that requires a different decision-making framework.

Agreement on the correct treatment of uncertainty because of its obvious "uncertain" nature has not been achieved among economic theorists. Each farm operator has his own peculiar image of the future, which is reflected in his predictions. Models of behavior under uncertainty, even the most mathematically elaborate, begin with a normative judgment about how and why a decision maker chooses between several actions and their uncertain outcomes.

The Expected Income-Variance Hypothesis. Decision problems often force the individual to choose between outcomes with various expected incomes and variance of those incomes. A farmer selecting an optimal cropping pattern, or an investor choosing between income earning assets are two examples. Both the expected income and associated income variance influence the farm operator's and investor's decisions.

Markowitz (1952) pioneered this approach in his analysis of decision making in investment portfolio selection. The typical investor would like a portfolio that maximizes his expected income (E) while minimizing the variance (V). Since simultaneous maximization of more than one criterion is impossible, a compromise must be found. The investor, who is a risk averter, is hypothesized to restrict his choices to those strategies that have a minimum variance for the given expected income. The possible alternatives, called efficient expected income (E) -

variance (V) pairs, define an efficient boundary over the set of possible strategies. If an action falls under the efficiency boundary, one of three possibilities exists: 1) a plan on the frontier yields equal E with less V, 2) a plan with the same V but higher E, or 3) a plan with greater E and less V. The efficiency frontier, restricting rational choices to those where variance is a minimum for each expected income, narrows the range of alternatives.

Halter and Dean (1971) provide a mathematical model for generating an E-V frontier to determine the optimal cropping pattern in an irrigated farm area. The major crops are alfalfa, sugar beets, tomatoes and barley. The differences between total revenue and total variable costs determine gross margin, ($I_i = TR_i - TVC_i$). The model includes n crop alternatives with q_i representing the proportion of land area devoted to the ith crop, ($\sum_{i=1}^{n} q_1 = 1$). The net income variance of the ith crop is σ_i^2 and the correlation between net income of crop i and j is r_{ij}. Assuming the acre distribution of I_i has the same mean and variance regardless of the number of acres planted and a normal distribution of gross margins, the equation,

$$\bar{I} = \sum_{i=1}^{n} q_1 \bar{I}_i \tag{1}$$

expresses the expected per acre net income for cropping system I. The net variance per acre for I is,

$$\sigma_I^2 = \sum_{i=1}^{n} q_i^2 \sigma_i^2 + 2 \sum_{i,j=1}^{n} q_i q_j r_{ij} \sigma_k \sigma_j \tag{2}$$

where the covariance terms, (r_{ij}, σ_k, σ_j), exhibit the interdependency between crops. Equations 1 and 2 can be used to compute the E-V farm plans knowing the correlation matrix, means, and standard deviations of net per acre income.

Hand computation of enough points to approximate the E-V frontier is a formidable task. Halter and Dean (1971), show how one can use quadratic programming subject to linear constraints to derive the E-V frontier. The problem can be formulated as:

$$\begin{aligned} &maximize\ f(q) = q'I - q'Bq \\ &subject\ to q_1 + q_2 + \ldots + q_n \leq 1 \\ &q_1 \leq A \\ &\vdots \quad \vdots \\ &qn \leq M \\ &q'I = K \\ &q_i \geq 0 \end{aligned} \tag{3}$$

Where q is a lxn row vector of crop proportions,

I is an IXN column vector of expected incomes for the crops,

B is nxn variance - covariance matrix for the crops,

K is a constant that varies parametrically from 0 to a maximum possible value.

A. . .M are technical crop constraints.

This methodology maximizes the expected income minus the variations of income subject to linear constraints. The solution process varies K parametrically from zero to a maximum value determining the maximum difference between E and V for each level of q'I. The result is equivalent to finding the minimum variance for each E.

The major theoretical difficulty of the E-V decision model is the assumption that a farmer's preference between alternative plans is based solely on the risk-averse trade-off between E and V. Assuming that farmers are adverse to departures from the mean, even in the case where risk increases, this model might not represent actual behavior. Individual risk utility functions may vary because of other factors than just E and V.

The Annual (Intermediate Run) Planning Model

This study adopts the Markowitz E-V hypothesis and the associated assumptions about farmer behavior under certainty. The farmer is a risk averter who is willing to undertake a cropping strategy with more variance only if the expected income is greater. Before applying the E-V methodology, two problems must be solved. The first problem is that quadratic programming (Q-P) techniques generating the E-V efficient frontier require a special programming code. This code is not as efficient or readily available as Standard Linear programming (L-P) routines.An alternative has been developed by P. B. R. Hazell (1971) which employs a linear model and standard L-P code to solve for the efficient frontier.

The second problem is that while Hazell's L-P and Markowitz's Q-P generate the E-V frontier in the absence of a risk utility function, final selection of a farm plan is left to the individual farmer. The present study requires knowing exactly what cropping patterns the farmer in the South Platte might choose. The specification of risk preference coefficient solves this problem.

The model Hazell provides uses an expected income (E) - mean absolute income deviation (A) criterion instead of E-V. Using A as a measure of uncertainty, the E-A plans are those having a minimum mean absolute income deviation for a given expected income. A is an unbiased estimator of the population defined as:

$$A = \frac{1}{S} \sum_{n=1}^{n} \quad \sum_{j=1}^{n} (C_{nj} - g_j) X_j \tag{4}$$

g_j = sample mean

C_{hj} = gross margin for the jth activity

X_j = the level of the jth activity

n = number of activities

S = the number of observations

with the addition of three new variables

$$Y_h = \sum_{j=1}^{n} C_{hj} X_j - \sum_{j=1}^{n} g_j X_j \tag{5}$$

such that

$$Y_h = Y_h^+ - Y_h^- \tag{6}$$

the L-P problem is to

$$minimize\ sA = \sum_{h=1}^{s} (Y_h^+ = Y_h^-) \tag{7}$$

such that

$$\sum_{j=1}^{n} (C_{hj} - g_j) X_j - Y_h^+ + Y_h^- = 0 \ (for\ all\ h, h=1,\ldots,S) \tag{8}$$

Further simplifying equation (7), Hazell's complete L-P model is:

$$Minimize \sum_{h=1}^{s} Y_h^- \tag{9}$$

such that

$$\sum_{j=1}^{n} (C_{hj}-g_j)X_j + Y_h^- \geq 0 \quad (for\ all\ h,\ h=1,...,s) \tag{10}$$

$$\sum_{j=1}^{n} f_jx_i = \lambda \quad (\lambda = 0\ to\ unbounded)$$

$$\sum_{j=1}^{n} a_{ij}x_j \leq b_i \quad (for\ all\ i,\ i-1,...,m)$$

$$x_j, y_h^- \geq 0 \quad (for\ all\ h,\ j)$$

Where f_j = the expected (forecasted) gross margin of the jth activity

a_{ij} = the technical requirement for activity j, ith resource

b_{ij} = the ith constraint level

λ = 0 to unbounded.

Using the sample mean absolute deviation instead of the sample variance does result in some loss in reliability in the prediction of E-V farm plans. To find out how much difference there is between E-A and E-V, Thompson and Hazell (1972) simulated a range of factors affecting the ability of either model to estimate the efficient farm plans. They discovered that there were only slight differences with farm plans ranked by A instead of V. The increases in computational efficiency are judged to more than compensate for the small loss in reliability for the purpose of this report.

To determine the effects on the net income of farmers from changes in water management institutions, our model must go beyond generating the efficient E-A farm plans and select one realistic strategy. To accomplish this task, Hazell's L-P model must be modified slightly. Instead of minimizing the mean absolute deviation for levels of expected income, the model in this report maximizes expected net income given an individual's preference toward uncertain incomes.

The farmer chooses between farm plans with differing mean and variance outcomes. He must weigh these two aspects and decide on a proper allocation of water to his crops. The farmer's utility function is characterized by a diminishing marginal utility of income and a general preference for higher mean returns, but variability of those returns carries with it a disutility. It is possible to draw alternative combinations of mean return and variability of returns that are indifferent to the farmer. As he moves along these isoutility curves, the increase in expected income is sufficient to compensate for the increase in variance. Movement in the northwest direction leads to a higher level of utility because such investments promise a higher expected return with less risk. This system is known as a gambler's indifference map.

If the utility function is quadratic, expected utility of each outcome is estimated using the mean and variance of income. For example, if

$$u = q_0 + q_1 I + q_2 I^2 \tag{11}$$

then

$$E(u) = q_0 + q_1 E(I) + q_2 \left[v(I) + F(I)^2 \right] \tag{12}$$

where u is utility and E(I) and V(I) are the mean and variance of the expected income. The slope of the isoutility curve or E-V indifference curve provides an index of the farmer's preference toward risk for a particular farm plan.

VonNeuman and Morgenstern (1947) were the first to develop an expected risk utility curve. Other derivations of these utility functions including Bernoullian and Lexicographic preference functions require substantial amounts of resources and time. For this reason a simpler constraint is used in the model to empirically generate internally the slope of the farmer's utility curve. The constraint, E(I) - CV(I) = 0, was adjusted until the model accurately predicted past planted acreages. The value of the constant, C_j is then used to forecast future uncertain behavior of farmers.

The Short-Run Water Allocation Model

After making the intermediate-run planning decisions, the farm operator still faces uncertainty in the short-run choices of how and when to irrigate, fertilize, and harvest. Also, the stochastic nature of stream flows in the study area causes the water the irrigator actually receives during the growing season to vary from the amount the irrigator initially expected. The deviation between actual and projected water supplies cause inefficient production and corresponding lower net returns. If larger deficits in water deliveries than expected occur, the resulting net farm returns are less compared to the net return from a small scale production strategy. If water supplies exceed forecasts, the increase in benefits is less compared to the benefit from production initially planned on a larger irrigation supply.

The short-run model predicts the response of irrigators facing uncertain water supplies. It generates the amounts and timing of irrigation, the acreage of each crop irrigated, surface water diversions, and groundwater withdrawals within the constraints of planted land set by the planning model at the beginning of the summer growing season. The objective is to maximize net farm income in the study area. The short run model employing a standard L-P program run each month, consisting of activities, technical coefficients, resource constraints, and an objective function.

A realistic short-run response model must represent the complex relationship between irrigation and crop production. The model has to predict production output (yield) for any cropping and irrigation strategy the farmer chooses. The yield is a function of the timing of water allocations to the individual crop and the total water allocation between all crops. Many dynamic models (e.g., Hall and Butcher, 1968)) can solve either the optimal water allocation for one crop or the optimal irrigation pattern between crops but few exist that combine both the multi-stage, multi-crop elements of irrigated farms.

Anderson and Maass (1971) were among the first to develop a computer simulation of decision making on irrigated farms. Delucia (1969) formulated a different model termed "sequential linear programming." His model contains a series of linear programs for each decision period, each linked to the solution of the preceding period. Incorporating elements of both models, Young and Bredehoeft (1972) developed an irrigation response and benefit model that captures the complex water-plant relationship. More recently, Blank (1975) formulated a multiple crop planning model that determines the timing and amounts of irrigation water for various production levels. He uses an evapotranspiration (ET) prediction model with an additive or multiplicative production function to calculate yield from one crop under varying irrigation applications. His dynamic model generates an optimal production process under limited water conditions. The short-run irrigation response model in this study uses technical water coefficients and irrigation schedules similar to Blank's.

Technical Coefficients. The technical water coefficients represent the quantity of water needed to produce one unit of crop output. The Blank model uses the intermediate variable, ET, to relate crop output to various irrigation inputs. The plant uses sunlight, water, and carbon dioxide to produce carbohydrates. Given the availability of sunlight, the plant transpires water vapor and breathes in carbon dioxide through its open stomata. The lack of water causes a chain reaction, first reducing the ET, causing the stomata to close, in turn, prohibiting the intake of carbon dioxide, finally reducing yield. It is assumed that the absence of ET has varying effects on the final yield during different growth stages of the plant.

For corn, Blank used Colorado State Field trial data where the crop was grown under alternative irrigation regimes. The field trial data became the basis for the parameters in a three-growth stage ET estimation model. The ET rates for the other crops, pinto beans, sugar beets, and alfalfa came from Stegman (1969).

Even though rainfall is limited, the precipitation the crops receive is not negligible and must be included in the model. This study assumes the farmer allocates his irrigation supply expecting 100 percent of the mean monthly rainfall. The efficiency rate of 100 percent is used for two reasons. Even though some rainfall does not penetrate into the root zone, it will evaporate from the plant leaf in place of the plant transpiring water from the root zone. Secondly, the pre-season precipitation is assumed to balance the part of large, sudden rainfalls that run off before percolating into the ground. Using the 100 percent precipitation assumption does favor a crop mix containing the slightly higher water use crops usually associated with greater returns.

The water resource rows in the LP containing the technical water coefficients form water balance equations where the quantity of water required to irrigate all crops in one period must equal the total water allocated in that period. The remaining technical coefficients are integers relating the different activities to the activity constraints.

Activities. The farm operator, knowing the functional relationship between irrigation inputs and plant outputs, must decide how to allocate his water supplies among his crops. Under conditions of water shortages the farmer may want to irrigate one crop at a critical growth stage while skipping irrigation of another not in its critical stage. The farmer may even decide it is not profitable to irrigate a crop at all since the increase in return is less than the extra water cost. The irrigation activities expressed in acres of crop irrigated following a particular water application schedule represent the irrigation choices available to the farmer.

The L-P model contains 26 possible irrigation activities. The activities for each crop include the "optimal" irrigation schedule plus combinations representing water shortages during one or more irrigation periods. Skipping a scheduled irrigation reduces the crop yield below the maximum yield obtained if the farmer followed the optimal irrigation regime. The yield reduction depends on the irrigation periods skipped, the plant growth stage during the stress period, the plant species, and a particular assumption about water availability. The first assumption represents the farmer who has enough water supplies following a stress period to return the root zone back to the optimal moisture level. Any reduction of crop yield occurs only during the stress period. This assumption biases the model decisions toward high return and high water use crops. The second assumption models the farmer who has water available after a stress but not enough to refill the root zone to optimum levels. Reductions in yield can occur during the stress period and in later periods since the moisture level in the root zone can stay below the level necessary to avoid crop yield reductions. The yield loss for corn was calculated using the following equation derived from Blank (1975).

$$\frac{Y}{Y_{\max}} = A_1 \frac{ET_1}{ET_{1\ \max}} + A_2 \frac{ET_2}{ET_{2\ \max}} + A_3 \frac{ET_3}{ET_{3\ \max}} + A_4 \tag{13}$$

where Y is the predicted yield

$Y_{\max}$ is the maximum attainable yield

A a constant

ET_1 is the measured ET in the period 1

$ET_{1\max}$ is maximum ET in period 1.

The total number of irrigation activities for all crops under both water availability assumptions is approximately 100. Limited computer time prohibits including all 100 in the simulation. To choose which activities to include in the simulation, we ran an L-P model with all possible irrigation regimes parametrically decreasing water supplies. The irrigation activities that entered the solution had the greatest return for a given water supply. The inefficient activities were deleted from later simulations. The efficient activities and their water requirements are shown in Table 4.

Table 4 Water Requirements by Time Period for the Crop Activities (acre inches).

Efficient Crop Activities	Corn												
	0*	1	4A	6	7	10	13	11	15	18	32	25	28
Period 1	5.6	0	5.6	0	0	5.6	0	0	0	5.6	0	5.6	0
Period 2	5.6	11.8	5.6	11.8	11.8	5.6	11.8	0	5.6	5.6	5.6	5.6	5.6
Period 3	4.2	4.2	4.2	0	4.2	0	0	0	4.2	4.2	4.2	0	0
Period 4	11.3	11.3	5.0	16.8	5.0	12.8	10.5	24.6	11.3	0	5.0	5.0	5.0

Efficient Crop Activities	Sugar Beets					Beans	Alfalfa						
	0*	4	8	10	30	0*	0*	2A	3	4	6	12	16
Period 1	4.1	4.1	4.1	0	4.1	0	2.5	2.5	2.5	2.5	0	0	2.5
Period 2	4.8	4.8	.9	8.7	.9	8.7	12.6	4.0	12.6	12.6	12.6	8.7	.4
Period 3	6.5	6.5	0	8.1	0	8.1	4.2	4.2	0	4.2	0	4.2	0
Period 4	11.3	0	4.2	4.2	4.2	4.2	6.6	2.7	2.7	0	2.7	0	2.7

* Optimum irrigation schedule.

The additional activities in the L.P. tables are water purchase activities. The farm operator can use surface water depending on the priority of his right, stored reservoir water according to his share in the irrigation district, groundwater, or any combination.

Objective Function. The objective function determining the total net benefits the farmer receives given the technical, legal, and social constraints is the key element in the simulation L.P. subroutines. The objective function row presents the net revenue per acre of irrigated crop and the costs for ground, surface, and reservoir water. The expected net revenue, C_{ijk}, for the ith crop in period j under the kth irrigation regime is equal to,

$$C_{ijk} = \left(Y_{ijk} \cdot P_i\right) - D_{ij} \quad i=1,2,3,4 \quad j=1,2,3,4 \quad k=0,1,2,... \tag{14}$$

where Y_{ijk} is the expected yield of crop i given the kth irrigation regime,

P_i is the expected price for crop i, and

D_{ij} is the variable production cost of crop i in period j excluding water and irrigation labor costs.

The short-run prices are the average of the previous five years adjusted to 1974 values. The D_{ij} values for the four crops, corn, beans, beets, and alfalfa come from CSU Bulletin No. 491A, "Costs and Returns for Irrigated Crop Production in the Lower South Platte Valley, Colorado, (Conklin, 1974). A 280-acre cash farm is the representative farm operation in the model.

Groundwater costs are estimated using the engineering equation,

$$V_g = \frac{(1.024)\ (Pe)\ (L)}{E} + (.0055)\ (L)$$

where 1.024 is the kilowatt hour of electricity required to lift one acre-foot of water if the efficiency is 100 percent,

E is the actual efficiency, 50 percent,

Pe is the price of electricity per kilowatt hour, and

L is the lift (equal to the depth of the static water table plus drawdown).

The ditch companies and reservoir districts assessment fees are the basis for surface water costs. The average ditch assessment in the study area is $2.50 per acre foot and the reservoir assessment is $4.50 per acre foot. The total cost of all water supplies includes the cost of labor needed to irrigate the crops.

Resource Constraints. The resource constraints in the L.P. models restrict the farmer's potential agricultural output. The constraints are either physical limitations on resource availability or institutional restrictions on the activity levels.

The physical constraints represent the actual land and water amounts available to the farmer in each subarea. The land constraint is the potential irrigated areas under the subarea's ditch companies. Surface water constraints represent the existing amounts of water in the river during the respective time period. The groundwater constraint is the maximum pumping capacity of the farms in the subarea. Reservoir constraints are different from the other water resource constraints. These constraints reflect the possibility of transferring stored water from one period to the following period. The maximum amount the farmers can use in any one period is equal to the beginning storage minus any withdrawals, seepage, and evaporation. The beginning storage capacity is the mean of the ten years between 1966-1976.

The uncertainty restrictions limit farm crop activities. The planning model passes planted acreage constraints to the allocation model according to the farmer's risk aversion. For example, if the planning model plants 500 acres of corn in activity 1, the subsequent maximum acreage in the short-run model is 500. Institutional constraints also affect the water activity levels. The priority system limits the surface water supplies and groundwater regulations limit pumping rates.

Short-Run Water Allocation Linear Program

During each time period and for each subarea, the short-run water allocation L.P. maximizes the incremental net revenues given the planted acreage and water constraints. This process determines the pattern and amount of groundwater and surface water used to irrigate the crops. This section presents the mathematical formulation and an illustrative L.P. Tableau (Table 5) for a representative subarea during the monthly stage. Mathematically:

$$\textit{Maximize} \sum_{i=1}^{4} \sum_{k=0}^{4} C_{ijk}X_{ijk} - pS_j - rG_j \tag{16}$$

subject to

$$\sum_{i=1}^{4} \sum_{k=0}^{4} a_{ijk}X_{ijk} - S_j - G_j \leq 0$$

$$\sum_{k=0}^{4} X_{ijk} \leq X_i^*$$

$$S_j \; \bar{W}_j \; G_j \; \bar{N}_j$$

i = the crop index, equal to 1,2,3,4

j = the time period index, equal to 0,1,2,3,4,5

k = the activity number, equals 0,1,2,3,4

X_{ijk} = the acres of crop, i following irrigation sequence k in period j

C_{ijk} = incremental net revenue activity k, crop i, in period j

A_{ijk} = irrigation water applied to crop i under activity k in period j in acre-inches

S_j = acre-inches of surface water used in period j

G_j = acre-inches of groundwater used in period j

$\bar{W}_j$ = available surface water in period j, acre-inches

$\bar{N}_j$ = available well water in period j, acre-inches

X_i^* = total acreage constraint on crop i from planning model

p = cost of surface water, dollars per acre-inch

r = cost of groundwater, dollars per acre-inch

Table 5 Linear Programming Tableau for Planning Stage Model

Row and Unit	Corn Variables	Beet Variables	Bean Variables	Alfalfa Variables	Water Variables	Variance Variables	Constraint Value
Objective Function:		Expected Net Income...			- Costs	Y-1,Y-2,...Y-10	Maximize
<u>Constraints</u>							
1) Total acreage	1 1 1 1 . . .						$\le \bar{X}_1$
2) Min. alfalfa acreage				1 1 1			$\ge \bar{X}_1$
3)	Water use coefficient in time period 1				-1		$= 0$
4) Water	Water use coefficient in time period 2				-1		$= 0$
5) balance	Water use coefficient in time period 3				-1		$= 0$
6)	Water use coefficient in time period 4				-1		$= 0$
7) Available					1		$\le \bar{D}_1$
8) surface					1		$\le \bar{D}_2$
9) water					1		$\le \bar{D}_3$
10) (Periods 1,...,4)					1		$\le \bar{D}_4$
11) Available					1		$\le \bar{G}_1$
12) ground					1		$\le \bar{G}_2$
13) water					1		$\le \bar{G}_3$
14) (Periods 1,...,4)					1		$\le \bar{G}_4$
15) Activity	Time period 1 mean deviation					1	≥ 0
16) Gross Margin	Time period 2 mean deviation					1	≥ 0
17) Deviations	.	.				1	≥ 0
. from sample	.	.				.	.
. mean in	.	.				.	.
. nth year						.	.
25)	Time period 10 mean deviation					1	≥ 0
26) E - kv constraint	Expected net income...				.575	-.575 -.575 -.575	≥ 0

CHAPTER 5

THE SIMULATION MODEL

Many real world economic problems are so complex that it is impossible to obtain realistic analytical results using standard techniques. In the South Platte River Basin, the interdependencies in the stream-aquifer relationship and the economic influence of water institutions on farmers favor computer simulation to predict over time the changes from alternative management policies. This chapter highlights the hydrologic and legal subsystems that, when combined with the economic subsystem discussed above, form the complete simulation model. It also presents briefly the alternative ground and surface water regulations and institutional changes that we analyzed using the simulation model.

Computer Simulation

For problem-solving, simulation uses an abstract representation of the economic and physical system rather than the actual system. Naylor's (1966) definition of simulation is "a numerical technique for conducting experiments with certain types of mathematical and logical models describing the behavior of an economic system on a digital computer over extended periods of time." Simulation provides a tool for tracing out the effects alternative water institutions have on irrigation behavior on a computer in place of changing the current water regulations and observing the consequences.

All abstractions from reality have important limitations and simulation is no exception. For example, simulation does not directly provide a global optimal solution to the problem. Each simulation result varies depending on the particular institution and physical conditions in the model. However, if the researcher can analyze enough alternative actions he may approximate the optimum. Another limitation is the inflexibility in the computer program. In the study area, the priority system allocates the limited surface water to the various irrigation ditch companies. Any radical change of this structure requires developing and testing at the very least a new subroutine and probably involves changes in the total simulation program. The use of historical stream flow records to represent future water flows also limits the analysis; one cannot expect the future stream flow to precisely follow any specific pattern.

The three primary elements in an economic simulation are controllable and uncontrollable variables, a predictive model, and an objective function. Controllable or decision variables represent the alternatives that the policy-maker can manipulate. Water supplies, climate, and other randomly varying variables are the uncontrollable parameters of the simulation. The predictive model, expressed as a set of mathematic equations, represents the important economic and physical relationships in the system. It forecasts the effect of changing the controllable variables on the existing water allocation. The objective function, expressed as the annual net benefits, measures the consequences from various alternatives that attempt to alleviate the externality problem of conjunctive ground and surface water use.

The Hydrologic Subsystem

The hydrologic model represents the interaction between the South Platte River and its alluvial aquifer. In an undeveloped river system, the river and aquifer reach a prevailing equilibrium condition; aquifer recharge to the system equals discharges from it, and hence, there is no net change in underground storage. A river system in disequilibrium may have water flowing from the stream to recharge the aquifer or it may flow from the aquifer to the stream as return flow, depending upon the hydrologic and geologic conditions. The direction of the flow, aquifer to stream or vice versa, depends on the level of the water table of the river compared to the water table of the aquifer.

Any irrigation use of surface or groundwater disturbs the natural stream-aquifer balance. Surface diversions for irrigation lower the water level of the river below the water table in the aquifer near the diversion headgate. Later, part of the surface diversions in the form of farm irrigation runoff enter the groundwater aquifer, raising its water table. Water may return to the river as the two water tables try to equalize.

Pumping ultimately causes some water to leave the stream and replacing the depression in the aquifer. Pumping diversions lower the aquifer water tables relative to stream water levels near the well in a cone of depression. This depression intercepts irrigation return flows moving toward the river and may cause water to leave the stream if the aquifer water table is low enough. The amount of aquifer recharge depends on the physical characteristics of the aquifer, the location and rate of withdrawal.

Morel-Seytoux (1975) has developed a hydrologic model that determines the effect of pumping diversions on the stream-aquifer relationship. Dynamic flow equations consider such things as aquifer transmissivity, porosity, storage coefficients, positioning of withdrawals, and the hydrologic boundary conditions (lithologic, geochemical and hydraulic conditions at the groundwater reservoir boundary). A finite difference model of the surface flow response computes river influence coefficients or"Deltas" in a system of flow equations of an aquifer without any stream interaction. After generating and saving the deltas a less costly epsilon program can be derived to simulate the aquifer behavior under any pumping pattern. The most important advantages of this model for this report are that:

> A finite difference model is used only to generate basic response functions to specialized excitations (e.g., pumping from a single well at a unit rate for the first period of time and no pumping thereafter) in an aquifer without any stream interaction. Once these basic response functions have been calculated for a particular aquifer and saved, simulation of the aquifer behavior to any pumping pattern is obtained without ever making use any longer of the (costly) numerical (e.g., finite difference) model. (Morel-Seytoux, 1975b, p.p. 119-29.)

Study Area Water Supply and Legal Priorities

We assume that farmer can use three water sources: mainstream irrigation ditches,reservoirs, and groundwater, subject to one major legal constraint: the South Platte River Compact with Nebraska. The study area contains 31 ditches with decreed water rights. Under present law, the ditch company owns the water right, not the individual farmer the ditch serves. Each ditch diverts water from the river according to its priority then distributes that amount proportionally to its members. The South Platte ditch owns the earliest direct flow water right, May 1, 1872, and the Bravoditch owns the last, April 1, 1906. Only 20 out of the 31 ditches regularly divert water because of the inadequate flow and generous water rights owned by many senior ditches. The date that usually serves as the lower limit for mainstream diversions is June 14, 1897, the priority date of the South Platte River Compact with Nebraska. Table 6 tabulates the amount and priority of each ditch and reservoir.

Table 6 Ditch and Reservoir Priority System

Ditch	Appropriation (CFS)	Appropriation Date
South Platte	157.50	05-01-1872
Schneider	11.00	04-10-1873
Sterling No. 1	236.10	07-15-1873
Pawnee	133.60	09-17-1873
Davis Bros.	12.34	07-15-1875
South Platte	8.73	02-15-1876
Schneider	190.97	10-20-1880
Henderson and Smith	12.50	11-30-1880
Pawnee	174.00	06-22-1882
Lowline	39.90	10-14-1882
South Platte	20.00	04-21-1883
Sterling No. 2	50.00	06-07-1884
Springdale	62.50	07-19-1886
Iliff and Platte Valley	150.00	10-01-1883
South Platte	37.50	05-01-1890
Davis Bros.	3.00	12-01-1890
Red Lion	3.50	04-02-1891
South Reservation	25.00	09-14-1892
Bravo	40.00	02-21-1893
Red Lion	2.00	08-22-1894
Lone Tree	10.00	09-17-1894
Davis Bros.	20.00	09-20-1894
Powell	91.00	12-12-1893
Ramsey	34.00	02-19-1895
Harmony No. 1	252.00	04-28-1895
Chambers	30.00	05-04-1895
Farmers	16.00	07-11-1895
Harmony No. 2	50.00	05-03-1897

Table 6 Ditch and Reservoir Priority System

Ditch	Appropriation (CFS)	Appropriation Date
Lone Tree	83.00	07-15-1895
Red Lion	52.00	10-31-1895
Liddle	10.00	01-04-1891
Carlson	16.00	12-01-1894
Peterson	164.00	03-01-1895
Settlers	89.00	12-13-1897
Batten	23.00	09-03-1894
Harmony No. 2	162.00	11-10-1898
Tamarack	134.00	04-23-1902
Harmony No. 1	450.00	11-10-1898
Long Island	54.50	02-10-1897
Hemming House	10.00	01-22-1897
Prewitt Reservoir	32,300 ac. ft.	05-25-1910
North Sterling Reservoir	64,446 ac. ft.	06-05-1908
Julesburg Reservoir	28,178 ac. ft.	02-12-1904

The priority and location interact in the legal subsystem to determine ditch diversions from the South Platte River. For example, consider the relationship between the Sterling No. 1, Pawnee, and the Iliff and Platte Valley ditches. The sequence of diversion priority is the Sterling No. 1, then the Pawnee, and lastly the Iliff and Platte Valley. The Sterling is located between the upstream Pawnee and the downstream Iliff and Platte Valley. The Sterling No. 1 with its senior right diverts water throughout the growing season. But the Pawnee, even though its right is senior to the Iliff and Platte Valley, diverts relatively less water and then only before or after the critical portion of the growing season. The ditch location causes the deviation from the priority system. The senior Sterling No. 1, commanding most upstream flow, forces the Pawnee to pass up diversions but the Iliff and Platte Valley downstream divert the return flow.

In addition to the mainstream ditch in the study area, there are three reservoir irrigation districts, the Prewitt, the North Sterling, and the Julesburg. Prewitt and Julesburg reservoirs provide supplemental water to the ditches they serve. The North Sterling is the sole source of water for its member farms.

The Prewitt reservoir augments the water supplies of the South Platte, Pawnee, Davis Bros., Schneider, Springdale, Sterling No. 2, Bravo, Farmers, Iliff and Platte Valley, Lone Tree, Powell, Harmony Nos. 1 and 2, and Ramsey ditches. Storage water is available on demand with the amount each ditch can divert varying with the current storage and the number of reservoir shares the ditch owns. The storage capacity of the Prewitt reservoir is 27,000 acre feet. Losses to evaporation or seepage average 67 percent per year. Spring runoffs usually fill the reservoir at the beginning of each irrigation season.

The North Sterling reservoir has a storage capacity of 71,000 acre feet and is the primary source of water for the land north of Sterling, Colorado. It has storage rights and junior direct flow right, which permit filling only in the non-irrigation season. Even with the reservoir filled to capacity the supply can adequately irrigate only part of the total land available. While the reservoir itself is outside allow aquifer boundary, the inlet and irrigation canal system are porous, allowing seepage water to enter the study area.

The Julesburg reservoir is a mixed system. It is the only water source for the Julesburg high line ditch and it supplements river flows for the Peterson, Settlers, and Harmony No. 1 ditches. Spring and fall surface runoffs normally fill the reservoir to capacity.

Groundwater is a major irrigation water source in the study area. Irrigators on all ditches (except a few of those with most senior rights) own wells to supplement their water supply in July and August. Presently there are approximately 750 large-capacity irrigation wells (greater than 100 gal/min) within the study area. The aquifer underlying district 64 is estimated to contain 2.2 million acre feet of water with the average depth to water between 30 and 40 feet (Huss, et al., 1975).

The South Platte River Compact with Nebraska signed on April 27, 1923, substantially affects the water supply. The Compact provides that between April 1 and October 15 of each year, diversions downstream of the Balzac gauge with appropriations junior to June 14, 1897, shall not diminish the mean daily flow at the Julesburg gauge below 120 cfs (Radosevich, Hamburg and Swick, 1975). When the gauge drops below 120 cfs, Nebraska has the right to demand that junior ditches in Colorado cease diverting.

The Simulation Model

The simulation model combines the economic, legal, and hydrologic subsystems to measure the system's reaction to alternative groundwater regulations. The economic planning and short-run allocation model join to compute the overall net economic yield. This net value represents the market value of the agriculture output minus the variable costs of production and the institutional costs of capital inputs, administration, and operation and repair.

The legal subsystem models the surface and groundwater regulations controlling water allocations. The hydrologic model determines the amount of water in the South Platte River at various points (reaches) for subsequent time periods. Ten economic subareas, made up of homogenous farm operations, and 90 hydrologic reaches comprise the study area. Simulation covers a one-year period with four 30-day sub-periods (May 15 to September 15), which represent the summer growing season.

A simulation run consists of the following steps:

1. The economic planning routine prior to the growing season specifies the crop acreage in each subarea. These acres become land and crop acreage constraints in the monthly short-run allocation routine.

2. The legal routine given historical surface water inflow at the Balzac gauge allocates the water to each sub-area according to the existing water regulations. The ground and surface water quantities each subarea can use become water constraints in the monthly short-run allocation routine.

3. The monthly short-run allocation routine decides which irrigation schedule to follow, given the activity constraints, costs, and revenues. Simulated ditch diversions, pumping rates, and applied irrigation quantities become inputs to the hydrologic subroutine.

4. The hydrologic routine calculates the amount of water in the river at each reach using the following flow equation;

$$\begin{aligned} Q_{i+1}(t) &= Q_i(t) - \sum_{v=1}^{t} \sum_{p=1}^{P} \epsilon_{ip}(t-v+1)\cdot W_p(v) \\ &+ \alpha \cdot \sum_{v=1}^{t} \sum_{r=1}^{R} \epsilon_{ir}(t-v+1) \cdot [G_r(v) + S_r(v)] \end{aligned} \tag{17}$$

where $Q_i(t)$ = the flow into reach i during time period t (t=1,2,3,4).
Note: $Q_1(t)$ = inflow to the study area.

P = the total number of pumping wells.

$_{ip}(v)$ = the effect of pumping (or recharge) at well p or farm area r on reach i for time (v-1) units after the pumping began.

$W_p(v)$ = pumping rate for well p for time period v.

α = the percentage of applied water recharging the aquifer (50 percent).

R = the total number of farm operations.

$G_r(v)$ = the applied groundwater to farm area r during time period v.

$S_r(v)$ = the applied surface water to farm area r during time period v.

5. Begin the next time period allocating the flow by the legal routine plus or minus the previous periods diversion and pumping effects on the river.

6. The last step is to recall the net revenues for each subarea over the simulated period, deduct the relevant institutional costs, sum the results for all subareas and determining the present value of the net economic yield. Alternative regulations are compared according to the efficiency criterion.

As is necessary with all models, we made some simplifying assumptions about the physical, economic, and hydrologic conditions. All the economic requirements for perfect competition must hold in order to rank the water institutions by the criterion of economic efficiency. The model assumes homogenous farm units, known production functions, and constant prices and costs. The physical characteristics of the study area are also assumed to remain constant. The simulation includes the exact number of wells, surface diversions, and farm acres. These physical conditions do not change over the simulated period. The relevant hydrologic assumptions pertain to the timing and duration of the effect on the river due to pumping or surface irrigation. In an actual river system, pumping simultaneously causes draw down in the stream flow. Modeling that type of system is at present beyond the scope of our resources. To circumvent this problem, we assume that the effect on the river has a one-period time lag. This assumption is valid if the epsilon in any one time period $(\epsilon_{ip}(1))$ is relatively small compared to the sum of all the remaining epsilons

$$\left[\sum_{\nu=2}^{t} \epsilon_{ip}(\nu)\right]$$

which seems to be the situation in the study. It is also true that pumping in this year continues to influence stream flow in subsequent years. At present little is known about the magnitude of this effect. We assume winter snows and spring runoff replenishes the aquifer such that any carryover influence is insignificant.

Policy Alternatives

The simulation model has the ability to generate economic outcomes and water use patterns under various conjunctive use water policies and/or under differing water availability assumptions. The results will reveal useful insights about the effects on farm income from changes in water management policies during years with normal water supplies and years with scarce water supplies.

A number of institutional changes could provide a solution to the externality problem caused by groundwater mining. The externality is a reduction in surface water previously available for senior surface right holders. Taxes or charges on groundwater mining might produce revenues to bribe the surface water users into accepting the externality. Legal constraints or standards could limit the externality pumpers create and quotas on groundwater withdrawals directly reduce the externality producing action. Centralized control in the form of public districts are examples of public cooperative solutions to the problem. The public agency could allocate the area's total water supply to farmers without regard to the source, ground, or surface. The public district could also control the criterion (equity, efficiency, etc.) on which to base the water allocations. While all these alternatives are interesting, Colorado has developed a different and unique solution to the problem, which forms the basis for this study. This new approach is the primary simulated water institution.

Colorado's solution is a market system in the form of the previously described augmentation plans. Two other water management policies provide benchmarks to measure the impact of the new Colorado system: 1) an unrestricted open access regulation and 2) a policy that prohibits any groundwater pumping.

CHAPTER 6

SIMULATION RESULTS

This chapter presents and interprets the results from each groundwater regulation and water supply condition simulation. The first section describes the water supply condition or groundwater institution that each model represents. The next section highlights the economic and policy implications concerning: l) Baumol-Oates depletable externalities, 2) market solutions to externalities and liability rules, and 3) the value of groundwater resources.

Groundwater Institutions and Water Supply Conditions

Five different groundwater regulations or policies govern ground and surface allocations. Policy l provides a benchmark solution where a governmental agency or aquifer characteristics completely prohibit groundwater pumping. Policy 2 represents unrestricted groundwater use. Policies 3, 4, and 5, model Colorado's augmentation plans.

In addition to groundwater policies, the river flow into the study area has a major impact on irrigation net benefits and water use patterns. Actual surface water discharge in the South Platte River Basin can vary from relatively large stream flows to extremely dry conditions, as illustrated by 1977's insufficiency followed by 1978's large surface water runoff conditions. If surface water supplies entering the study area at the Balzac gaging station exceed an average inflow, the groundwater externality will be less and the net farm income larger compared with an inflow below the average. Farmers who own senior surface rights will pump less and use more of the relatively less expensive surface water. Irrigators who must still pump groundwater will replace less surface water due to fewer senior right calls on the river. In a drought, groundwater withdrawal drastically increases, causing the externality to worsen. Simulated results show that an institutional change solving the externality problem is much more valuable under drought conditions.

To capture the impacts from various surface water supplies, we simulated each state under two water inflow conditions. The 1968 growing season was one of the driest on record, and the actual inflows are used to represent a drought situation. The average flows over the available period of record (1955-1968) represent the other surface water supply condition. Table 7 shows the two water inflow situations:

Table 7 Simulated Water Inflows at Balzac Gaging Station.

Period	Average		Dry	
	CFS	Ac. Ft.	CFS	Ac. Ft.
1	800	47,600	122	7,261
2	600	35,700	130	7,738
3	275	16,363	143	8,511
4	250	14,875	148	8,809
Totals	1,925	114,538	543	32,319

In addition to the "average" and "dry" water inflow conditions, two different surface water priority sequences were analyzed: the "actual" and "reversed" priority orderings. The initial study region contained the South Platte River and its aquifer from the Kersey gaging station, located near Greeley, to the Colorado state border with Nebraska. The data from the three gaging stations: Kersey, Balzac, and Julesburg would provide the necessary inflow data. Like all research efforts, this one has limited time and money resources forcing the selection of a smaller study area. The choice was between the region between the Kersey and Balzac gaging stations or the area between the Balzac and Julesburg gaging stations. The logical choice, at that time, was the area between Balzac and Julesburg. Since this region was the furthest downstream reach in Colorado, we reasoned that it would experience the greatest impact on surface flow from all the upstream pumping.

This logical conclusion did, however, lead to an unexpected bias in the results. Once selected, the area in the model becomes isolated from the effects of any groundwater pumping above the Balzac gaging station. Only pumping in the specified study region can influence modeled stream flows. The groundwater externality reflects on the withdrawal rate and location within the reach relative to senior surface right holders and not the magnitude of upstream pumping outside the study area. Only after the hydrologic model was developed did we learn that in the Balzac-Julesburg region most groundwater withdrawals occur downstream of the senior surface users.

To compensate for the possible bias that the locations of surface diversions and groundwater mining has on the predicted outcomes, the model was also solved with a "reversed priority" sequence. The reversed simulation runs change upstream senior surface rights into junior rights, while the downstream junior rights become senior ones. This reversed system, although hypothetical, is expected to capture the externality ground water users might impose on other water users since large scale pumping takes place upstream from senior surface water irrigators.

POLICY 1 - Zero Groundwater Pumping

Policy 1 models water regulations that completely prohibit ground water use. This policy, eliminating any external effects, provides benchmark net benefits to compare against the other alternative states. The economy in the study region depends heavily on groundwater use, especially in dry years. This dependency makes the choice of Policy 1 as a solution to the externality problem both politically and economically unwise.

POLICY 2 - No Restrictions on Groundwater Pumping

Quite common in the early use of a common pool resource is an unrestricted or open access management strategy. Prior to 1950, the only constraint on groundwater use in Colorado was the individual's own ability and resources to drill a well. Once in place he could pump as much as his well physically permitted. In essence, any farmer had an implicit right to drill and withdraw water from the aquifer. During the 1950's and '60's, laws were passed requiring farmers to register their existing wells and apply for a permit to drill a new well. The State Engineer could in some instances deny the right to drill but rarely exercised that option.

Unrestricted access creates an environment where groundwater users are completely free of any responsibility for any external impact caused by their pumping. Senior surface right owners under this zero liability rule can either bribe groundwater users to reduce their pumping rates or seek help from existing political entities. This water institution can lead to efficient water use if the withdrawal rate is relatively low and the resulting externality is small, when compared to large transaction or regulation costs to eliminate the external effect.

POLICY 3 - 5 Percent Surface Water Replacement Augmentation

During the 1960's, water managers began to recognize that an unrestricted groundwater policy generated excessive withdrawals and possible injury to senior surface water users. The State Engineer tried various water regulation changes, each limiting pumping rates, but the courts of Colorado rejected the early attempts to control groundwater use. Finally, in 1969, the State Engineer acquired the legislative power and court approval to limit new drillings and regulate existing wells. Presently, the State Engineer permits new wells only if the applicant proves his well is non-tributary to any stream. Farmers owning existing wells can continue to utilize the aquifer only if they join an augmentation plan.

Policy 3 models the largest augmentation plan, Groundwater Users Association of the South Platte (GASP). GASP is a user's cooperative that, acting for member groundwater users, obtains water rights to augment surface supplies. Augmentation plans must have the ability to replace five percent of member farmer's annual groundwater use. GASP fulfills this requirement primarily by leasing or purchasing upstream storage and surface water rights. Policy 3 replicates GASP by including in both the planning and operating linear programs a number of water purchase activities. These activities represent the water supply function faced by the GASP members in the study area.

The supply function for water determines the prices and associated replacement surface water quantities. We assume the water supply curve is of conventional shape, with the price a direct positive function of the needed replacement water quantities. Those who control the water supply sell additional surface water only at higher prices.

Most research uses either positive or conditionally predictive techniques to estimate supply functions (Shumway and Chang, 1977). The two procedures using different analytical tools and data sets generally differ in their estimates. The positive estimate uses linear regression and historical data to predict future responses. Conditional predictive techniques employ synthetic and parameter data to structure future outcomes. Positive estimates relying on past information are accurate only if the underlying structure remains stable. Linear programming, however, has the ability to incorporate the effect of policy changes where historical observations are unavailable. This flexibility and the lack of actual supply-price information are the primary reasons for using linear programming to estimate the water supply function.

The surface water supply function is derived from an L-P that models the entire irrigated area upstream from Balzac. The model also includes water "selling" activities to predict the quantity of water sold and that used on crops. Model constraints approximate the total surface water supplies and acreage of irrigated land in the upper South Platte River Basin, above the study area. Parametric increases in the selling prices of surface water cause the upstream area model to sell more surface water.

Observe that for a linear supply both TSC and TE are non-linear. For example, if the demand for water is:

$$P_w = a + bq_w$$

where P_w and q_w are price and quantity of water supplies respectively, then

$$TE = aq_w + bq_w^2$$

$$TSC = aq_w + 1/2bq_w^2$$

$$PW = MC \ = a + bq_w$$

where TE is the total expenditure, TSC is the total social cost and MC represent the marginal social cost. The linear programming planning and monthly models in the simulation program include the direct segmentation of TSC instead of the supply curve. TSC is a negative component of the objective function. Any point above the curve is inefficient. Notice that the solution to the problem with the linear supply is the same if the actual price and quantity bought were known and included as an activity in the model. The objective function where both price and quantity are known a priori equals;

$$\max \pi = \sum_i P_i X_i - \sum_i C_i X_i$$

where P_iX_i is the total benefit; C_iX_i total cost. The objective function with a linear supply, and nonlinear TSC is

$$\max \pi = \sum_i P_i X_i - \sum_i TSC(X_i).$$

The principle advantage of a piece-wise approximation is that by adding only two extra constraints and eight activities, the model estimates the total social cost. One constraint insures that only adjacent activities enter the solution, the other guarantees the convexity requirement of linear-programming (Duloy and Norton, 1975).

The respective equations are:

$$P = 0.0372\ Q$$

$$TE = 0.0372\ Q^2$$

$$TSC = 0.0186\ Q^2$$

where Q: acre feet of water

POLICIES 4 and 5

Policies 4 and 5 resemble Policy 3 except for the required replacement percentage. Policy 4 stipulates that groundwater users replace 25 percent of their annual withdrawals; Policy 5 calls for 50 percent replacement.

For easy reference, we combined the results into Tables 8 through 11. Each table shows the net benefits and water use under the five alternative groundwater regulations (no restriction to 50 percent replacement requirement). Tables 8 and 9 illustrate the model of the existing priority sequence for "average" and "drought" surface water supply conditions respectively. Tables 10 and 11 present model results for a reversed priority ordering also during an "average" and "dry" year.

Table 8 Net Economic Benefits and Water Use, under Typical Water Conditions and Actual Priority System, Lower South Platte River Valley, Colorado

Policy 1: No Groundwater Pumping			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	0	0	0
2	1,378,638	12,332	0
3	1,059,533	2,510	0
4	1,057,167	6,226	0
5	4,272,263	34,620	0
6	2,297,096	19,521	0
7	1,718,990	8,567	0
8	60,187	210	0
9	1,573,967	3,376	0
10	741,445	1,658	0
11	1,674,389	7,759	0
Totals	15,833,675	96,779	0

Policy 2: Open Access, No Restrictions on Groundwater Pumping			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,759,264	0	87,123
2	1,380,185	12,323	0
3	3,212,676	13,740	15,090
4	1,144,279	4,055	4,055
5	4,369,260	31,477	7,487
6	3,059,811	20,034	6,389
7	2,907,929	9,984	12,549
8	1,044,224	2,614	5,660
9	3,020,812	4,730	12,117
10	3,029,676	4,489	22,008
11	3,417,784	6,399	24,449
Totals	37,345,900	109,845	196,927

Table 8. (Continued)

Policy 3: 5 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,738,349	0	87,123
2	1,380,182	12,332	0
3	3,213,172	14,145	14,686
4	1,145,058	6,642	3,665
5	4,384,370	38,924	41
6	3,057,826	18,880	8,428
7	2,888,251	8,645	13,352
8	1,030,714	1,993	5,744
9	3,020,430	4,730	12,117
10	3,028,755	4,490	22,008
11	3,416,813	6,531	24,317
Totals	37,303,920	117,312	191,481

Policy 4: 25 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,562,473	0	87,123
2	1,380,090	12,332	0
3	3,241,785	28,832	0
4	1,152,603	10,307	0
5	4,382,123	38,966	0
6	3,055,175	21,250	6,020
7	2,923,005	17,613	7,051
8	1,043,916	2,983	5,483
9	3,042,326	6,390	12,117
10	3,010,426	5,068	20,436
11	3,392,315	6,547	22,900
Totals	37,186,237	150,288	161,130

Table 8. (Continued)

Policy 5: 50 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,177,192	0	76,592
2	1,379,996	12,332	0
3	3,240,108	28,833	0
4	1,152,603	10,307	0
5	4,379,712	38,967	0
6	3,054,391	25,382	2329
7	2,950,677	25,870	868
8	1,055,119	5,174	3859
9	3,082,916	12,475	11118
10	2,977,844	5,694	16931
11	3,366,144	9,550	15907
Totals	36,816,702	174,584	127,604

Table 9 Net Economic Benefits and Water Use, under Drought Conditions and Actual Priority System, Lower South Platte River Valley, Colorado

Policy 1: No Groundwater Pumping			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	0	0	0
2	1,378,638	12,332	0
3	574,253	0	0
4	872,025	2,618	0
5	3,717,355	13,898	0
6	1,324,691	6,250	0
7	1,256,015	3,446	0
8	56,942	0	0
9	1,231,149	0	0
10	550,908	0	0
11	804,669	1,195	0
Totals	11,766,645	39,739	0

Policy 2: Open Access, No Restrictions on Groundwater Pumping			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,759,264	0	87,123
2	1,380,185	12,332	0
3	3,192,920	2,673	26,156
4	1,147,038	4,935	5,368
5	4,323,102	8,850	30,114
6	3,022,658	2,371	24,916
7	2,815,467	718	17,037
8	1,026,833	0	7,737
9	3,044,410	0	16,156
10	3,020,518	0	26,498
11	3,405,025	57	30,790
Totals	37,137,420	31,936	271,895

Table 9. (Continued)

Policy 3: 5 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,738,349	0	87,123
2	1,380,182	12,332	0
3	3,192,132	2,733	26,096
4	1,146,361	4,663	5,640
5	4,340,662	17,725	21,239
6	3,031,007	6,742	20,568
7	2,814,991	718	17,037
8	1,026,612	0	7,737
9	3,003,950	0	16,156
10	3,019,262	0	26,498
11	3,403,314	57	30,790
Totals	37,096,822	44,970	258,884

Policy 4: 25 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,562,473	0	87,123
2	1,380,090	12,332	0
3	3230271	23,568	4,710
4	1154810	9,273	1,031
5	4374553	36,052	2,914
6	3028537	11,889	14,177
7	2815038	1,448	17,044
8	1020209	0	7,737
9	2990616	0	16,156
10	2994378	0	25,245
11	3372222	57	29,389
Totals	36,923,197	94,619	205,526

Table 9. (Continued)

Policy 5: 50 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,177,192	0	76,592
2	1,379,996	12,332	0
3	3,226,274	24,119	4,714
4	1,153,733	9,272	1,032
5	4,370,505	36,050	2,917
6	3,045,062	22,956	3,335
7	2,926,605	16,956	8,155
8	1,026,306	520	7,737
9	2,966,310	0	16,156
10	2,950,633	0	22,603
11	3,322,376	57	24,399
Totals	36,544,992	122,262	167,640

Table 10 Net Economic Benefits and Water Use, under Typical Water Conditions and Reverse Priority System, Lower South Platte River Valley, Colorado

Policy 1: Zero Groundwater Pumping			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	0	0	0
2	336,904	752	0
3	302,243	857	0
4	791,724	3,366	0
5	1,161,297	2,556	0
6	434,386	2,167	0
7	702,767	1,579	0
8	276,200	534	0
9	3,196,180	28,580	0
10	3,050,108	27,498	0
11	3,433,768	31,034	0
Totals	13,685,577	98,923	0

Policy 2: Open Access, No Restrictions on Groundwater Pumping			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,759,264	0	87,123
2	1364791	2016	10313
3	3191778	4714	24118
4	1152984	6674	3627
5	4310250	6375	32041
6	3028767	6114	21197
7	2821054	4407	13352
8	1047555	4592	4080
9	3189549	27762	0
10	2997782	24056	0
11	3344074	25885	0
Totals	37,207,848	112,595	195,851

Table 10. (Continued)

Policy 3: 5 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,738,349	0	87,123
2	1,364,485	2,016	10,313
3	3,190,613	4,714	24,118
4	1,152,869	6,675	3,627
5	4,308,138	6,676	32,039
6	3,028,036	6,114	21,197
7	2,820,629	4,407	13,352
8	1,047,479	4,592	4,080
9	3,196,180	28,580	0
10	3,047,922	27,791	0
11	3,435,304	31,213	0
Totals	37,330,004	122,778	195,849

Policy 4: 25 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,562,473	0	87,123
2	1,355,845	2,021	9,748
3	3,167,108	4,728	22,795
4	1,150,685	7,038	2,794
5	4,271,823	6,397	30,237
6	3,028,502	13,054	13,014
7	2,817,958	5,009	13,352
8	1,078,655	9,645	0
9	3,196,180	28,580	0
10	3,049,360	27,623	0
11	3,437,392	30,865	0
Totals	37,115,981	134,960	179,063

Table 10. (Continued)

Policy 5: 50 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,177,192	0	76,592
2	1,346,743	2,026	9,745
3	3,125,064	4,754	20,723
4	1,147,719	7,040	2,793
5	4,212,268	6,432	25,200
6	3,018,983	16,417	10,000
7	2,813,356	5,864	13,352
8	1,078,655	9,645	0
9	3,196,180	28,580	0
10	3,050,464	27,439	0
11	3,437,392	30,865	0
Totals	36,604,016	139,062	158,405

Table 11 Net Economic Benefits and Water Use, under Drought Conditions and Reverse Priority System, Lower South Platte River Valley, Colorado

Policy 1: No Groundwater Pumping			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	0	0	0
2	250,479	0	0
3	238,039	0	0
4	449,214	0	0
5	867,542	0	0
6	143,900	0	0
7	521,387	0	0
8	145,982	0	0
9	3,058,896	16,125	0
10	2,962,492	20,090	0
11	2,910,298	13,662	0
Totals	11,548,229	49,877	0

Policy 2: Open Access, No Restrictions on Groundwater Pumping			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,759,264	0	87,123
2	1,373,932	6,536	5,231
3	3,182,162	0	28,832
4	3,155,700	8,012	2,214
5	4,297,246	0	38,415
6	3,022,358	4,014	23,297
7	2,812,064	0	17,759
8	1,036,248	0	7,737
9	1,960,392	3,742	0
10	2,095,765	8,914	0
11	1,420,866	3,169	0
Totals	35,115,997	34,387	210,608

Table 11. (Continued)

Policy 3: 5 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,738,349	0	87,123
2	1,369,404	4,406	7,923
3	3,180,645	0	28,833
4	1,153,672	7,094	2,738
5	4,294,657	0	38,415
6	3,020,072	3,428	23,883
7	2,811,557	0	17,759
8	1,036,067	0	7,737
9	3,113,054	19,703	0
10	2,881,253	15,551	0
11	1,751,994	5,270	0
Totals	35,350,724	55,452	214,411

Policy 4: 25 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,562,473	0	87,123
2	1,350,844	95	11673
3	3,152,185	0	27523
4	1,148,530	6,238	3779
5	4,251,634	0	36634
6	2,997,497	3,436	22635
7	2,796,839	0	17766
8	1,071,449	5,465	3651
9	3,194,905	28,201	0
10	2,988,938	20,702	0
11	2,920,166	15,046	0
Totals	36,435,460	79,183	210,784

Table 11. (Continued)

Policy 5: 50 Percent Surface Water Augmentation			
Subarea	Net Benefits ($)	Surface Water (ac. ft.)	Groundwater (ac. ft.)
1	10,177,192	0	76,592
2	1,352,779	3,922	7,848
3	3,100,493	0	24,968
4	1,146,939	6,793	3,041
5	4,179,715	0	36,439
6	2,973,733	7,748	16,994
7	2,770,895	85	17,781
8	1,076,292	8,064	1,580
9	3,194,905	28,201	0
10	3,055,302	27,436	0
11	3,400,875	28,353	0
Totals	36,429,120	110,602	185,243

Economic and Policy Implications

Depletable Externalities. The South Platte conjunctive water use problem is seen to provide an actual and significant example of a Baumol-Oates depletable externality. A depletable externality has the private good characteristic of rival consumption. As an individual consumes more of the externality, the amount available for everyone else is reduced. The absence of a well-structured property rights system makes it difficult to establish an appropriate pricing arrangement and usually causes a depletable externality. Baumol and Oates' conjecture that suitable property institutions and a competitive market will eliminate the externality if the potential gains exceed the transactions costs of collecting a price for the externally produced good. Conversely, if the costs of charging a fee exceeds the gain or if the externality has minor economic impacts, the depletable externality will persist.

In Colorado, the South Platte River-aquifer hydrologic interdependence and the lack of well-defined property rights to water had resulted in a depletable externality. Prior to 1969, Colorado ignored groundwater, in effect, treating it as a common property resource. Farmers had free access to the aquifer underlying their land without charge. Since pumping reduced expected surface flows, thereby changing relative water property rights, the farmer using groundwater, in effect, received a more senior prior water right than the legally defined senior surface rights. This condition represented a depletable negative externality where reduced stream flows have rival good characteristics. If individual farmer maximization of groundwater use leads to inefficient pumping rates, the economic solution is easy: create expedient property rights and pricing procedures.

Assuming Colorado water managers want to maximize net economic benefits, an incentive arises for altering the inefficient water allocation. The deceptively simple solution is to define the water rights and create a suitable price structure that insures that the farmer operate where the MSC equals the VMP. Colorado could charge a fee or tax equal to the difference between the MPC and MPS or it could restrict groundwater using a quota equal to the efficient pumping level. A major problem with these approaches is that both solutions require information about each individual farmers' VMP curve and cost curves.

Colorado's unique quasi-market system, augmentation plans, avoid these burdensome information requirements. The individual farmer who uses groundwater must replace into the stream surface water equal to a proportion of his withdrawals, the proportion equalling the hydrologic impact during the irrigation season. The farmer, knowing his own VMP, continues to pump as long as the benefits from an additional groundwater use exceeds the augmentation costs plus his own pumping costs. This system, recognizing senior surface water users prior rights to the available water sources, forces groundwater users to pay for the external costs created by their pumping. This clarification of property rights to water resources and the market price for supplemental replacement surface water can yield an efficient solution to the depletable groundwater externality. Note, however, that some pumping rates and/or physical characteristics may cause augmentation costs to exceed the external surface flow damage. In such instances, the continuation of undepletable externality can lead to efficient conjunctive water use.

Simulation Solutions Representing Actual Priorities. In the first simulation runs, representing the actual priority system, with an average water inflow situation, predicted net farm income indicates that the present depletable groundwater externality is insignificant and should probably continue uncorrected (Table 8). Each simulated augmentation plan slightly reduces area net benefits compared with benefits from an open access management policy. The 5 percent replacement augmentation plan reduces net benefits by $41,983 (.1 percent), the 25 percent replacement lowers net benefits by $159,629 (.4 percent), and the 50 percent replacement requirement decreases net benefits by $529,200 (1.4 percent).

The augmentation plan, while eliminating the depletable externality through purchase of supplemental surface water, produces an inappropriate price structure. Groundwater prices under the new institution (equal to the cost of pumping, cost of obtaining replacement surface water, plus GASP operating and transactions costs) exceed the price equating marginal social cost of pumping and the marginal benefit. The external damage to surface water right holders is so slight that an open access policy comes very close to maximizing social benefits.

Simulating drought conditions and the actual priority system reveal results similar to the average water input simulations (see Table 9). The 25 and 50 percent surface water replacements generate net benefits smaller than those under the open access institution by $174,223 (.5 percent) and $532,427 (1.5 percent). The five percent replacement, however, shows essentially no reduction in the area net benefits. An augmentation percentage between the private price and the five percent augmentation price could result in maximum social net benefits.

Specific model assumptions and actual well locations in the study area tend to underestimate the true external impact of groundwater on surface flows. Because most pumping in the study area occurs downstream from the major senior ditches, they have a small economic impact; senior surface water users suffer only minor reductions in stream flows. Pumping effects those economic subareas having junior surface rights already making it improbable that they would receive surface water under any water inflow conditions. Modeling only the area between Balzac and Julesburg ignores any impact from pumping above Balzac and any impact pumping has on Nebraska farmers.

Actual well development in the study area may also bias the results. All simulations use the actual well location listed on the State Engineer's well listing. Following this listing, the model includes a large number of wells in each economic subarea. This aggregation implicitly assumes that every individual farmer has previously invested in groundwater as an alternative to surface water. Since all farmers can meet crop needs using groundwater, the externality cost in terms of the economic impacts from reduced stream flows becomes insignificant. Any net income reduction results from the difference in price between surface water and groundwater as farmers who have less surface water simply turn on the pumps. Assuming away the sunk costs, the price of surface water is $.50/ac. in. with the price of groundwater being $.67/ac. in.; a difference of $.17. This difference is much less than the lowest replacement price, $.37/ac. in.

The huge investment in wells, especially by farmers who own senior surface water rights, represents a private solution to the depletable groundwater externality problem. Farmers owning senior surface water rights who had historically received water even in dry years found that as others drilled wells they could no longer depend on their surface right. Recognizing the implicit property right of groundwater over surface water, those with surface right also turned to groundwater. The benefits of owning a certain water supply were substantially greater than the costs of developing a well. Given the current groundwater capacity, the analysis will, of course, suggest that the optimal solution is not to restrict pumping and continue to permit the insignificant depletable externality. But, this policy ignores one very important development. The private solution where everybody invests in groundwater produced a substantial redistribution of income away from the surface water users who, due to groundwater use or in the absence of any externality solution, had to make large capital outlays for wells to supplement a previously certain surface water supply.

Simulation Results Representing Reversed Priorities. The reversed priority simulations, which are representative of the basin as a whole, dramatically illustrate a Baumol-Oates depletable externality and the ability of well-defined property institutions and appropriate resource prices to generate the optimal conjunctive water use allocation. Reversing the ditch priorities locates senior water right ditches at the lower end of the study area, downstream from the majority of the pumping. In addition, we assumed three ditches represented as subareas 9, 10, and 11 can use only surface water supplies for irrigation. These changes, avoiding the problem when all farmers own and use groundwater as a substitute for uncertain surface supplies, explicitly reveal the impact pumping has had on the incomes of senior surface right owners.

Unlike actual priority simulations, in the reversed models, defining property rights and establishing correct groundwater prices, shows that the augmentation plan maximizes net social benefits. In an average water inflow year, the five percent replacement requirement augmentation plan produces the largest net benefits (Table 10). Assuming that the reversed priority-average water supply models represent the more typical conjunctive water use situation, surface water users claims of injury are correct. The open access groundwater management reduces maximum area net benefits by $122,157.

Changes in net benefits of subareas 9, 10 and 11 (or from now the "tri-area") who can't substitute groundwater for surface water clearly illustrate the depletable groundwater externality. In the State 1 simulation where pumping is prohibited, farmers in the tri-area diverted 87,112 ac. ft. of surface water to produce crops worth $9,680,056. The open access simulation, which permits unlimited groundwater withdrawals, decreases surface flows to the tri-area by 9,409 ac. ft. (11 percent), which in turn reduces net benefits by $148,651 (1.5 percent). The average externality cost per ac. ft. of pumped groundwater imposed on the tri-area farmers under State 2, open access, institution is the difference between State 1's and State 2's tri-area net benefits divided by the total groundwater withdrawals ($148,651 -: 195,851 ac. ft. = $.76/ac. ft.). The 5 percent augmentation plan corrects the depletable externality by returning the tri-area surface diversions and net benefits to pre-ground water pumping levels.

Even though the differences in the tri-area benefits with and without augmentation plans seem trivial they do conform to actual experiences in the South Platte basin. Dugan Wilkerson, Division Water Engineer, in a January 1977 interview stated that prior to the current drought, the surface replacement requirement was approximately one percent to three percent. His statements and the model results are both consistent with the supposition that during years with average runoffs the groundwater externality is small.

Low surface water flows drastically magnify the depletable externality problem. Among all drought condition simulations, the 25 percent augmentation plan pricing system maximizes the social net benefits (Table 11). The 50 percent, 5 percent, and open access management policies reduce area benefits by $1,006,340 (2.7 percent), $1,084,736 (3 percent), and $3,319,463 (9 percent), respectively. During drought years, augmentation plans will make meaningful contributions to net incomes and substantially end the depletable externality problem.

Again, analyzing the tri-area reveals the large negative externality, and benefits from a quasi-market solution for farmers who don't own wells. Table 12 summarizes the effect of pumping on net benefits and surface water supplies of the tri-area. The benchmark solution, Policy 1, doesn't allow pumping, and accordingly there is no externality. The 25 percent augmentation plan almost exactly compensates the tri-area for the loss in benefits due to pumping (2 percent increase from benchmark net benefits). The most inefficient solution is an open access, common property institution. This policy reduces tri-area net benefits by $3,454,663 or 39 percent. The average externality cost from an open access groundwater policy on the tri-area is equal to $16.40 per ac. ft. of groundwater withdrawn from the aquifer.

Table 12 Tri-Area Net Income and Surface Water Estimates under Reversed Priority--Dry Water Inflow Conditions.

State	Net Income	Change in Net Income		Surface Water	Change in Surface Water Diversions	
	($)	($)	(%)	(ac. ft.)	(ac. ft.)	(%)
1	8,931,686			49,877		
2	5,477,023	-3,454,663	-39	15,825	-34,052	-68
3	7,746,301	-1,185,385	-13	40,524	- 9,353	-19
4	9,104,009	172,323	2	63,946	14,072	28
5	9,651,082	219,396	8	83,990	34,113	68

Simulating an open access state and constraining groundwater pumping down to zero withdrawals approximated the groundwater depletable externality. The total damage externality, in the form of smaller incomes to the tri-area, is equal to the net benefits in the absence of pumping minus the net income when upstream farmers use their groundwater resources. Table 13 illustrates the predicted external damage at 1/8, 1/4, 3/8, 1/2, and 3/4 of the maximum groundwater constraint. The curve is non-linear since the hydrologic function determining the reduction in stream flows is non-linear. The external cost somewhat unexpectedly decreases as groundwater withdrawals increase. Farmers using the added pumping capacity late in the growing season have a smaller impact on stream flows due to the time lag before pumping reduces surface flows.

The results show the economic and policy insights revealed by the reversed priority drought simulation. The MPC is constant at the $.67 price in the linear programming model. The marginal externality cost curve is the first derivative of the total externality cost function. Adding the MPC and externality cost curves vertically generates the MSC curve. The VMP is the value of groundwater to all farmers upstream of the tri-area. At the private and five percent augmentation plan groundwater prices, farmer's excessive pumping decreases the tri-area

Table 13 Tri-area Net Income and Surface Water under Alternative Upstream Pumping Rates (Reversed Priority--Dry Water Inflow Condition).

Groundwater Constraint	Net Income	Change in Net Income	Surface Water	Change in Surface Water	Upstream Pumping
	($)	($)	(ac. ft.)	(ac. ft.)	(ac. ft.)
0	8,931,686		49,887		0
1/8	7,996,412	-935,274	35,103	-14,774	39,109
1/4	7,090,556	-1,841,130	27,014	-22,863	75,541
3/8	6,602,012	-2,329,674	23,370	-26,507	110,794
1/2	6,222,048	-2,709,638	20,192	-29,685	140,377
3/4	5,807,668	-3,124,018	17,800	-32,077	180,353
Full	5,477,023	-3,454,663	15,825	-34,052	210,608

net benefits (MSC $\geq$ VMP). The optimal conjunctive use of water occurs at a price approximately equal to the 25 percent plan price where MSC equals the marginal private benefits of groundwater.

Market Solutions to Externalities and Liability Rules. Among the solutions—taxes, quotas, standards, etc.—to externality problems, academic economists tend to favor market solutions. The Coase theorem demonstrates that given a two-party externality, zero transactions costs, and perfect competition, regardless of which party is responsible for the externality, market exchanges will exhaust all possible gains. According to Coase (1960), the Pareto optimal final market resource allocation is not a function of what liability rule might be in operation.

Randall (1972) proved that Coase's theorem may not be neutral with respect to liability rules. If transactions costs exist, a change in the legal responsibility for the externality will alter the income budget constraints of all parties, which then induces shifts in the demand and supply of externality abatement. The level of the activity producing the externality will be less under a full liability, where the externality producing party has responsibility for abatement, than in the absence of any liability. Randall's findings suggest that before markets solutions could progress toward eliminating the South Platte conjunctive use problem, Colorado had to make two changes. They needed to initiate institutional changes that switch the zero liability open access rule to one that approximates a full liability rule. Secondly, the state must establish institutions that lower the transaction costs of eliminating the groundwater externality.

The recent augmentation plans are efficient market solutions according to Randall's requirements. Augmentation plans switch the zero liability rule toward full liability as replacement percentages increase. These plans encourage farmers to form organizations such as GASP reducing the transactions costs of purchasing augmentation water. The results indicate the reduction in ground water use, the action producing the externality, in simulations of augmentation plans. If policy makers can alter property institutions to insure full liability rules, then they should consider market solutions to the groundwater and other externality problems.

Vernon Ruttan's (1977) theory of institutional innovation is given support by the analysis above. Ruttan hypothesized that institutional change occurs in response to shifts among the marginal benefits and marginal costs of alternative institutions. The increasing external costs of groundwater use in the South Platte provide the source of increased benefits of a market solution, and justifies incurring the transaction costs required to operate the system.

The Marginal Value of Groundwater Resources. One of the most fascinating questions in economics concerns value. Applied economists, policy makers, and others, are always asking: what is the value of a commodity or resource? Many individuals in Colorado, at least in the Platte River Basin, feel that groundwater is extremely valuable. Indeed, groundwater has dramatically increased the net income to farmers in the study area. Comparing Policies 1 and 2 simulations, the current configuration and pumping capacities of study area wells have at least doubled the net income to irrigators. Even though this tremendous increase in net benefits emphasizes the significance of groundwater resources, it doesn't measure its value.

In economics, the benefits from the marginal, or last additional, unit put to use determines its value. The value of groundwater equals the increase in net benefits from pumping and applying one additional acre foot of water. Modeling the actual priority ordering with a range of different groundwater constraints, yielded an estimate of the marginal value of groundwater use in the study area. Table 14 presents the results of these simulations.

Each simulation run increased the groundwater constraint by one-third until the last run, which modeled unrestricted groundwater pumping. The actual location and well capacity in the study area represents the upper

Table 14 Marginal Value of Increasing Groundwater Capacity.

Groundwater Constraint	Percent of Total Groundwater Capacity	Change in Groundwater	Net Benefits	Change in Net Benefits	Marginal Value
(ac. ft.)	(%)	(ac. ft.)	($)	($)	($/ac. ft.)
Average Water Inflows (Actual Priority)					
0	0		17,417,570*		
139,149	33	139,149	29,927,046	12,509,176	89.90
278,299	66	139,149	36,318,598	6,391,552	45.93
417,448	100	139,149	37,345,902	1,029,304	7.38
Dry Water Inflows (Actual Priority)					
0	0		13,465,563*		
139149	33	139,149	28,308,966	14,843,403	106.67
278229	66	139,149	35,856,370	7,547,404	54.24
417448	100	139,149	37,097,420	1,241,050	8.92

* Policy 1 net benefits from Tables 5 and 6 plus net benefits from dry land farming ($26/acre in 1974 dollars).

constraint on groundwater withdrawals (417,488 ac. ft.). Varying groundwater constraints do not exactly measure marginal value, it does approximate the average marginal value over the incremental change.

Even though groundwater produces a large increase in total area net income, the marginal value may be small. In both dry and average runoff years, the marginal value of the earlier groundwater pumping increases was quite large ($90/106 ac. ft.). But today, given the existing pumping capacity, additional groundwater pumping is only worth between $7 and $9 per acre foot. Decreasing marginal return characterizes resource use in most production activities; groundwater is not an exception to that rule.

CHAPTER 7

SUMMARY AND CONCLUSIONS

Summary

The Problem. In river basins where a major river is closely interconnected with an underground water supply (aquifer), groundwater users can impose an external cost on other farmers, which use surface water to irrigate their crops. Extensive groundwater withdrawals will eventually reduce stream flows, hence jeopardizing irrigation supply of senior surface water right owners. This externality, causing a divergence between private and social pumping costs, may lessen net economic product in the river basin. Water managers, in areas where groundwater development has created this undesirable effect, must select the optimal economic and legal institutions that recognize the physical and economic interdependencies.

In the terminology of Baumol and Oates (1975), one may describe the interdependency between farmers using groundwater and those using surface water as a "depletable externality." It is an "externality" since withdrawals from the aquifer directly influence the production function of senior surface water right holders without regard for the surface irrigator's welfare; "depletable" because the diversion of stream flows by one irrigator with surface rights reduces the externality, reduced stream flow, others can divert. The Baumol and Oates formulation and Randall's (1972) conceptualization regarding liability rules relating to external costs suggest that water institutions that correctly assign property rights and appropriately price the externality can lead to an efficient conjunctive use water allocation.

During Colorado's history, water managers have implicitly or explicitly attempted three solutions to conjunctive ground and surface water management. Before 1930, the low level of technology and high costs limited groundwater withdrawals to an insignificant amount. This implicit water policy, zero groundwater use, obviously did not create any spillover problems. Between 1930 and 1969, advances in well and pump technology and reductions in real energy costs resulted in a drastic increase in well use. However, water managers still chose not to regulate groundwater. By ignoring the groundwater externality and permitting unrestricted groundwater use, Colorado conjunctively managed tributary aquifers as open access resources. Any farmer that wanted to use the aquifer had the right to drill a well and pump at any rate. Open access management was the primary cause of excessive pumping and its associated externality. By the mid-1960's, depletion of stream flows from pumping became a major water policy issue. Finally, in 1969, Colorado passed a water management act, which facilitated a market-like solution, called "plans of augmentation" as a response to conjunctive water use difficulties.

Objectives of the Study. This report evaluates and compares Colorado's quasi-market system, plans of augmentation, with other conjunctive water use management policies in terms of the economic efficiency criterion. The optimal policy must recognize the physical and economic interdependencies that exist in a stream tributary aquifer system. The goal of the water policy is assumed to be maximum net income to the water resources. The optimal institution should be flexible enough to accomplish the goal with very high or very low stream runoff conditions.

Procedures. A simulation model evaluates the impact of alternative institutions on water allocations and corresponding net farm income. Even though any simulation necessarily simplifies the actual economic and physical systems, using a computer to analyze alternative water policies does have cost advantages over actual experimentation changing current regulations and observing the consequences. But because the simulation model is an abstraction and we compare just a few of the possible alternatives, the results can only approximate the true social optimum allocation of water supplies.

The interdisciplinary simulation model combines hydrology, economics, and the legal institutions to allocate water supplies. The economic subsystem models the individual irrigator's crop production decision making. Each year the farmer must choose what crops to plant, given the uncertain conditions surrounding eventual crop prices, weather, and water supplies. An intermediate-run linear programming planning model predicts farm cropping patterns, employing the Markowitz hypothesis concerning utility maximization under risk.

Throughout the summer, irrigators must decide which and how much to water their crops. A short-run allocation model, also a linear program, uses the acreage from the planning model and the historical record of surface water flows to optimally allocate ground and surface water supplies among alternative crops for each month of the four-month summer irrigation season.

The hydrologic model predicts stream flows at any point on the river in response to upstream inflows and groundwater pumping. Undeveloped streams and aquifers reach an equilibrium condition where aquifer recharge to the system is equal to the discharge from it. Any irrigation use of ground or surface water disturbs the natural equilibrium. In disequilibrium, water may flow from the stream into the aquifer or vice versa depending on pumping rates and location, surface diversions and the location of their application, rainfall, and actual stream runoff. The hydrologic model allows for effects of flows and pumping at one-mile intervals on a 20-mile by 90-mile grid.

The legal model representing the water allocation regulations allocates ground and surface water supplies to the economic subareas. Each economic subarea receives surface water according to the doctrine of prior appropriation as embodied in Colorado water law. Subareas with senior water rights divert surface flows first followed by junior right holders. The rights to groundwater use depend on the specific management policy being modelled. The benchmark management policy represents a conjunctive water use allocation according to the strict doctrine of prior appropriation. This policy would completely prevent any groundwater use due to its extremely junior appropriation right. No restrictions on groundwater use represent an open access management strategy. Other simulations model the augmentation plans embodied in recent statutory changes.

Study Area. The 90-mile reach of the South Platte River in northeastern Colorado from the Balzac gaging station to the Nebraska border is the study area. Farmers in the river valley grow irrigated corn, alfalfa, sugar beets, and pinto beans. Most irrigators own some surface water rights —only eight percent of the irrigated farms have well water as the single source. Among those farmers with surface water rights, 88 percent use wells as a supplementary water supply. Even though surface supplies are approximately equal to irrigation requirements, the distribution of the supply doesn't correspond to monthly crop needs so most farmers have invested in wells.

Conclusions

The Benefits of Conjunctive Water Use Management. Ground and surface water allocations according to a strict construction on the doctrine of prior appropriation in the South Platte River Basin will result in large economic losses to the study area. This inappropriate water policy ignores the temporal and spatial use relationship between ground and surface water. Because of the time and space lag between groundwater withdrawals and their eventual effect on the level of stream flows, forcing wells to close down in the event of shortage may not benefit surface water users.

The problem rests with the provision of the strict appropriation doctrine that prevents junior surface water right owners from changing their irrigation supply from surface flows to groundwater. This "no-injury" provision (Ditwiler, 1975) prevents any water change that might impose an injury on other users. Under the doctrine of prior appropriation, groundwater users could pump only if they could prove that their pumping would not cause any injury to surface flows—a very difficult and costly requirement.

This no-injury provision, effectively prohibiting groundwater use, places an implicit infinite value on senior surface rights. A relatively small part of the value equals water's productivity in crop production; the large remaining portion equals a security value of being able to divert surface flows, even during drought years.

Simulation runs with and without groundwater pumping provided a way to measure the security and production value of senior surface rights under a strict application of the appropriation doctrine. Without groundwater, predicted area net income decreased from $37 to $16 million in an average runoff year and $37 to $12 million in a dry year (Tables 8 and 9). Groundwater value is such that users would be willing to pay an average of $23 million/year—a present value of $195.8 million over 20 years with a 10 percent discount factor—for the right to withdrawal from the aquifer.

A change in water policy from the appropriation doctrine to open access, permitting any pumping remedies part of the conjunctive use problem by increasing area net income. But, it incorrectly prices the associated external effect of pumping at zero. The quasi-market water system, plans of augmentation, appropriately prices the externality and permits efficient water use.

Water Management and the Groundwater Depletable Externality. The simulation results confirm two major hypotheses concerning conjunctive water use in the South Platte River Valley.

1. Until the middle 1960's, Colorado's open access management policy governing groundwater use efficiently allocated water resources. The groundwater externality was small when compared to the regulatory costs or collection of appropriate compensation. Even with the number of wells existing today, if runoff is average or above, the decrease in incomes to farmers using only surface water to irrigate is slight under an open access policy. The difference between income

of farmers having only surface water for irrigation with or without any pumping in the study area (from Table 10) is only 1.5 percent.

Nonregulation can be consistent with economic efficiency. Any attempt to eliminate or reduce pumping external costs entails large transactions costs. The required compensation from groundwater users is less than the administrative costs of transferring the money to surface water right owners; reducing the external effect by limiting groundwater withdrawals would not reduce net incomes to groundwater farmers more than it would increase the net income of surface water right holders. Any attempt to alter the open access allocation would decrease net social welfare. Area farmers as a group are better off continuing to suffer some external effect rather than eliminating or reducing groundwater use.

2. If the South Platte Valley experiences summer drought and below average stream runoff during the growing season, unrestricted large-scale withdrawals from the aquifer will cause farmers using senior surface rights for irrigation to suffer substantial external diseconomies. The simulation shows that the net income of farmers with access only to surface water declines by 39 percent (Table 13) from a situation where there is no pumping (and, hence, no depletable externality) to one where groundwater use is unrestricted. Under these conditions occurring about once every ten years, the depletable externality is significant.

The simulation results indicate that Colorado's plans of augmentation are flexible enough to produce an efficient allocation of resources given any water supply condition. Only a normal runoff water supply condition produced a situation where area net income under an augmentation plan fell below an open access area net benefit. However, the difference was a slight .1 percent (Table 9). All other water supply and priority assumptions generated results where at least one augmentation plan produced area net income that exceeded the net income from an unrestricted policy.

This new management system is not only the best of those analyzed—it generates the greatest area net incomes using both water resources efficiently—but it effectively protects senior surface water right owners. Groundwater irrigators can continue to pump only if they submit and receive approval of a plan of augmentation that purchases, rents, or develops supplemental surface water. Water managers use the supplemental water to satisfy senior surface water rights, thereby replacing the loss in flow due to pumping. Simulation results of a dry year show that augmentation plans produce enough supplemental surface water so that senior water right holders receive net incomes equal to those in the absence of any pumping (Table 12). The additional augmentation pumping cost eliminates the socially inefficient over-use of groundwater, which can occur under an open access common property right system. Augmentation plans achieve a Pareto optimal position, equilibrating the marginal social cost of pumping with the marginal private benefit. However, this solution does require adequate upstream reservoir storage and a well-developed water market where groundwater users can purchase or rent augmentation water supplies.

Liability Rules and the Amount of a Depletable Externality. Economic theory (Randall, 1972) suggests that changes in the legal responsibility for an externality will induce shifts in the demand and supply of the action creating the spillover effect. The severity of a depletable externality will be less with a full liability rule where those producing the externality are responsible for abatement, than a legal environment where the externality producing party has no responsibility for the externality. The switch from an open access property right where groundwater users are not liable for their externality to augmentation plans where they are liable tests the economic theory. Again, simulation results support the conclusion that a full liability rule reduces groundwater use, thus decreasing the depletable externality.

Ruttan's (1978) hypothesis that institutional adaptations follow shifts in benefits and costs among various institutional alternatives is given support by the analysis.

The Marginal Value of Groundwater Resources. One very interesting policy implication concerns the value of supplemental water supplies in the South Platte River Valley. Many in Colorado would like to have the U.S. government construct a large surface storage reservoir, known as the Narrows Unit, on the South Platte River to provide supplemental irrigation water. They justify the large expenditure citing the large benefits the area receives from irrigated crops. Even though supplemental irrigation water produces large increases in area net income, the value of additional water supplies are given by the marginal or last additional unit. By parametrically increasing the amount of groundwater users in the area can pump—recall that 88 percent of the farmers have wells—we calculated the marginal value of additional water supplies. Table 14 shows that at current water use rates, additional groundwater or any supplemental water is worth between $7 in a normal year and $9 in a dry year. The reservoir will increase water supplies by 133,000 ac. ft. Even using a $10/ac. ft. marginal value, the total annual irrigation benefits amount to $1,330,000. The capitalized present value of this benefit stream over 50 years is $13.2 million at 10 percent, far short of the $130 million project cost.

What about the 12 percent of area farmers that haven't invested in wells or cannot do so due to aquifer properties? If Colorado water managers want to increase irrigated agriculture in the South Platte River Basin, the most logical and least costly alternative is to allow more development of groundwater resources in the aquifer and use the existing surface canal system to deliver the water. Combining augmentation plans and increased well use expands the area's irrigated agriculture and solves the depletable externality problem.

Limitations and Extensions of the Model

The analysis described above stimulated many ideas for extensions and improvements, including:

1. An obvious extension is to simulate a 10 to 20-year time period. An extended time horizon could capture the dynamic characteristics of crop prices and pumping-stream flow interconnections. The extreme variation in crop prices throughout the 1970's illustrates the flexibility of prices in the agriculture sector. The pattern of undersupply-high prices followed by oversupply-low prices could be built into the simulation.

   The hydrologic variables are equally complex. Pumping on the aquifer's outer edge may continue to reduce stream flows in subsequent years. A casual examination of the epsilon or influence coefficients over a six-month period reveals that the pumping effect on stream flow from a well four miles away from the stream increases over the whole six-month time span. It is probable that the groundwater-stream flow influence function may peak and then decline in the following year. A more complete study would be able to determine the impact of crop price changes and year-to-year carryover of the groundwater externality.

2. Increasing the dimension of the study area would be another major improvement. Ideally, the model would include all irrigated acres along the lower South Platte River and its aquifer from Denver to the Nebraska state line. This extension would more precisely measure the depletable

groundwater externality and eliminate any need to model a hypothetical study area with reversed priority orderings.

3. A third extension would directly estimate the augmentation water supply function and the risk coefficient in the uncertainty model. We used the linear programming economic model to calculate water supply price-quantity combinations and the expected income-variance coefficient. A survey estimating these important model parameters would provide valuable checks on the accuracy of the values in the current model.

4. A very important addition to this study would involve developing and simulating other major alternative externality solutions and institutional changes. For example, public districts and centrally controlled water policies changing property rights from private to public might be the most efficient externality solutions. Tax, quota, standards, methods of groundwater control could produce Pareto optimal resource allocations. Comparing all alternatives would make the policy maker's conjunctive water use decisions much easier and more informed.

5. Finally, any improvement in the accuracy of model parameters should provide more realistic models. Lengthening the growing season from four to five months could improve the model calculations of the pumping effect on the river. Improved stress and crop water requirement coefficients enhance any future results. Additional disaggregation of the economic subareas might identify oversimplified assumptions and reveal useful insights into conjunctive water use problems and situations.

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