Management of Montanas groundwater resources - an industrial analysis and case study of Crow Creek valley, Montana

by Virginia Evelyn Worthington

A thesis submitted in partial fulfillment of the requirements for the degree of MASTER OF SCIENCE in Applied Economics
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Abstract:
The commonality problems associated with groundwater use have led to inefficient allocation and economic waste of the resource. Under an institutional regime of poorly defined property rights, groundwater users fail to consider both the true cost of current extraction activities and the stock value of the resource in their pumping decisions.

This study examines groundwater management in Montana. State groundwater law is reviewed and various management approaches are briefly evaluated. A cursory review of Western states' laws related to groundwater management in areas where use conflicts exist indicates that current Montana statutes provide greater flexibility than most. This is seen as a positive feature in promoting efficient resource use.

A case study using linear and dynamic programming is made of the Crow Creek Valley in Southwestern Montana to demonstrate the use of an optimization model in determining the most efficient temporal allocation of groundwater. Results of the analysis indicate that when groundwater systems are confined, there is a decided economic advantage in maintaining the artesian pressure in the system by not exploiting the stock component of the resource. Marginal pumping costs rise rapidly when groundwater is mined from a confined system. If stocks are depleted to the point where the piezometric surface falls below the confining stratum, the system becomes unconfined and the artesian pressure is lost. If stocks continue to be depleted beyond this level, eventually the system moves to a second equilibrium state.

Sensitivity analysis is used to examine the impact of changes in the discount rate, size of the basin, energy costs and land productivity on the derived decision rule. Energy costs have the greatest impact on the general structure of the optimal use policy. Assumptions about land productivity also have a critical influence. When land is treated as homogeneous, the optimal allocation is identical to that under a common pool setting. With diminishing marginal land productivity, however, the difference in the two decision rules is more pronounced.

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Date 5/25/82

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VIRGINIA EVELYN WORTHINGTON

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of the requirements for the degree

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Head, Major Department

Graduate Dean

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ABSTRACT

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CHAPTER 1

INTRODUCTION

Water has always been a vital yet limiting resource to the economy of the arid West. In the past surface diversions provided the bulk of water used in agricultural, domestic and mining activities. But over the last several decades groundwater -- subsurface water in soils and geologic formations beneath the water table -- has become an increasingly important source. In 1970, 19 percent of the water used in the U.S. came from groundwater sources (Freeze and Cherry, 1979). By 1980 this figure had grown to 25 percent (Newsweek, Feb. 23, 1981).

Increases in groundwater use have been particularly dramatic in the West where it now accounts for 46 percent of the public supply and 44 percent of the industrial use (Freeze and Cherry, 1979). According to Frederick (1981), growth in western irrigation over the last three decades has been based on the use of groundwater. He reports a three-fold increase in groundwater withdrawals for irrigation between 1950 and 1975. Today these withdrawals account for 39 percent of all western irrigation water (Frederick, 1981, p. 21).

In Montana more than 95 percent of the total water withdrawn is for irrigation (Montana Department of Natural Resources and Conservation, 1975). While currently 99 percent of this water comes from surface sources, the use of groundwater for irrigation has grown significantly since the 1950s (Figure 1.1).

Unfortunately groundwater users often face less long-term security than do surface water right holders. Supplies and extraction costs are affected by the addition of new wells, increases in pumping rates from existing wells, pollution and higher energy prices. Thus groundwater resources are depletable in both an economic and physical sense. This depletable nature, along with the failure of individual pumpers to consider the true costs of their actions, has created a host of environmental and use problems. Frederick (1981) estimates that more than 22 million acre feet of groundwater is being mined (use in excess of natural recharge) from western aquifers each year. In some areas chronic overdraft has caused wells to go dry, land to subside, aquifers to be tainted with saltwater and pollutants, and surface flows to be altered.

In the past management efforts to combat these problems primarily concentrated on strategies to increase supplies rather than improve the efficiency of water use and the allocation of water rights. Today, however, supply side solutions involving large-scale water projects are no longer feasible for economic, political and physical reasons (Ingram et al., 1979). Thus if groundwater is to continue to be an important part of our water economy, new institutions must be developed to improve the efficiency with which this resource is used

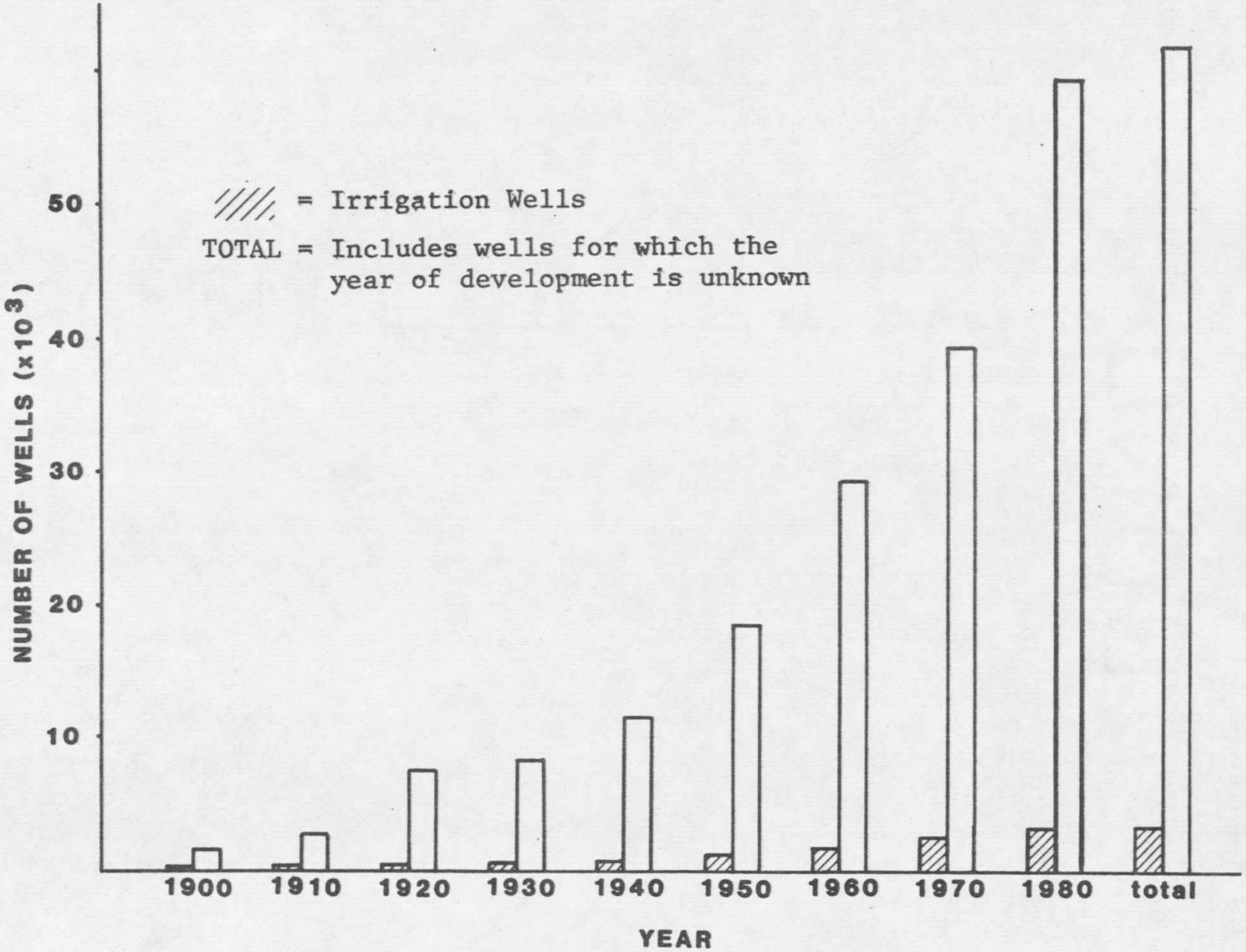

Figure 1.1 Number of Wells in Montana at 10-year Intervals.
Numbers Exclude Ravalli County.

Source: Montana Bureau of Mines and Geology Well Log Inventory Records.

and managed.

Study Objectives

The primary objective of this study is to establish the conditions necessary for efficient groundwater use in Montana and to evaluate various management strategies proposed for achieving this goal. An optimization model using dynamic programming is developed for the Crow Creek Valley basin in Southwestern Montana to demonstrate the welfare gains achieved under an optimal allocation policy versus on open access rule. The empirical results of the optimization and their implications for groundwater management are analyzed.

Organization

This thesis is divided into essentially two parts. The first part is a theoretical discussion of the commonality problem as it relates to groundwater use, groundwater law (both in Montana and elsewhere) and management options. The second section is an empirical application of an optimization model for groundwater use. Pertinent literature is reviewed within each section.

Specifically, the second chapter describes the common pool problem and why it exists, commonality aspects of groundwater, the definition of an externality, and theoretical solutions to externalities. The third chapter explains what is meant by economic efficiency, why it is used as the primary objective in this study, and various violations in the marginal conditions necessary for efficiency. Chapter four focuses on groundwater law -- the basic doctrines, key characteristics of a well-defined property right, the historical development of groundwater law in Montana, criticisms of current groundwater law, and the management of groundwater basins in Montana and other states. Chapter five evaluates various groundwater management strategies described in the literature or currently in practice. The strategies are briefly evaluated in terms of how well they restore the marginal conditions necessary for economic efficiency, their informational needs, ease of administration and implementation, enforcement potential and overall flexibility. Specific centralized management options considered are: strict temporal priority; use preferences; well drilling moratoria; well spacing regulations; use rotation regulations; quota systems; and, use taxes. Decentralized options include deed systems and water banking. The sixth chapter describes the optimization model used in the empirical part of the analysis, assumptions made in its construction, and the physical and economic setting of the study area. Results of the baseline model are described. Sensitivity analysis is used to examine the impact of changes in the discount rate, size of the basin, energy costs and land productivity on the derived decision rule.

Finally, chapter seven summarizes the major conclusions of the study and makes recommendations for further research.

Chapter 2

THE COMMONALITY PROBLEM AND GROUNDWATER

The problems associated with common pool or open access resources have occupied an extensive segment of economic literature related to natural resources in the last several decades. Sweeney et al. (1974) identify the lack of explicitly defined property rights as the setting in which common pool problems arise:

> The fundamental cause of any common-pool problem is the difficulty of identifying, keeping track of, and asserting property rights over some part of the resource in question. As a consequence, each person with access to the resource has an incentive to exploit currently as much as he profitably can, thus reflecting the effects of his actions on resource availability in the future . . . . (p. 182).

In his seminal article on the commonality of the fishery, H. Scott Gordon (1954) describes how "wealth that is free for all is valued by none because he who is foolhardy enough to wait for its proper time of use will only find that it has been taken by another" (p. 135). Clark (1976) explains that the open access institutional setting forces resource users, fisherman in his example, to evaluate future revenues from fishing at an infinite discount rate. Thus, returns from fish stocks preserved for future use are given a zero value. The inevitable result, concludes Gordon, is a competitive race for possession by current users "with attending overexpansion of productive facilities and gross wastage of the resource" (Gordon, 1954, p. 135).

More than a decade later, Garrett Hardin (1968) terms this waste "the tragedy of the commons."

In a more rigorous mathematical treatment of the commonality problem associated with extractive resources, Peterson and Fisher (1977) describe how firms operating with a common pool resource drive economic rents to zero due to overexploitation. Since ownership of the resource is implied only by seizure, firms have no incentive to maximize the present value of their resource use. As a result, external diseconomies due to crowding and the user cost of stock depletion are ignored or underestimated. McDonald (1971), in his economic analysis of petroleum conservation in the U.S., finds similar consequences to the "rule of capture" in oil field production.

Hirshleifer et al. (1960), in their classic treatment of water supply,extend the commonality problem to water:

> It is important to note that the common pool problem is a manifestation of the "fugative" nature of water resources. The span of property rights in such resources fails to include all the significant consequences of the private exploitation decision. Ordinarily the inducements are such as to encourage excessive exploitation, since a decision to conserve for future use does not provide a property right in the preserved resource still subjected to the law of capture (p. 60).

COMMONALITY AND GROUNDWATER

A number of economists have explored commonality problems as they relate to groundwater use (Renshaw, 1963; Burt, 1966; Bredehoeft and

Young, 1970; Jaquette and Moore, 1978; Noel et al., 1980, and others). Milliman (1956) observes that the "commonality of use prevents the onus of cost from falling upon the particular pumper and causes a divergence between private and social costs. As a result, optimum allocation of water is hampered" (p. 426). Likening groundwater to the "oil-pool" example, Milliman identifies the two basic spill-over costs or external diseconomies associated with the commonality of groundwater. First, since property rights are not secure in the future (particularly in the case of an aquifer with little or no natural recharge) there is little incentive to maximize the present value of total extractions over time. Hence, the individual user pumps as long as current marginal benefits exceed current marginal costs. The resulting tendency is to over-utilize the stored supply. A second spill-over cost is the negative externality which results when one pumper lowers the water level (due to his extraction activities), thereby spreading the cost of the extra pump lift to all pumpers. Explains Milliman, "It is clear in this type of spill-over cost as well as in the first one that production will tend to exceed the social optimum because the decision makers do not bear all of the costs attributable to their production decisions" (Milliman, 1956, p. 429).

These problems perhaps can be best conceptualized by using a simple example. Imagine two children, John and Sarah, sharing an ice cream soda on a hot summer afternoon. Both are given identical straws. As they put their straws into the glass, the "race for possession" begins. Sarah likes to savor her soda and normally would sip it slowly, letting the ice cream melt. However, she knows that with John also sharing the soda, the more slowly she drinks, the more John will get and the less will be left for her. So she decides to drink the soda as fast as she can -- so fast that she gets a headache from the cold ice cream. In fact, the soda is consumed so quickly that Sarah really isn't sure if she enjoyed it or not; certainly she enjoyed it less than she would have had she sipped at her own leisure. In the context of economic jargon, Sarah ignores the future value of her ice cream soda due to the uncertainty of its availability. By consuming all the soda now and forgoing the pleasure of drinking some five minutes later, she fails to maximize the present value of the drink over time.[8] Hence, she consumes it at a suboptimal rate.

But there is another facet to the story. John is so concerned about getting as much of the soda as he can he doesn't notice that every time he takes a sip the level of the drink in the glass drops. With each sip, John has to suck a little more forcefully to get the soda up the straw. At the same time, each of his sips also makes it more difficult for Sarah to get the soda. But that doesn't matter to John. All he considers is the effort required on his part to get more of the drink. Returning to the context of economics, without the restraint of a clearly defined allocation of soda, John ignores the total social impact (on himself and Sarah) of his sipping activities.

THE EXTERNALITIES OF GROUNDWATER USE

Within the context of two children sharing a soda the presence of spill-over effects hardly seems worth much attention. But where other resources are concerned, the results can be critical.

Traditionally, technical externalities are said to exist when there is some physical interdependence between economic decision units, e.g. some activity by X imposes a cost or benefit on Y for which X is not charged or compensated for by the price system of a market economy.

For the consumer, an externality is represented by an additional variable in his utility function,

$$U_y = f(a_1 \ldots a_n, z_x),$$

where $a_1 \ldots a_n$ are activities under Y's control and z_x is the external effect produced by X and not under Y's control. Similarly, for a producer an externality is represented in the cost function:

$$C_y = f(a_1 \ldots a_n, z_x).$$

When technical externalities are present there is a divergence between private and social costs and resources are misallocated. Resource allocation is said to be efficient if it is Pareto optimal.

That is, no other allocation of that resource is possible without making some users worse off. Within the context of production under conditions of Pareto optimality the private cost of producing a unit of output must equal the social cost of producing that unit.

Technical externalities can be either economies or diseconomies. An external diseconomy exists when the social marginal cost of an output is greater than the private marginal cost (Figure 2.1). For example, a manufacturer of tires produces noxious fumes as a by-product of his production process. These fumes are vented into the air surrounding the manufacturing plant. While the fumes pose a cost on area residents in the form of air pollution, the firm is not held accountable for this cost. Thus, it is not included in the firm's production cost calculations. The firm maximizes its profits by producing Q_p units of tires. However, from society's point of view only Q_s tires should be produced. Resources are being misallocated into the production of too many tires.

By contrast, an external economy results when social marginal cost is less than private marginal cost (Figure 2.2). An example might involve a farmer who drains his marshy fields by pumping water out, thereby improving the productivity of his lands and those adjacent to them (Hirshleifer, 1980). While the majority of the externalities associated with groundwater use are in the form of diseconomies, economies of this nature can and do occur. In the case of the external

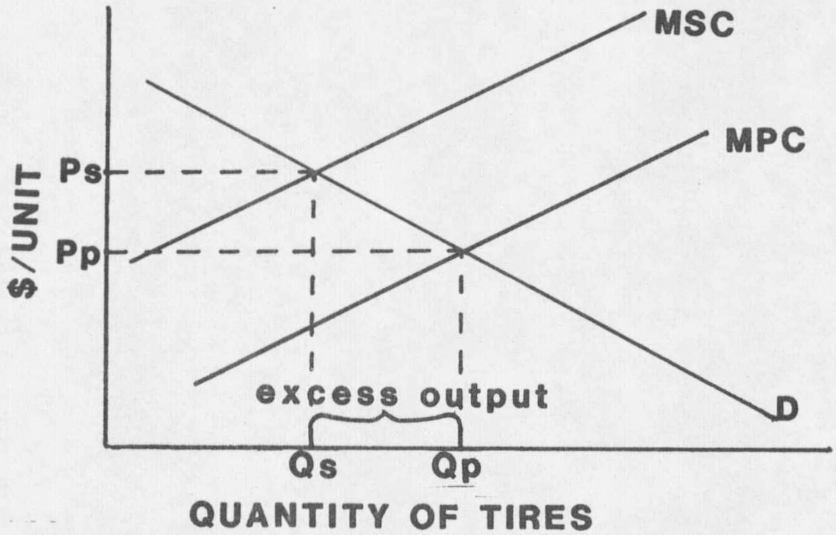

Figure 2.1. External diseconomy.

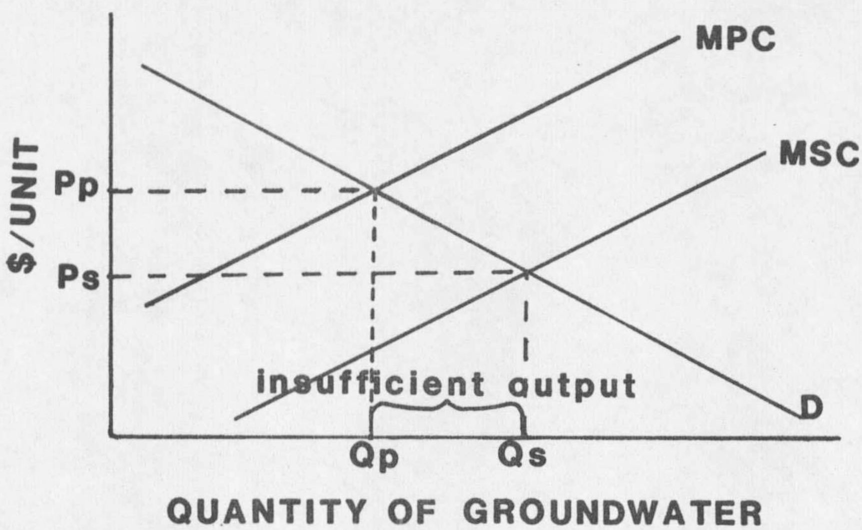

Figure 2.2. External economy.

economy, the farmer is not compensated for the beneficial effects his pumping has on neighboring farmers, and thus his cost calculation is higher than society's. From society's point of view he should be extracting more groundwater (Q_s). Resources are being misallocated in the sense that too little groundwater (Q_p) is being withdrawn.

In the market economy, prices are the primary signalling device for directing the allocation of resources. Scitovsky (1954) argues that when externalities exist, this pricing system fails to accurately "transmit information about present plans and future conditions as they are determined by present plans" (Scitovsky, 1954, p. 150). Thus, resource allocation diverges from Pareto optimality.

As discussed in the previous section, literature on the commonality problems associated with groundwater identifies two areas where market-mechanisms fail to properly function in the allocation of groundwater. First, individual pumpers do not properly account for the foregone opportunities associated with current use. Secondly, given the mobility of groundwater and the resulting interdependence among users -- termed congestion externalities (Brown, 1974) -- individual pumpers ignore the effects of their actions on other users.

The implications of these spill-over effects are borne out by real life problems. They include saltwater intrusion and other water quality problems, economic and/or physical exhaustion of aquifers, land subsidence, and conflicts over water level and pressure decline. On the High Plains of Texas researchers have quantified the benefits associated with use limitation programs designed to extend the life of water supplies from the Ogallala Aquifer, a non-recharging groundwater basin (Hardin and Lacewell, 1980). Heavy groundwater pumping along the San Joaquin Valley in California over the last 50 years has caused an area the size of Connecticut to subside, in some places as much as 30 feet. Once compaction occurs, the aquifer can never fully recharge (Camby, 1980). More dramatically, in Florida large sinkholes have suddenly appeared as a result of prolonged groundwater extraction from various basins. In Savannah, Georgie, heavy pumping from the Ocala Aquifer has created a cone of depression 50 miles wide beneath the city, slowly drawing salt water toward the city's wells (Newsweek, 1981). Incidents of sea water intrusion have been reported in other coastal states, including California, Texas, Florida, and New York.

APPROACHES TO THE EXTERNALITY PROBLEM

Economic literature considers two basic approaches to dealing with the externality problem. Burton (1980) terms the two as the "intervention solution" and the "private property solution." Similarly, Whitcomb (1972) classifies them as either a "centralized" or "decentralized" approach.

The so-called intervention solution has its roots with the work of Pigou on welfare (1932) in which he argues that the presence of market failures (with the resulting externalities) necessitates corrective governmental intervention in the form of taxes, subsidies, regulations, or other control measures to induce firms to produce socially optimal levels of output.

Beginning with the work of Coase (1960), a growing segment of the theoretical literature on externalities has attacked the Pigovian approach and instead advocated a decentralized or private bargaining solution. Under Coase's analysis, given perfectly defined property rights -- fully enforceable and transferable -- and zero transaction costs, parties affected by an externality will trade until an efficient solution is reached, regardless of the initial distribution of the resource. The underlying logic behind this approach rests with the invisible hand of the free market system. Since the socially optimal level of output maximizes combined profits, firms affected by externalities have an incentive to agree to produce the optimal output and redistribute profits such that each firm faces a profit greater than or equal to the one earned without bargaining. Thus taxes or subsidies are not needed.

Considerable debate has centered on the relative merits of these two approaches. Whitcomb (1972) notes that while the tax/subsidy scheme is decentralized in the decisional sense -- firms are free to decide how much of an externality to produce — it is informationally centralized. That is, the "center" must know the cost functions of each firm to calculate the correct tax/subsidy level. He considers this a "severe requirement," noting that it is often advantageous for the firm to transmit incorrect information. "Imperfect information gives imperfect results; and, like a stern religion, welfare economics condemns all degrees of imperfection equally" (Whitcomb, 1972, p. 89).

Others have criticized Coase's analysis on the basis of his assumption of costless transactions. Dahlman (1979) argues that it is the very presence of transaction costs which prevents Pareto optimality from "ruling sublime." "Transaction costs are therefore a necessary condition for the persistence of unwanted effects from externalities, for with zero transaction costs side effects will be internalized and will not negatively affect resource allocation. The conclusion is thus unambiguous: in the theory of externalities, transaction costs are the root of all evil" (Dahlman, 1979, p. 142).

Still others have taken issue with Coase's claim that a Pareto-efficient outcome will result regardless of the liability rule in force; that is, regardless of whether the acting or affected parties must pay (in the context of a negative externality). Randall (1972) argues that the two liability rules are not allocatively neutral and that the degree of externality abatement critically depends on which rule is in force. He concludes "that market solutions can be seriously considered in a world with pervasive externalities only if something approaching a full liability rule [acting party is liable] is established. Even then, excessive transaction costs may limit the success of market solutions" (Randall, 1972, p. 175).

Within the context of groundwater several alternative institutional arrangements have been suggested for dealing with the externality problem. Maddock and Haimes (1975) emphasize that an enforceable policy must be established which forces recognition of future values of water while providing recourse for external effects between pumpers. Hirshleifer et al. (1960) list three approaches: 1) centralized control of the groundwater supply; 2) assignment of pro rata production rights or quotas; and 3) imposition of "use" taxes. Following the decentralized, bargaining approach, subsequent studies have called for greater reliance on the private market and associated price system (McKeachnie, 1970; Johnson, 1971; Ditwiler, 1975; Tregarthen, 1977; Oeltjen and Fischer, 1978; and others). Smith (1977) proposes a water deeds solution whereby groundwater rights are composed of an annual entitlement to the flow component of the resource and a one-time allocation of the stock portion. Regardless of the specific institutional recommendations made, all of the studies underscore the need for better definition of groundwater property rights.

Chapter 3

THE EFFICIENCY OBJECTIVE

From the economist's point of view, efficiency is the yardstick by which most policies are evaluated. While other goals are considered, inevitably attention is focused upon the promotion of economic efficiency. This chapter attempts to justify the use of the efficiency objective, both in terms of general policy and as it relates to groundwater management in particular.

MAXIMIZING "SOCIAL WELFARE"

Whether from a centralized or decentralized perspective, few would argue that a policy which maximizes overall social welfare is an undesirable one. In water resources literature there is almost universal agreement on maximization of national welfare as being the primary objective of water resource policy (Marglin, 1962). Unfortunately, as Marglin points out, there is little hope that this objective is directly operational as a criterion for policy design and evaluation. "Translation would require not only agreement on a definition for the deceptively simple phrase 'national welfare' but also some assurance that the defined concept is measurable" (Marglin, 1962, p. 17).

In the context of conventional economic theory, welfare is maximized at the point of tangency between the social production possibilities frontier and the social utility indifference curve representing the greatest aggregation of individual utilities. But because interpersonal comparison of utility is not possible, economists are unable to strictly define social indifference curves. Thus the concept of welfare maximization in this context remains only theoretical.

In an effort to overcome some of the pragmatic limitations of welfare maximization, welfare economics has evolved. Welfare economics recognizes essentially two objectives: 1) efficiency, maximizing the size of the economic pie; and, 2) income redistribution, distributing the pieces of this pie according to society's values (Hirshleifer et al., 1960).

While the second objective still requires knowledge of elaborate value judgements, economists believe they can make definitive statements about efficiency (Henderson and Quandt, 1980). Under the Pareto criterion, a change which makes at least one individual better off without making anyone else worse off represents an increase in welfare. Pareto optimality occurs when no further Pareto moves are possible -- that is, no changes are possible which make no one worse off. Efficiency is maximized at the point of Pareto optimality.

However, even the Pareto optimality condition is not a decisive criterion since more than one point can satisfy it. In fact, any of the infinite number of points which make up the social production possibilities frontier represents a Pareto optimality. To eliminate this ambiguity, economists have introduced the concept of compensating side payments to achieve a Pareto redistribution. These side payments are a form of bribery in that they can be paid to compensate those made worse off by a particular transaction. Or compensation payments can be made to those made better off by the transaction to prevent it from taking place. With side payments, a Pareto optimum occurs at the point where neither party is willing to accept further compensation to affect a change. Thus, all possible gains have been exhausted and an efficient outcome is reached.

While the level of income is not a direct measure of well-being (Hirshleifer, 1980), from a practical standpoint, an increase in national income is often viewed as a proxy for an increase in welfare according to the Pareto criterion. Ciriacy-Wantrup (1956) explains why:

> The Pareto 'with' [with side payments] criterion is conceptually not identical with the criterion 'increase of national income.' But the latter criterion may be regarded as a practical, first approximation of the former, provided that the policy under consideration does not appreciably increase inequality of income distribution, but provided further that other policies operate independently and continually in the direction of greater equality of income distribution. (Ciriacy-Wantrup, 1956, p. 307).

Henderson and Quandt (1980) warn that Pareto optimality does not guarantee that distribution of income and utility are optimal. As a result, McKean (1958) notes that the efficiency criterion is only a partial test in that it says nothing about which position is best in any ultimate sense. A complete evaluation, however, requires knowledge about the relative "social worth" of wealth to different people. Given that utility is a subjective concept, efficiency remains the primary tool economists use to weigh and measure policy alternatives.

PARETO OPTIMALITY/EFFICIENCY CONDITIONS

As stated previously, Pareto optimality occurs when no change is possible where at least one individual is not made worse off. This result implies some rather specific conditions which must be met in both the consumer and producer sectors. In the following discussion these conditions are cursorily reviewed, appealing to their general intuitive interpretation. A more detailed derivation is available from any intermediate level microeconomic text.

For consumers, Pareto optimality requires that the marginal rate of substitution (MRSC) between goods X and Y be equated among all individuals. Those rates, in turn, must equal the ratio of the goods' prices (P_x/P_y).

(3.1) $MRSC^1_{xy} = MRSC^2_{xy} = P_x/P_y$

Very simply this states that the slope of individual 1's indifference curve where it is tangent to the budget line must equal the slope of individual 2's indifference curve where it is tangent to the budget line. If this condition does not hold, both parties could benefit from a further reallocation (trade) of the goods.

In the producer sector the value of the marginal product of an input (vmp_a) must be equal among all firms. This, in turn, is equal to the "hire" or factor price (r_a) of that input.

(3.2) $vmp^1_a = vmp^2_a = r_a$

This also implies that the ratio of the marginal physical productivities of inputs (mpp_a/mpp_b) -- the rate of technical substitution (RTS_{ab}) -- are equal for all firms.

Given the direct correspondence between the factor and product markets, the producer conditions can be described in terms of output prices and costs. The marginal cost of an output must be the same for all firms and equal to the price of that output.

(3.3) $MC^1_x = MC^2_x = P_x$

An inequality among producers implies a different marginal physical productivity for a particular input among the firms. Thus producers could improve profits by shifting their use of that input. Firms with larger mpps should use relatively more of that input while firms with smaller mpps should use less. Such a reallocation will eventually bring about the necessary equality, exhausting all possible gains.

The mediating role of price, in turn, results in an additional equality between the consumers' marginal rate of substitution and the producers' rate of technical substitution. In aggregate, these conditions can be generalized by the fundamental principle of equimarginal value in use (Hirshleifer et al., 1960): all users derive equal value in use from the marginal unit consumed or used.

VIOLATIONS OF EFFICIENCY CONDITIONS

It should be obvious from the above discussion that Pareto conditions fail to hold in disequilibrium or when markets are not perfectly competitive. For example in the case of a monopoly market, the profit-maximizing producer equates marginal revenue with marginal cost. But because the firm is a monopolist, to sell additional units of output prices must be lowered. Thus, marginal revenue (set equal to marginal cost) is less than price, and condition (3.3) is violated. From an efficiency standpoint, too little output is produced.

Efficiency conditions are also violated with the case of so-called public goods where the marginal cost of producing additional units of the commodity is zero. For Pareto conditions to hold, the price of the good should equal the sum of consumers' marginal rates of substitution rather than the individual rates.

In the context of groundwater, it is the presence of externalities (discussed in detail in Chapter 2) which prevent economic efficiency conditions from automatically being satisfied. When externalities are present individual maximization results in marginal conditions which are "wrong" or irrelevant from society's point of view (Henderson and Quandt, 1980). Society's opportunity cost in terms of the resources which must be given up to produce an additional unit of output is not the same as that for the private firm. Thus, private and social rates of product transformation are no longer equivalent. In the case of an external diseconomy, private marginal costs are less than the social cost and too much output is produced. With external economies, social marginal costs are less than private costs and too little is produced. In either case, resource allocation is not efficient. Gains that could be made by improved allocation are not experienced due to the presence of externalities.

In terms of groundwater management, economics provides a much less ambiguous guide for evaluating how well the efficiency (and externality) question is handled. A policy which increases net benefits or income closes the gap somewhat between the gains which are possible and those which are reaped. Society moves closer to an efficient allocation of the resource, and as a result, total welfare increases. Whether these gains are distributed optimally, e.g. to those who deserve them the most, is a question economics cannot answer. For that requires the resolution of an additional question -- a question which is beyond the scope of this study and the values of one individual.

Chapter 4

GROUNDWATER LAW

Fundamental to the management of water resources is the legal regime under which water allocation and distribution activities operate. A large body of law has evolved designed to deal with the common pool nature of water, both surface and ground. Despite the intent of this body, criticisms have been raised over the adequacy of present water laws to effectively address water management problems (Ciracy-Wantrup, 1956; Hirshleifer et al., 1960; Ditwiler, 1975; Johnson, 1971; Oeltjen and Fischer, 1978; Tregarthen, 1977; and others).

Trelease (1977) argues that the primary objective of any water law should be the promotion of an efficient allocation of water resources. Using economic efficiency as the point of reference, he defines such an allocation as "that combination of labor, capital, and resources which will produce the greatest net benefits." (Trelease, 1977, p. 62.) He emphasizes that to achieve such efficiency a system of water laws must be devised which provides "both security and flexibility of water rights" (Trelease, 1977, p. 64.)

Milliman (1959) further adds that to utilize the institutions of private property and the market system to address the commonality problem associated with water, two basic qualities must be present in a water right: "(1) the water right must be clearly defined and have legal certainty, and (2) the right must be capable of being transferred between competing uses and users" (Milliman, 1959 p. 46). Such conditions must exist if water is to move to its most highly valued use. How well do existing water laws as they apply to groundwater use meet these criteria?

In order to evaluate this question it is first necessary to understand the basic legal doctrines governing groundwater use in the United States today. In this chapter the basic legal doctrines are described, followed by a brief discussion of their limitations with respect to the criteria established above. Next, Montana's groundwater legislative history is explored, culminating with a description of provisions under current law. Finally, legal approaches to the management of "critical" groundwater areas in various other states are briefly examined.

GENERAL DOCTRINES

It is important to recognize that law is not a static institution, but rather continues to evolve and re-shape over time (Anderson and Hill, 1976). This is particularly true of groundwater law. Notes Trelease (1976), "It cannot be simply pictured, as in a snapshot . . . . Groundwater law is as dynamic and active as any law I know" (p. 271). Despite this dynamic nature, it is possible to classify the basic approaches to groundwater law according to four general doctrines. While few of these doctrines are applied in their purest form in the

United States today (Hutchins, 1974), it is possible to trace existing laws back to these basic approaches.

According to Corker (1972), Anglo-American law has its roots with the 1843 English "rule of absolute ownership." The ruling came out of a dispute between a miner and leather tanner over groundwater use. Under this doctrine the owner of overlying land has the right to use the water beneath that land in any way he chooses without liability. Trelease (1976) comments that this ruling reflected the court's "scientific and judicial ignorance" (p. 272) of the nature of groundwater. Several states (Connecticut, Illinois and Texas) still adhere to the absolute ownership doctrine (U.S. Dept. of Energy, 1980), although in Texas a statute provides for the formation of underground water conservation districts with special regulatory powers.

Initially there were few problems with the absolute ownership doctrine (Trelease, 1976). But as more and more individuals turned to groundwater as an additional source of water and with the advent of high-capacity pumping technology, problems of well-interference and dewatering began to develop. As a result, American courts created a modified version of the English doctrine, the "rule of reasonable use." This doctrine limits the water an overlying landowner can use to an amount that can be reasonably and beneficially used on that land. The water cannot be used wastefully or transported for use elsewhere if other overlying landowners are deprived of the reasonable use of their waters on their land (Hutchins, 1974). The reasonable use rule is most commonly applied in the Eastern states.

The correlative rights doctrine originated in California as a variation of the American reasonable use rule (Corker, 1972). This doctrine basically stipulates that in times of shortage or overdraft in a groundwater basin, each overlying owner is limited to a proportionate share of the water based on historical records of use. Arkansas, California and Florida utilize various versions of the correlative rights doctrine in their groundwater management laws (U.S. Department of Energy, 1980).

Water is not uniformly distributed throughout the United States or even regionally. As a result, water law has been modified according to the conditions typically present in a particular region. In general the eastern portion of the nation is endowed with far greater quantities of atmospheric moisture and surface and subsurface water than is the West. Thus, legal doctrines which tie water use rights to lands adjacent to or overlying sources of water have been found to be too inflexible for agricultural and mining practices of the arid West. Instead, a doctrine of prior appropriation has evolved. (For an interesting and concise discussion of how this particular institution evolved see Anderson and Hill, 1975.) Corker (1972) notes that this doctrine originated with surface water, but was later adopted to groundwater beginning with New Mexico in 1927. Under the prior appropriation system, a person, regardless of land ownership, can obtain water by diverting or pumping (capturing) water and putting it to beneficial use. The first date of use establishes the right holder's priority relative to other users, with senior right holders having preference over junior right holders. Thus, in times of shortage senior right holders must have their rights satisified before junior right holders can exercise their water rights - hence the descriptive phrase "first in time, first in right." Unlike the absolute ownership or reasonable use doctrines, under prior appropriation the water must be used to establish or "perfect" the right. Depending on the specific requirements of the state, non-use for a certain period of time is viewed as abandonment and results in the loss of the water right. The prior appropriation doctrine is typically applied in the Western states. Currently most appropriation states require that a permit be filed with the designated state agency before water can be utilized. The agency generally issues a permit once it has been determined that unappropriated water is available and that the proposed use will not "unreasonably" interfere with the uses of existing right holders (U.S. Dept. of Energy, 1980). There is a growing trend for states operating under the reasonable use doctrine to also require permits before water can be used (Trelease, 1977).

CRITICISMS OF CURRENT GROUNDWATER LAW

Facets of all four doctrines have been criticized in terms of their ability to provide secure and flexible water rights with respect to both ground and surface water use.

According to Hirshleifer et al., (1960) certainty (or in Trelease's terminology, security) is perhaps the most important characteristic of a real property law. By the very stochastic nature of water, there always exists some uncertainty regarding the physical supply of water that will be available at a given point in time. Obviously little can be done legislatively to eliminate the physical dimension of uncertainty. However, laws governing the use of water have a very direct impact on the certainty of tenure; that is, the certainty regarding the legal right to use water. A basic tenet of economic theory is that individuals respond to incentives. Without certainty with respect to a water right there is little incentive for an individual to invest in or develop water resources. For example, it would be irrational for a farmer to expend a large sum of money on a new irrigation system this season if there was a good chance his water right would be invalid the next season.

Initially it might appear that a doctrine of absolute ownership would provide the greatest degree of certainty with respect to groundwater. However, as Trelease (1976) points out, such ownership is not as absolute as the name would imply. With a sufficiently powerful pump a landowner can extract water underlying adjacent lands as well, making the water his property while at the same time leaving neighboring landowners dry.

With the reasonable use doctrine there is uncertainty with respect to how a "reasonable" use is defined. What is reasonable today may not be so judged tomorrow. Similar uncertainties exist when use preferences are administratively or legislatively specified, or, in the case of an appropriation doctrine, when the use must be a "beneficial" one.

The correlative rights doctrine does not specify the actual amount an individual pumper is entitled to and, thus, the uncertainty associated with a common pool resource persists.

As mentioned previously, water rights are not lost through non-use under the absolute ownership, reasonable use or correlative rights doctrines. While from an efficiency point of view it may be more profitable for an individual to let his rights lie "dormant" until a more appropriate time, the uncertainty of groundwater availability under the law of capture discourages such behavior (see Chapter 2). The non-use loss provision of the prior appropriation doctrine, however, leaves the individual water user no choice as to when to exercise his right.

Hirshleifer et al. (1960), Trelease (1977), and others suggest that the prior appropriation doctrine provides more legal certainty than do the other doctrines since actual quantities and priorities are specified in the water right. This is true only for the most senior right holders, however. In times of shortage the most senior right holder is guaranteed his right. Whether junior right holders receive all or only a fraction of their appropriation depends on their relative priority and the total supply of water available. Also, as discussed above, the definition of "beneficial" use is not known with certainty but subject to the whims of judicial interpretation or even legislative action. For example, in Montana the use of water for the slurry transport of coal is singled out as non-beneficial under the 1973 Water Use Act (Rogozen, 1980).

Many state laws have provisions for the creation of special or "critical" groundwater zones where conflicts have arisen between groundwater users (U.S. Dept. of Energy, 1980). In many instances the appropriate management entity is granted almost complete authority in deciding how the water is to be allocated, existing water rights not withstanding. The uncertainty of water rights under such a setting is obvious.

Frequently under the prior appropriation doctrine a water right is granted only for the use of water (a usufructuary right) and not for outright ownership of the water. This occurs in states such as Montana where waters are declared to be ". . . the property of the state, for the use of its people" (Constitution of Montana, Art. IX, Sec. 3). The certainty associated with a use right as contrasted with a property right is unclear and is subject to judicial interpretation.

The certainty question also extends to water quality attributes of a water right. In many instances water quality is as important as quantity. A domestic well-water user finds little solace in a well capable of producing 15 cubic feet of water per second if the coliform count of the water is too high for safe consumption. Hirshleifer et al. (1960) suggest that definition of a water right in terms of the full condition of the diversion, including water quality, is an important element in promoting certainty. Unfortunately, from a technical point of view, such conditions may pose serious enforcement problems in the case of groundwater. If an individual's well becomes contaminated it is extremely difficult to pinpoint the source (or the individual) responsible for the water quality decline. It is not clear clear whether water quality deterioration would be construed as preventing the reasonable exercise of a water right by overlying landowners under reasonable use and correlative rights doctrines or by senior right holders under the prior appropriation doctrine.

With this discussion it is important not to lose sight of why certainty is such a critical component of a water right. Certainty is intimately tied with flexibility or the ability to transfer water rights among competing users. Without certainty to the title of a water right, the marketability or transferability of this right is impaired (Tregarthen, 1977), opportunity costs are ignored and a less efficient allocation results. In common sense terms, uncertainty means an individual is not sure of what he has. How, then, can he trade something he is not sure he even owns?

Turning to the concept of flexibility, it can be shown how a water right must be transferable if water is to move to its most highly valued use. Uses for water are not static. Given technological advance, changes in population, tastes and preferences and general economic conditions, it is obvious that what was a valuable use of water 50 years ago may not be so today. Similarly while water may be very valuable today in a particular use, there is nothing to guarantee it will still be so next year. Yet if water is locked into certain prevailing use patterns it cannot be allocated to other uses with possibly greater value. Inefficiency results; the opportunity cost of using a unit of water is no longer equal to its marginal value product. It is this sort of flexibility of water use or transferability which Trelease (1977) refers to when he states that water law must be structured so as to promote economic efficiency (see page 26).

Under the prior appropriation doctrine in most states certain conditions must be met before water rights can be sold or purchased or conditions of the right changed (such as type of use, place of withdrawal, place of use) without the loss of priority. The most common stipulation is that such changes must be approved by the appropriate management authority (state or local). Often approval requires that the changes cannot be detrimental to existing right holders. From an economic perspective this is a perfectly legitimate requirement in that it provides third party protection and thereby serves to further strengthen the certainty of other water rights.

However, in many states additional conditions are specified which limit transferability. Obviously the new use must be a beneficial one. In some states, however, a request to change or transfer a water right is interpreted as meaning that the water is not needed for its current use and, thus, is not being put to beneficial use. Loss of that right may result. Anglides and Bardach (1978) suggest that the California State Constitution can be interpreted in this manner.

Under all the doctrines, restrictions are often placed as to where the water can be transfered. Ohio, Pennsylvania, Tennessee, Virginia and West Virginia explicitly prohibit transfer of water use to nonoverlying lands (U.S. Dept. of Energy, 1980). Under the prior appropriation doctrine many states empower local districts with the authority to forbid the transfer of water outside the basin or natural watershed (California, Colorado, New Mexico; U.S. Dept. of Energy, 1980). Frequently states prohibit the transfer of water out-of-state either entirely or subject to legislative approval. Such approval also may require reciprocal agreements between states.

In addition to these broad-based limitations to the transferability of water rights, most states have more subtle restrictions directed at specific uses or geographic regions. An examination of virtually any state water code will reveal isolated restrictions. For example in

Montana, the law specifically prohibits an appropriator of more than 15 cubic feet per second from changing the purpose of use from an agricultural use to an industrial one (MCA §85-2-402 [3]).

Use preferences, while not restrictions on transferability per se, do pose serious limitations on the attainment of water use efficiency. In some states a list of statutorily preferred uses is specified and allocation of water is in accordance with this list. For example, in Arizona the state water commissioner gives preference to water use applications according to a list ranked by their relative value to the public: (1) domestic and municipal uses; (2) irrigation and stock uses; (3) power and mining uses; (4) recreation and fish and wildlife. (AR Rev. Stat. Ann. § 45-147). California's Water Rights Board is guided by the policy that domestic use is the highest use and irrigation is the next highest use. (Similar provisions are present in Texas, Oklahoma, and Nebraska statutes.) The effect of these preference clauses is to freeze water use into certain allocation patterns which reflect market values only by sheer coincidence (Oeltjen and Fischer, 1978; Tregarthen, 1977). In other states (Colorado, Idaho, Montana, Nebraska, Oregon, and Utah) preference clauses can be used to ration water supplies during times of shortage, giving certain right holders "preferred" status over others regardless of the initial priorities. As mentioned previously, this can also limit the legal certainty of a water right.

In the past many states have treated ground and surface waters separately in their laws as well as distinguishing between so-called percolating waters and definite underground streams (Hutchins, 1974). Such artificial divisions are at odds with the principles of hydrology and, as a result, have been the focus of much criticism. Thomas (1961) explains,

> In making such a distinction in the classification of underground water, the courts have been at variance with hydrologic principles which recognized that all groundwater . . . constitutes a part of the generally available water supply and has a common ultimate disposal with surface streams by means of outflow to the ocean or other large body of water, becoming inseparable from surface flows in the process (p. 640).

Today a great portion of the states are modifying laws to allow for the conjunctive treatment of ground and surface waters. For example, Montana water statutes now use a comprehensive definition: "'Water' means all water of the state, surface and subsurface, regardless of its character or manner of occurrence, including but not limited to geothermal water, diffuse surface water, and sewage effluent." (MCA §85-2-102 [14].)

Another area of concern often neglected by state water laws involves liability for land subsidence induced by groundwater extraction. As cited in the previous chapter (page 15) such occurrences are becoming more widespread and are likely to grow in intensity as groundwater resources are more fully developed. It appears that in this instance there is room for overlap between land and water property right laws to provide additional security for the land right.

MONTANA GROUNDWATER LAW

Compared to other western states, Montana was rather slow in addressing groundwater use in its state laws (Dunbar, 1976). To a large extent this reflects the relatively minor role groundwater played in the state's water profile; its use during the late 1800s and early 1900s was primarily limited to stock and domestic purposes except for a few mining and railroad-related activities. As a result, conflicts over groundwater rights were virtually non-existent and the doctrine of absolute ownership, borrowed from the water-rich East, was applied to the use of percolating waters. The only restriction was that the use be made without malice or negligence (Ryan v. Quinlan, 1912).

By the late 1930s, however, individuals began to turn more and more to groundwater as an additional source of irrigation water. The availability of better pumps and cheap rural electricity expanded the use of groundwater. By 1950 records of the Montana Bureau of Mines and Geology (MBMG) indicated that there were 221 irrigation wells in the state. In contrast, Dunbar (1976) reports that census-takers in 1899 found no acres irrigated from well-water in Montana.

It was not until 1947 that the Montana State Legislature passed a bill which, to a very limited extent, attempted to address some of the concerns raised over the use of artesian wells. The "Artesian Well Act," as it is sometimes termed, reaffirmed absolute ownership of artesian water but prohibited its waste and required that artesian wells be cased and effectively capped. In addition, it required well-drillers to file a log with the state engineer describing the well and the depth, thickness, and characteristics of strata penetrated. Dunbar (1976) notes that the act was only a small beginning since it affected only a limited portion of the groundwater resources of the state and failed to modify the property rights structure.

By this time the doctrine of prior appropriation had been firmly established for surface water allocation in most of the Western states, including Montana. Beginning with New Mexico in 1927, many of these states began to extend this doctrine to groundwater as well.

Despite several attempts to produce a comprehensive groundwater code which would establish a legal method for appropriating groundwater in Montana, it was not until 1961 that the state legislature enacted a groundwater law (Chapter 237, R.C.M. 1947). The law applied the doctrine of prior appropriation to groundwater and established beneficial use as the extent and limit of the appropriative right. It recognized groundwater put to a beneficial use prior to January 1, 1962, as a water use right. To obtain a water right after January 1, 1962, an individual had to complete four forms and submit them to the County Clerk and Recorder before a right was legally recognized. The state engineer was designated as the "Administrator" to carry out provisions of the law. In addition, the 1961 Groundwater Law provided for the establishment of controlled groundwater zones (to be detailed later in this section), the investigation of groundwater areas, the prohibition of groundwater waste and contamination, and permitted the change in location of a water right without loss of priority. The appropriative right established under the 1961 law applied only to the quantity of water used and not the condition of use, including water levels, means of use or ease of withdrawal (R.C.M., 1947, §89-2912).

In describing the bill signed into law Dunbar,(1976) questions whether the 1961 legislation actually changed the property rights structure of groundwater in Montana. While the law established that "first in time is first in right," the bill reported out of the House Judiciary Committee and eventually signed into law did not contain "the key declaration" (Dunbar, 1976, p. 36.) of the original Senate version: "The use of groundwater now appropriated, or that may hereafter be appropriated for a beneficial use shall be held to be a public use." According to Dunbar the question remained unresolved until 1972 when a new constitution was approved, declaring that all waters "within the boundaries of the state are the property of the state, for the use of its people." (1972, Constitution of Montana, Art. IX, Sec. 3).

In 1973 the state legislature enacted the Water Use Act, creating a comprehensive water code regulating both ground and surface waters under s single administrative unit. Thus, ground and surface waters are no longer treated as separate hydrologic systems.

Provisions of the current law are administered by the state Department of Natural Resources and Conservation (DNRC), with a seven-member board overseeing its actions. Water resources are to be managed in a way which provides for "the wise utilization, development, and conservation of the waters of the state for the maximum benefit of its people with the least possible degradation of the natural aquatic eco-systems" (MCS§85-2-101 [3]).

The law further recognizes and confirms all existing water rights (prior to 1973), with new rights (post-1972) being conditional upon existing claims. Quantification of these existing rights, however, has become a major administrative task. Prior to the 1973 Act (prior to 1961 in the case of groundwater) an individual could acquire a water right simply by appropriating the water and putting it to a beneficial use. Such a right was termed a "use right." No records or notices were required. Any records that were kept were scattered in county courthouse files, often only partially complete. At least one estimate indicates that nearly 76 percent of the state's water rights fall under the category of "use rights" with no records available (Lessley, 1981).

To avoid some of these problems, the 1973 law initiated a permit and certificate program for administering water rights and a centralized record-keeping system. Under provisions of the law individuals seeking new water appropriations must obtain a permit from the DNRC before they can use the water. These permits are considered provisional until all existing rights are adjudicated by the courts (on an area-by-area basis). The only exception to this is for wells withdrawing less than 100 gallons per minute. In these cases certificates of water rights are automatically issued once a notice of completion of groundwater development is submitted to the DNRC.

Currently much of the DNRC's water program is directed at expediting the adjudication process. At the present time nine field offices have been established across the state to aid individuals seeking to confirm their water rights or apply for new ones. Initially existing right holders had until January 1, 1982 to file a statement of claim containing evidence supporting the claim. This deadline was eventually extended until April 30, 1982 to give existing right holders additional time to file their claims. Objections to claims are handled by the courts with the burden of proof falling on the individual(s) contesting the claim. Four water judges have been appointed to handle the adjudication process. After various periods in which objections can be raised, a final decree is issued by the water judge with the assistance of a watermaster. This decree establishes all valid existing rights and priorities for a particular basin or area. Right holders are then issued a certificate of water rights by the DNRC which specifies the following (MCA §85-2-234):

- -name and address of right holder
- -amount of water included in the right: rate and volume
- -date of priority of right
- -purpose for which the water is to be used
- -place of use and a description of land, if any, to which the right is appurtenant
- -source of water
- -place and means of diversion
- -inclusive dates during which the water is used each year
- -any other information necessary to fully define the nature and extent of the right.

As noted above, persons applying for new appropriations of water (post-1973) are granted provisional permits. Permits are issued if the department determines that: there are unappropriated waters in the source of supply which will meet the conditions specified in the application; the rights of prior appropriators (both senior right <u>and</u> permit holders) will not be adversely affected; the use is a beneficial one; and the proposed means of diversion or construction are adequate. Once a permit is issued water can be applied to its proposed use. In general the DNRC will specify a time limit within which actual application of the water must begin. However, until a final decree is issued by the courts, the water use permit retains its provisional status -- it is conditional on the outcome of the final decree. Once the final decree is issued the provisional permit may be revoked, reduced or modified however the DNRC deems necessary to protect existing right holders (MCA§85-2-213). In the "Crumple Horn" case (DNRC v. Crumple Horn, No. 7076 MT 9th Jud. Dist., May 16, 1978), the court held that a permit issued by the DNRC establishes the right to "hunt" for water but does not guarantee that the permit holder will find or receive water. Thus for some permit holders their water development activities involve risk -- they are gambling on the outcome of an unknown decree.

As with claims to existing water rights, objections can be raised to permit applications. However, unlike existing water right claims, these objections are handled by DNRC's Water Rights Bureau. According to Compton (1981) if objections are taken to a hearings examiner, the burden of proof falls on the applicant for the new appropriation to show why his request for water should be approved. If the applicant cannot devise a workable agreement with the objecting party(s), the hearings examiner may refuse to issue the permit or may specify additional conditions on the permit to satisfy all parties.

Once a final decree has been issued, permit holders are granted certificates of water rights on the basis of the availability of unappropriated water and their relative priority (the date of their initial permit application). To date only one basin, the Powder River in Southeastern Montana, has been adjudicated.

As specified in the state constitution, outright ownership of water by an individual or group is not permitted. Instead rights are usufructurary; they are established for the use of water (Moon and Bowman, 1978), and this use must be beneficial. The Act defines a beneficial use as:

> . . . a use of water for the benefit of the appropriator, other persons, or the public, including, but not limited to, agricultural (including stock water), domestic, fish and wildlife, industrial, irrigation, mining, municipal, power and recreational uses. (MCA§85-2-102[2].)

Only the use of water for the slurry transport of coal (MCA [1979] §85-2-104) is specified as non-beneficial. The law specifically forbids the wasteful use of water (MCA§85-2-114). Scott Compton, field engineer with the DNRC's Water Rights Bureau in Bozeman, notes that a use can be beneficial while at the same time wasteful. He explains that waste must be determined on an individual basis but generally relates to the amount of water requested relative to its intended use (Compton, 1981). To minimize groundwater waste, all flowing wells must be capped or equipped with valves so that only the water actually being put to beneficial use is extracted. In addition, wells must be constructed and maintained so as to prevent contamination or pollution of groundwater supplies.

Since May, 1979, no applications for permits to appropriate more than 3,000 acre feet of groundwater per year can be granted without specific legislative approval (MCA§85-2-317). Only municipalities or cropland owners who intend to use the water for irrigation of their land are exempted from this provision.

Under the prior appropriation doctrine, senior right holders have priority in the exercise of their water rights. However, the law specifies that this priority does not protect the senior right holder from such changes as water level or artesian pressure decline due to the water use activities of junior appropriators as long as the senior right holder can still reasonably exercise his right (MCA §85-2-401). This provision has sparked a great deal of controversy. In one case (DNRC v. Crumple Horn) the court awarded damages to a senior appropriator in Teton County whose well was no longer free-flowing due to the decline in artesian pressure resulting from the pumping activities of a junior appropriator. The damages awarded included the cost of a pump, cement and electricity for ten years. Laurence Siroky, Chief of the Water Rights Bureau, explains that since a number of wells in the area were free-flowing and were not equipped with pumps, the court determined that the senior appropriator could no longer reasonably exercise his right. He adds that if the appropriator had been the only well-owner in the area without a pump, the court would not have held the free-flowing condition to be critical in the reasonable exercise of that right. All this suggests that, as with waste, reasonable exercise of a right also must be determined on a case-by-case basis (Siroky, 1981).

While a right holder may change the point of diversion, place of use, purpose of use, or place of storage specified in the appropriation, he must first receive approval from the DNRC (MCA §85-2-402). The DNRC will approve the changes if it determines that such changes will not adversely affect the rights of other appropriators. In practice, the DNRC relies on objections raised by the other right holders in response to notification of the proposed changes as an indication of possible adverse effects. If objections are substantiated (according to Compton the burden of proof lies with the objector), the DNRC can refuse to approve the change or specify any terms, conditions, or limitations it considers necessary to protect the rights of existing appropriators.

In 1975, a special clause was added to the law prohibiting the change of any agricultural use of 15 cubic feet of water per second or more to an industrial use. According to Compton the provision was designed to prevent industrial interests from buying out farm operations. Apparently the state either does not have much confidence in the market's ability to allocate water to its most valued use or views maintenance of the farm community as a more important goal.

Water rights, once acquired and perfected (put to use), become "appurtenant" to the land upon which they are used. Thus, rights automatically pass with land that is sold unless specifically severed from it. Severance sales and transfers of water rights without loss of priority are possible subject to DNRC approval. As with changes in the condition of appropriation (see above), transfers cannot adversely affect the rights of others (MCA§ 85-2-403). Out-of-state transfers are not permitted without specific legislative approval (MCA§ 85-1-121).

Unlike the other water rights doctrines, the prior appropriation doctrine requires that water be used for the right to be valid. An appropriator is given a specified time limit within which actual application of the water to the proposed beneficial use must commence. This time limit may be extended by the DNRC if good cause is shown. If an appropriator ceases to use all or part of his right for ten successive years, it is construed as a prima facie presumption that the right (or a portion of it) has been abandoned (MCA§ 85-2-404). Speculation in groundwater is expressly forbidden. (MCA§ 85-1-101 [9]). Only the state, the federal government or a political subdivision or agency can reserve water for existing or future beneficial uses or to maintain a minimum flow, level, or quality. A reservation right is handled in the same manner as a use right and is subject to the priority of senior appropriators. However, the DNRC board must review all existing reservations at least once every ten years to ensure that the objectives of the reservations are being met. Based on its review, the board can then modify the reservation (MCA§85-2-316).

Despite the intimate relation between surface and ground waters, groundwater does pose some unique characteristics which make its management particularly difficult. The most obvious is that groundwater is not visible without a well or some means of extraction. As a result, without relatively expensive and time consuming studies, little can be said about the extent of a groundwater basin, its rate of renewal (recharge) or its tie with surface waters. Given this dearth of information -- particularly acute in Montana where groundwater development is a relatively recent phenomenon -- it is extremely difficult for DNRC water specialists to determine how the pumping activities of one appropriator potentially affect other appropriators. There is a far more extensive and complicated physical interaction between groundwater users than with surface water users. Even though a groundwater appropriator can still physically obtain water, the costs of extracting that same volume of water may drastically increase due to another user's pumping activities. In general this is not the case with surface water where the effects of different users on each other are more localized and less subtle.

To address this unique set of problems, the law authorizes the creation or designation of controlled groundwater zones in areas where permits or certificates for groundwater use have been issued (MCA

§85-2-506).

The controlled area is a management option for basins or sub-basins where controversy has arisen over the use of groundwater. Specifically the law states:

> Designation or modification of an area of controlled groundwater use may be proposed to the board by the department on its own motion or by petition signed by at least 20 or one-fourth of the users (whichever is the lesser number) of groundwater in a groundwater area wherein there are alleged to be facts showing:
>
> (a) that groundwater withdrawals are in excess of recharge to the aquifer or aquifers within such groundwater area;
> (b) that excessive groundwater withdrawals are very likely to occur in the near future because of consistent and significant increases in withdrawals from within the groundwater area;
> (c) that significant disputes regarding priority of rights, amounts of groundwater in use by appropriators, or priority of type of use are in progress within the groundwater area; or
> (d) that groundwater levels or pressures in the area in question are declining or have declined excessively (MCA§ 85-2-506[2]).

In some states (as will be discussed in the following section), mining of a groundwater basin (rate of extraction exceeds recharge) is expressly forbidden. Montana's law with respect to mining only requires the establishment of a controlled area. Once established, a variety of management strategies can be pursued, including a mining option. As is discussed in Chapter 5 (p. 74), from an economic perspective mining may be the most efficient method for utilizing the resource to the maximum benefit of people in that area. An outright mining prohibition, then, would be incongruous with the intent of the law. What appears to be critical is not mining versus no mining, but the optimal rate of extraction.

Once a proposal to create a controlled groundwater area is submitted to the DNRC, the board must conduct a hearing to obtain relevant information. If, after the hearing, the board finds evidence that: 1) the public health, safety, or welfare requires a corrective control be adopted; and 2) there is wasteful use of water from existing wells or undue interference with existing wells; 3) any proposed use or well will impair or substantially interfere with existing rights to appropriate surface water or groundwater by others; or, 4) the alleged facts in the petition are true, the board can establish a controlled groundwater area (MCA§ 85-2-507). If there is insufficient evidence on the basis of the hearing, the board may designate the area as a temporary controlled groundwater zone and require the DNRC to conduct a further investigation.

A variety of management options are open to the board in pursuing corrective control actions. The area may be closed to further appropriations. Total withdrawal from existing wells may be reduced according to the relative dates of priority of the rights. A system of well use rotation may be imposed. Appropriators with two or more wells may be ordered to reduce total withdrawals or forbidden from using one or more of the wells. Individual appropriators may be ordered to reduce withdrawals, regardless of priority. A system of priorities based on use, not temporal seniority, may be imposed such that domestic and livestock uses are given the highest priority followed by agricultural, industrial, municipal and recreation purposes in whatever order deemed appropriate by the board. A final provision gives the board power to incorporate "additional requirements as are necessary to protect the public health, safety, and welfare in accordance with the intent, purposes, and requirements of this part and the laws of the state" (MCA§ 85-2-507[4g]).

There are advantages and disadvantages inherent in each of the options specified. In subsequent chapters these aspects will be briefly explored in the context of economic efficiency, political and administrative feasibility and enforcement. At this point, however, it is sufficient to simply list them to provide the reader with a better understanding of the unique setting posed by a controlled groundwater zone.

To date only one such area has been established--the South Pine Controlled Groundwater Area in the eastern part of the state, north of Baker. The area was officially designated in November, 1967, after several years of controversy. Objections were raised by ranchers adjacent to Shell Oil Company's South Pine oil field over the company's use of water from the Hell Creek - Fox Hills aquifer for secondary oil recovery operations. According to the petitioners, water levels in the surrounding area had dropped due to depressuring of the aquifer and many flowing wells had ceased. The crux of the problem centered on the increasing lift required to extract water from the wells. For many ranchers the declines required significant alteration of their wells since they were no longer flowing. Shell Oil contended that despite the level declines there was still plenty of water available. It added that domestic, stock and municipal wells were also contributing to the drawdown of the aquifer's pressure surface. During the hearings a representative of the U.S. Geog-logical Survey's Oil and Gas Operation branch indicated that use of the Fox Hills water was the most economic source for Shell Oil Company's oil recovery operations and without it a great deal of oil would be wasted. As a possible solution, Shell Oil offered to pay expenses incurred for well changes necessary to provide farmers and ranchers with adequate water supplies.

While the board in its order creating the control area did not limit industrial well withdrawals, Shell Oil later agreed to limit withdrawals from the aquifer to 11,000 barrels per day, averaged on a monthly basis (Guse, 1970). The board did establish a monitoring program to assess rates of withdrawal and general trends in water level (Rediske, 1981). After receiving additional complaints and in light of information on continued water level decline, the board modified its 1967 order. Specifically it held Shell Oil Company responsible for the continued falling water levels which created "an unreasonable economic burden on the landowner affected." (Montana Water Resources Board Findings of Fact and Order, June, 1972.) The board ordered Shell Oil to either limit its total withdrawals to 7,000 barrels of water per day or "to pay all additional charges for electricity necessary to pump water from any depth below the water level of each well as of January 1, 1964, or as near to this date as the level can be determined plus twenty five percent (25%) (Montana Water Resources Board Findings of Fact and Order, June, 1970).

The company opted for the second alternative. Rediske (1981) reports that the industrial wells causing the decline in water levels were phased out of production between 1975 and 1977. The company no longer uses fresh water aquifers for secondary recovery activities. Its only pump still active in the Fox Hills - Hell Creek aquifer is for domestic and periodic construction purposes (pumping approximately 56 to 80 gallons per minute). According to Rediske most of the water currently drawn from the aquifer is pumped by domestic and stock water wells, some free flowing. In addition, water levels over much of the area have risen since 1975. Only in a limited section have levels continued to decline, probably due to continued or increased rates of domestic and stock groundwater use.

MANAGEMENT OF GROUNDWATER USE CONFLICTS ELSEWHERE - A SELECTED SURVEY

The problem of groundwater overdraft is not unique to Montana. Many states (most notably in the West: Arizona, California, and Texas) have experienced problems with groundwater use conflicts. Thus, an important element to this study is a brief examination of how other states have attempted to "cope" with groundwater use problems.

In the majority of the prior appropriation states provisions are made for the creation of special groundwater management areas. However the scope of these provisions vary considerably. On the one extreme South Dakota expressly forbids groundwater withdrawals to exceed "average estimated annual recharge" (SDCL 46-6-3.1). A water use control area may be established if the state Water Resources Commission feels it is necessary "to properly and equitably proportion the available water supplies for use among the water right holders of record" (SDCL 46-10-19). Once a control area has been established the commission can, without regard to priority, reduce withdrawals by large capacity wells (greater than 18 gpm) equally to the extent necessary to protect domestic well water users. The reduction can be accomplished by placing a percentage limitation on the specified water right, limiting drawdown, limiting daily operating periods, rotating operating periods, or other measures necessary to alleviate shortages. If specific large capacity wells can be identified as directly contributing to the water supply problem, the degree of reduction in those wells can be greater than that for other large capacity wells. In addition, annual fees can be assessed against each water right holder in the control area and the commission may require the installation of water measuring devices.

By contrast New Mexico appears to have adopted a controlled mining philosophy in non-rechargeable basins. In Mathers v. Texaco, Inc. the state's supreme court held that a statute protecting existing water rights against impairment from new wells did not prevent the state engineer from granting additional permits which would necessarily lower the water table and increase pumping costs due to the non-rechargeable character of the basin (Grant, 1981). The state engineer can declare basins where hydrologic boundaries can be reasonably ascertained. In this particular case, the engineer established a management plan which would permit the mining of two-thirds of the water in the basin over a 40 year period.

In Colorado, a distinction is made between tributary and nontributary groundwater. Under a relatively recent management program users of tributary groundwater must belong to a state-approved augmentation plan before a permit will be issued by the state engineer. The program requires that a percentage of annual groundwater use be returned to surface water flows. In most cases, users' cooperatives have formed. Along the South Platte River, the Ground Water Users' Association of the South Platte leases or purchases upstream storage and surface water rights to replace the required five percent of members' annual groundwater use (Daubert, 1978). In the case of nontributary groundwater, the Ground Water Commission can create "designated groundwater basins" whereby groundwater permits are issued only if the new uses will not lower the water table or potentiometric head beyond reasonable economic limits of use (Rogozen, 1980).

In Oregon, critical groundwater areas can be established by authority of the director of the Water Resources Department (ORS 537.730). Control provisions are virtually identical to those in Montana.

Washington requires that groundwater supervisors appointed by the state Department of Ecology limit groundwater withdrawals by appropriators to maintain "a safe sustaining yield from the groundwater body" (WCA 90.44.130). Designated groundwater areas, sub-areas, or zones can be established to achieve this goal.

Within such a designated area withdrawal priorities are based on the principle of first in time, first in right. Digital groundwater models are used in the management of these basins. For example, in the Odessa Groundwater Subarea, the state has established that over a particular zone the rate of water level decline will be limited to 30 feet in three years from a base time of Spring, 1972. Additionally in this same zone the water table cannot decline more than 300 feet beneath the altitude of the static water level as measured in 1967 (WAC 173-130-030). To maintain these levels, a proportionate decrease in withdrawals from the zone may be required based on a point system. A point is earned for each month of priority and for each month the water has been actually put to beneficial use. Appropriators with the greatest number of points receive the greatest proportionate volume of groundwater.

Wyoming's Board of Control may designate "critical groundwater areas" on the basis of several criteria (similar to those used in Montana). If the state engineer determines that there is insufficient groundwater supplies to meet every appropriator's rights, he may close the area to further appropriation and require junior appropriators to reduce their withdrawals so that senior rights are satisfied. If this fails to provide relief to senior appropriators, he may require the rotation of water use throughout the area (Rogozen, 1980).

Idaho laws require the director of the Department of Water Resources to designate groundwater areas as critical if water supplies are not sufficient "to provide a reasonably safe supply for irrigation of cultivated lands, or other uses in the basin at the then current rates of withdrawal, at rates of withdrawal projected by consideration of valid and outstanding applications and permits. . ." (ICA 42-233a). Currently there are six critical groundwater areas along the southern edge of the state. In these areas the department can deny permits for additional groundwater appropriations. As an alternative option, a water district can be formed with a watermaster regulating deliveries of water according to temporal priority. Basin water rights must have been decreed by the court for a water district to be formed.

Both California and Oklahoma follow a correlative rights type doctrine, but approach groundwater management in a very opposite fashion. Californians have experienced problems with overdraft since the 1930s and 40s. Despite the fact that groundwater supplies nearly 40 percent of the state's annual applied water requirements (Schneider, 1977), California basically remains without a comprehensive groundwater law, with limited management responsibilities delegated to local agencies. The majority of these programs rely upon supplementing groundwater supplies (with deliveries of surface water for use or to recharge aquifers) rather than explicitly controlling groundwater extractions to address such problems as sea water intrusion, declining water tables, water quality degradation and land subsidence Jaquette and Moore, 1978). For example, the Orange County Water District follows a basin equity assessment program in which a ratio of groundwater to supplemental water is established which best meets the management needs of the area. A basin equity assessment is levied against water producers who pump too much groundwater, with the assessments going to subsidize other users who then must purchase more expensive supplemental waters. In 1980, the state legislature enacted a bill relating to groundwater management in the Sierra Valley and Long Valley basins. While these areas currently do not have critical groundwater problems, representatives of the state Department of Water Resources believe the legislation may serve as a prototype for a comprehensive law in the future (Robie, 1980). The law establishes possible extraction control measures in the event of an overdraft threat. These measures include well spacing, use rotation, suspension or reduction of extraction by exporters and off-basin users, and proportionate reductions by overlying users. It also provides for the adoption of groundwater extraction charges to finance management activities.

In 1972 Oklahoma enacted a new groundwater law radically altering its groundwater use regulation. In brief, the state adopted a mining approach to groundwater management. Under the 1972 law, the Water Resources Board is required to conduct hydrologic surveys and investigations of fresh groundwater basins or subbasins and determine the maximum annual yield based on a minimum basin life of 20 years. Overlying landowners are then allocated a proportionate share of this yield per acre of land (OKS§840.1). This proportion is net of the groundwater requirements of prior (pre-1973) right holders. No provisions are made for the establishment of controlled groundwater zones but the law does authorize the formation of irrigation, conservancy and master conservancy districts for the purpose of water management at the local level. In addition, the board may require well spacing if deemed necessary for the orderly withdrawal of water. By 1981, eight years after the law's enactment, less than ten of the estimated 150 basin studies had been completed (Smith, 1981). As a result temporary permits have been issued in the remaining 140 basins allocating overlying landowners two acre feet of water per acre of land. The ultimate allocations are conditional upon completion of the hydrologic studies. Temporary permit holders are required to file standard water use reports annually. While the law specifies that the board will update hydrologic surveys at least every ten years (OKS§870.5), officials with the Water Resources Board are doubtful the updates will actually be performed in the light of the delays experienced in completing the initial surveys (Smith, 1981).

Under Nebraska's reasonable use doctrine groundwater management activities are carried out on a local basis. Concerns over groundwater mining associated with irrigation development led to the passage of a groundwater management act in 1975 (Aiken and Supalla, 1979). This act gives the 24 Natural Resource Districts in the state (a conglomeration of soil and water conservation districts and watershed districts) the authority to create groundwater control areas. A control area may be established if conflicts between groundwater users are occurring or may be reasonably anticipated, or if users are experiencing or will experience in the foreseeable future substantial economic hardship as a result of current or anticipated groundwater use (Neb. RRS 46-658 [2]). Once a control area has been established, a variety of management options can be pursued by the Natural Resource Districts, including well spacing restrictions, rotation of pumping restrictions, withdrawal quantity limitations, and well drilling moratoria (Neb. RRS 46-666[1] a-c). By 1979 two control areas had been established.

In 1980, the Arizona legislature passed the first comprehensive groundwater management code in the state's history. While the state follows a reasonable use doctrine, it does allow for the transfer of groundwater to non-overlying land. Under the 1980 law, active management areas (AMA) can be established by the director of the Department of Water Resources if it is determined "that preservation of groundwater supply is necessary, land subsidence or fissuring is endangering property or use of groundwater has serious water quality implications." (Groundwater Management Act Summary - Article 2, June, 1980, p. 2.) An area director must be appointed for each AMA in addition to a Groundwater Users Advisory Council. In addition the law protects the rights of existing legal users of groundwater (grandfathered rights) in an AMA. Four AMAs were established when the law was enacted: Phoenix, Pinal, Prescott, and Tucson AMAs. In the Tucson, Phoenix, and Prescott AMAs a management goal was established whereby a long-term balance is to be achieved between the annual amount of withdrawal and annual net recharge (safe yield) by 2025. Gradual reductions in groundwater withdrawals are required over a 45-year period. These requirements include the use of increasingly sophisticated conservation practices in irrigation and the latest commercially available conservation technology by industry. Municipal users are required to reduce overall per capita consumption and institute other conservation measures. If conservation alone is not sufficient for achieving the management goal, the director may purchase and retire grandfathered rights after 2006. The management plan also includes provisions for water supply augmentation and water quality problem assessment. Management programs, water supply augmentation, and purchase and retirement of grandfathered rights are to be funded by groundwater withdrawal fees levied against all AMA groundwater users.

The High Plains of Texas have experienced some of the most well documented and publicized problems with groundwater overdraft. Texas law follows the absolute ownership doctrine and recognizes groundwater as private property. Regulation of groundwater is only through the formation of local underground water conservation districts. These districts are designed to "provide for the conservation, preservation, protection, recharging, and prevention of waste . . . and to control subsidence caused by withdrawal of water . . ." (TLR 52.021). Much of the groundwater used in Texas comes from an extensive underlying aquifer, the Ogallala, where annual recharge is virtually zero. Thus groundwater mining is a common practice. However, underground districts can exercise some control over groundwater use. They may require permits for new well construction or well alterations. Conditions may be placed on well production and spacing to "minimize as far as practicable the drawdown of the water table or the reduction of artesian pressure, or lessen interference between wells" (TLR 52.117). In addition, districts may acquire land to erect dams or to drain lakes, draws, and depressions, or install pumps and additional equipment to recharge underground water reservoirs.

From this cursory review of legislation in other states as it relates to the control of groundwater use in overdrafted or water-short basins, it appears that Montana's current law provides greater flexibility than most. This is a decided advantage in that it enables management programs -- whether centralized or decentralized -- to be tailored to the needs of a particular economic and hydrologic setting. Economic and hydrologic conditions often vary dramatically from region to region within a state. Regulations which forbid one management strategy in favor of another destroy this needed flexibility.

Chapter 5

MANAGEMENT APPROACHES

As suggested in the previous chapter, a variety of management schemes have been proposed for dealing with conflicts that arise over the commonality aspects of groundwater use. These recommendations include a broad spectrum of institutional settings, ranging from strict centralized ownership and management to a decentralized approach in which management decisions are left with the individual. Each has its advantages and disadvantages. There is no one "correct" policy, given the myriad economic and physical conditions characterizing groundwater use.

In this chapter various management recommendations will be evaluated in very general terms. The key criterion in the evaluation is how well the goal of economic efficiency is met. Additional areas of concern include general informational requirements, ease of administration and implementation, political feasibility, enforcement potential and overall flexibility. A policy which "scores" well in one area but fails miserably elsewhere has little chance of achieving the desired results. For example, a management tool may be clearly superior in promoting economic efficiency; however the information necessary to implement the program may be unavailable or so expensive to obtain that the costs exceed the expected benefits of improved efficiency. (This cost-benefit relationship is explored in slightly more detail in the following section.) Similarly, a program which is totally offensive to those it affects or extremely complicated to administer has little chance of political success. It is often said that a rule is only as strong as its enforcement. In the context of groundwater, a policy which imposes strict limitations on withdrawals is meaningless if these limitations cannot be enforced.

In the previous chapter the importance of flexibility in water law was emphasized. The same is true for management programs. McDonald (1971) explains the necessity for this built-in flexibility:

> The optimum allocation of resources is not some fixed pattern of resource use which can be specified and achieved once and for all. Its specifications change with every advance in technology, every alteration of consumer preferences or expectations, and every change in the quantity or quality of productive resources. In short, its specification changes continuously in a growing, dynamically developing economy. It must be continuously sought. Consequently, the efficient economy is one which has built into its structure a flexible, positive mechanism for continuously seeking the optimum allocation of resources (McDonald, 1971, p. 64).

This chapter is not intended to single out the best management approach. None exists. Rather, it is hoped that the following discussion will provide the reader with a better understanding of the strengths and weaknesses of each so that more informed decisions can be made.

MARKET FAILURE - NECESSARY BUT NOT SUFFICIENT

The existence of market failures, such as the externalities associated with groundwater use, is often cited as grounds for corrective action whether via government intervention or improved delineation of property rights. However, the mere presence of market failures is only a necessary but not sufficient condition for corrective action. The sufficiency condition depends on the extent of the problem (in the case of groundwater, the severity of the spill-over effects) associated with market failure. For example, in the Ogallala Aquifer lateral movement of groundwater in the basin is extremely limited. Beattie (1981) suggests that the aquifer is structured more like an egg crate than the traditional bathtub analogy. As a result, he argues, there is little drawdown in wells due to the actions of neighboring pumpers. Even over time, at current discount rates the present value of long term impacts is minor. Thus, there is little efficiency impact from third party effects, and the externality problem in this context has little significance (Beattie, 1981).

Obviously the Ogallala situation is somewhat unique; there is no reason to believe that the conditions found there are typical of all groundwater basins. However, it is important to recognize that the theoretical presence of externalities does not necessarily coincide with what exists in the real world. A theoretical problem may have only minor importance in reality. Thus "hard and fast" rules cannot be uniformly applied; nature is too variable to permit such oversimplification. Unfortunately, such conclusions are not popular as they make the task of resource managers that much more complex.

Even if third party effects are more pronounced than the Ogallala case from a physical standpoint, there is another facet of the problem which must be considered. How severe are the economic impacts? Do the benefits of corrective action outweight the costs of those actions?

In their theoretical analysis of institutional change, Anderson and Hill (1976) argue that the cost-benefit analysis rudimentary to all economic decision making holds for institutional change as well. Corrective action is not costless. Resources must be expended for gathering information, defining and enforcing property rights, and implementing management schemes. Thus, corrective action is only justified when the anticipated benefits of that action are as great or greater than the costs of pursuing those actions.

Numerous studies have attempted to quantify the benefits associated with managed groundwater resources as opposed to policies which permit unrestricted use. Renshaw (1963) concludes that conservation of groundwater resources yields a substantial return, "more than justifying public intervention in behalf of rational usage." (Renshaw, 1963, p. 285.) Hardin and Lacewell (1980) suggest that both producers and society as a whole could benefit if some annual limitations were placed on water withdrawn from the Ogallala aquifer for furrow irrigation. In a computer simulation study of a segment of the South Platte River, Young and Bredehoeft (1972) conclude that centralized control of groundwater extraction by some institution produces a higher net value of production than unregulated development. In a similar study, Daubert (1978) concludes that Colorado's augmentation plan generates larger area net benefits than do policies which prevent groundwater use or permit unrestricted pumping. In California, Noel et al. (1980) find that taxation or pro-rata allocation policy instruments increase the social value of groundwater resources.

In none of these studies, however, are the benefits reported net of management program costs. These figures are admittedly difficult to approximate, but failure to recognize them makes them no less important. Only Noel et al. consider the possibility that inclusion of the transaction costs in the calculus of policy change may result in a situation where the status quo offers "the 'best' that can be done in terms of maximizing the social value of the water resource." (Noel et al., 1980, p. 495.) They add that a policy to control groundwater use appears to be justified only if the transaction costs are less than the costs of the externalities.

CENTRAL MANAGEMENT

General Discussion

The concept of government intervention has had the most extensive treatment in economic literature on market failures. The government or state is viewed as a neutral body representing the interests of all society in its actions. Its authority to enforce laws, tax and draw on sources of technical expertise, so the argument goes, makes it ideally suited as a management entity.

In recent decades, however, questions have been raised over the true motivations of the bureaucrats who make up the state. Niskansen (1971) argues that a bureaucrat, like any individual, seeks to maximize his personal utility. Variables identified as comprising the bureaucrat's utility function include: salary, perquisites of the office, public reputation, power, patronage, output of the bureau, ease of making changes and ease of managing the bureau. According to Niskansen, the survival argument in the bureaucrat's utility function serves to reinforce the budget maximization goal. Becker (1958) questions the ability of government to perform less imperfectly than the market given the similar incentives facing the private firm and public agency. Burton (1980) and others suggest that without the price system as a means for generating and transmitting information, intervention solutions are likely to be more defective.

Under the central management approach, Pareto efficiency conditions are restored by mandating socially optimal withdrawal rates through various schemes or by equating private and social costs with taxes and subsidies (Hirshleifer et al., 1960). In general, central management programs establishing specific withdrawal and tax/subsidy rates are easier to monitor than decentralized schemes. But by the same token there is no built-in enforcement mechanism such as the price system. Thus enforcement requires an additional commitment of personnel and resources.

One of the most serious difficulties of central management policies is that they require determination of the optimal rate of groundwater use in the basin. It is on the basis of this rate that quotas, taxes, and rotation and spacing regulations are derived. Unfortunately, determination of the optimal use rate is no simple task. As will be demonstrated in the following chapters of this study, considerable amounts of physical and economic data as well as sophisticated mathematical techniques are necessary to derive an optimal decision rule (Burt, 1964 a, b; 1966; 1967; 1970). Also, this rule is unique to each groundwater area and, thus, must be determined basin-by-basin with periodic revision as economic conditions change and better data are obtained.

In the past managers have used the concept of "safe yield" as a guide for establishing permissible withdrawals. The safe yield is equal to the level of natural recharge to the aquifer. By restricting withdrawals to this level, in effect, future values of groundwater are discounted at a zero interest rate (Clark, pp.42-44, 1976) and no mining of the water occurs. Taken to its logical conclusion, under a safe yield policy, no water could be withdrawn from non-recharging aquifers such as the Ogallala. Thus activities using water from that basin in portions of Texas, Oklahoma and Nebraska would have to cease. Such a policy cannot be considered optimal in that it fails to consider the size of potential benefits from withdrawals in excess of the safe yield limit (Daubert, 1978). Bachmat et al. (1980) offer an alternative definition of optimal yield:

> It is a plan for realization of the maximum economic, objectives of a groundwater development subject to physical, chemical, legal and other constraints on the use of the reservoir. As defined, the optimal yield is a function of time and of the state of the entire system, rather than simple specification of allowable pumping rates alone as is commonly the case with most safe yield and mining concepts. For a given development, optimal yield will not necessarily require substained yield. Large withdrawals in excess of equilibrium limits may be the optimal developmental plan under this concept (Bachmat et al., 1980, pp. 10-11).

In addition to physical parameters on the characteristics of the aquifer, explicit information on the production and cost functions of firms using the groundwater resource is necessary to establish an optimal withdrawal rate. This information may be prohibitively expensive to obtain. Also, as mentioned earlier, there is some incentive for firms to withhold data or transmit incorrect information if it will increase their profits. All of these factors as well as the inherent stochastic nature of such physical variables as recharge raise serious questions over the validity of policy directives established by a central management entity. Uncertainty plays a role in virtually every activity an individual pursues. In the private market each decision maker automatically weighs the relative costs and benefits of this uncertainty element and selects a level which is optimal for him. When withdrawal rates are dictated by a third party, however, this decision is no longer left to the individual and preferences toward certainty are not accounted for.

Specific Options

Management according to strict temporal priority is extremely popular among appropriation states in that the policy conforms with existing water use laws. As a result, political feasibility is not a problem and the basic framework for administration is already present. As with any centralized approach, significant information is required to determine the optimal use rate. The costs of obtaining this information are borne by all the taxpayers. In addition to the withdrawal rate, existing rights must be adjudicated before relative priorities can be established. Once this is done, "first rights" go to senior appropriators. Enforcement requirements would necessitate random inspection of wells by someone similar to "ditch riders" employed by private irrigation ditch companies. Despite its broad acceptance, a priority method does little to promote economic efficiency. By locking groundwater use into patterns established by temporal priority there is no guarantee that water will be used by those who value it the most. Thus the value of the marginal product of groundwater will not be equal among all firms and additional gains from trade are still possible. Total welfare is not maximized.

Efficiency conditions, however, could be greatly improved if water rights were more freely transferable. As discussed in the previous chapter there are restrictions in current groundwater laws which limit transferability. The benefits of improved efficiency would be partially offset by the transaction costs associated with the market exchange of groundwater rights. The significance of these costs will be explored later on in this chapter.

Although commonly used in many states, management of groundwater resources according to a use preference system is perhaps the weakest option from an efficiency standpoint. Under this option only certain "preferred" classes of uses are entitled to groundwater. Preferences dictated by legislative or judicial authority often bear little resemblance to those dictated by the market. It is unlikely that statutory preferences reflect the unanimous opinion of society, but rather that of a simple majority or even a powerful and vocal minority. As such there is no guarantee that the preferences which are established will benefit the entire basin; instead they may improve the position of only a few. In addition, use preferences provide virtually no flexibility. Thus preferences which represent an efficient allocation of groundwater today may not do so tomorrow. Even if preferences are re-evaluated on an annual basis -- a costly process -- there is no guarantee they will be relevant. More importantly, a continual revamping of the preference system would destroy whatever security might exist with a water right. Groundwater development would be pursued by those with only a minimal degree of risk-aversion.

Well drilling moratoria, although extreme measures, are utilized in many states. Typically this policy is instituted in basins suffering from overdraft. Permits to drill wells and appropriate new or additional groundwater are simply denied. From an administrative standpoint this is perhaps the easiest and least costly measure. Enforcement needs are minimal and the only data requirements are those necessary to establish when a basin should be closed. While drilling moratoria are likely to meet with substantial opposition from those denied permits, they receive enthusiastic support from those already extracting groundwater who see the ban as a necessary step to protect their vested rights <u>in full</u>. From an efficiency standpoint, however, drilling moratoria appear less favorable. Although efficient in the sense that existing users are not restricted as to how they can use their water and therefore can use it in the most profitable manner, it precludes new, potentially higher valued uses. This efficiency loss is likely to be substantial in

Montana where in many areas existing uses of groundwater primarily have been limited to domestic and stock activities. More importantly, moratoria do nothing to reduce externality problems already facing existing users. Thus if these problems are substantial, such a measure is an inadequate management tool. In addition, moratoria provide no flexibility.

Well-spacing is another regulatory device frequently used in the West. This regulation is designed to minimize externality problems associated with groundwater use by requiring that wells be spaced or located so as to reduce direct interference among nearby wells. In situations where ranches or farms are large, well location requirements can be designed to effectively eliminate externalities due to interference. These regulations are relatively easy to administer and enforce for new wells; permits are granted only if the new wells do not violate spacing requirements. Some problems may arise with respect to non-registered wells for which no information is available on their location or existence. For example, in Montana domestic and stock wells are exempted from filing requirements. To avoid this problem new groundwater users could be required to verify that their wells do not violate spacing regulations. Also filing exemptions could be eliminated. Well-spacing regulations do require greater physical data on the aquifer in order to determine actual spacing requirements. In situations where interference varies greatly throughout the basin (extremely non-uniform conditions in terms of aquifer shape and transmissivity), physical complexities may preclude the effective use of spacing regulations. However, in less complex systems it may be an extremely successful management tool. In addition, it is likely to draw minimal oposition. Well-spacing is a relatively efficient approach to groundwater management in that it does not restrict how the water is used nor preclude new uses. Inefficiency results only if well spacing forces the use of locations or construction techniques which cause higher extraction costs than would otherwise occur. Also if well densities are already at a maximum, new uses would be restricted. Spacing and location requirements are relatively flexible in that they account for technological change and the abandonment of existing wells. The primary weakness of a spacing regulation is that it still does not force the groundwater user to consider the future value of that resource; thus while short-term problems with drawdown are addressed the long-run intertemporal allocation problem still remains.

By contrast, rotation regulations specify when wells may be utilized, e.g. daily, weekly, monthly, or yearly. This management technique has a number of limitations. Administration and enforcement is a complex and costly process; the degree of complexity and expense grows as the rotation schedule is shortened. Substantial data is required to determine not only the optimal level but the timing of withdrawal from each well. Rotation is likely to be very inefficient. In many cases the timing of water use is as critical as the quantity. Rotation schedules are not likely to coincide with the needs of individual users, and, in the case of irrigation for example, crop yields are likely to be reduced or destroyed. As a result objections to a rotation policy are likely to be substantial. Critics are likely to argue that certain well owners are treated more favorably than others. Like spacing regulations, rotation schemes do nothing to address long-run intertemporal allocation questions and, thus, much of the commonality problem remains.

Pump or use taxes and subsidies have been proposed in much of the literature as a management policy for eliminating the gap between private and social costs in the use of groundwater (Milliman, 1956, 1959; Hirshleifer et al., 1960; Brown and Deacon, 1972; Maddock and Haimes, 1975; Wetzel, 1978). Under this approach a tax is levied on the amount of groundwater used such that the private cost of using an additional unit of groundwater is equated with its cost to society, resulting in a Pareto-efficient allocation (Figure 5.1). In the absence of a tax, when external diseconomies are present, the pumper equates MPC with VMP and uses N units of groundwater. With a tax (AB) MPC equals MSC and only T units are used. A tax less than AB would not result in a socially optimal level of groundwater use. Thus a major limitation is whether the "correct" tax is actually levied. This depends on the accuracy of private marginal cost and

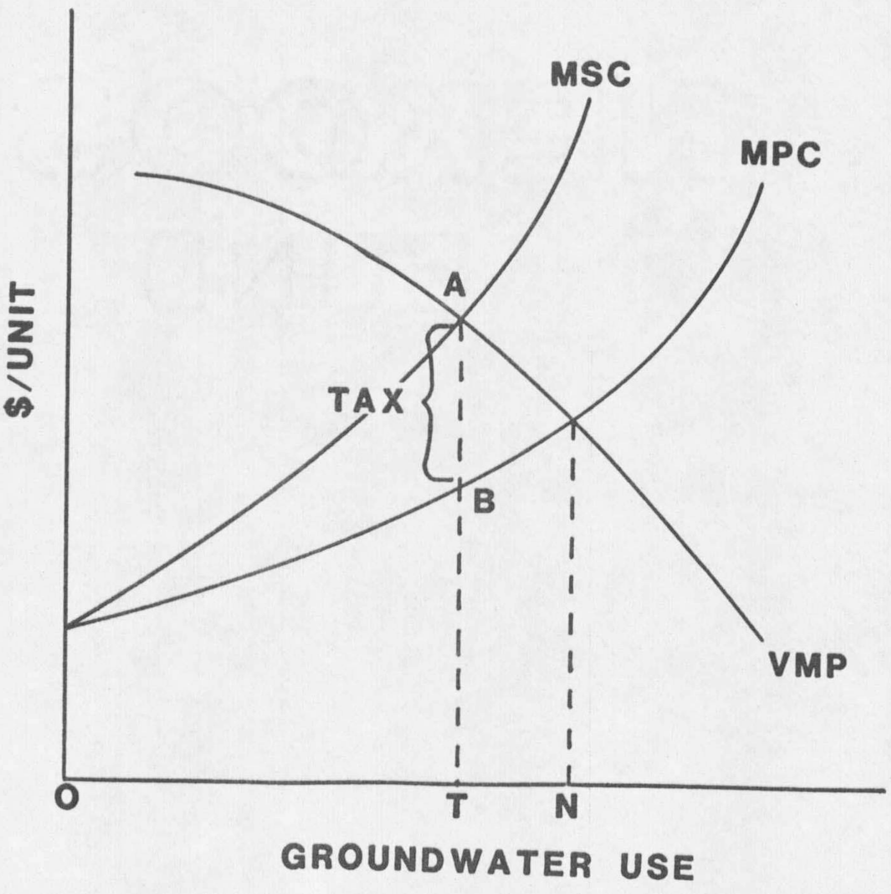

Figure 5.1. Optimal tax to restore efficiency conditions.

social marginal cost calculations. Marginal social costs are obtained in the derivation of optimal withdrawal rates. As noted earlier, determination of this rate is not a simple task and is subject to many variables. Administratively, a pump tax is more involved than either spacing or moratoria regulations. Enforcement is made more complex in that users have an incentive to lie about the actual amount of groundwater used. Without some form of metering, tax assessment would be difficult. Just as optimal withdrawal rates would have to be periodically revised, pump taxes would have to be re-adjusted to reflect changes in supply and demand (Milliman, 1959). Though a costly process, re-adjustment provides a great deal of flexibility. From an efficiency standpoint, an effective tax restores the marginal conditions necessary for a socially optimal allocation of the resource. Each pumper is free to choose how the water is to be used and at what rate, but both the private and social consequences of his actions are considered in the decision process. Thus no economic "waste" occurs.

Since the tax represents a loss to producers some mechanism must be established for redistributing tax revenues. Bredehoeft and Young (1970) warn that a tax may prematurely extinguish economic activity in a basin unless its proceeds are returned to those who paid it. Burt (1970) and others have suggested that non-profit groundwater user associations be formed, with tax revenues being returned to members in the form of dividends. According to Burt, dividends should be paid proportional to water rights but <u>not</u> according to the quantity of groundwater used. Wetzel (1978) suggests redistribution in the form of a per unit subsidy on the amount of land used by each producer. Maddock and Haimes (1975) develop a tax-quota scheme whereby taxes are assessed when use exceeds quota levels established by the management entity. The tax is used to compensate those affected by neighboring pumpers who withdraw more than their quota entitles them to. Similarly, pumpers who use less than their quota are granted rebates from the tax fund. Taxes are collected and redistributed in such a way that zero funds are accumulated from year to year. Milliman (1959) suggests that a rebate system provides important incentives for conserving water use.

Quotas are another method for controlling groundwater withdrawals. In nonappropriation states the quota allocates specific shares of the resource to each user, usually based on historical levels of use. In appropriation states where water rights already specify the level of use permitted, quotas can be used to further limit withdrawals. A quota is designed so that each pumper uses only the socially optimal amount of groundwater (T units in Figure 5.1). The outcome is identical to that under a use tax except that no revenues are generated for compensating those suffering losses (Hirshleifer et al., 1960). Like the tax, a quota system is subject to the same weaknesses; that is, the socially optimal level of groundwater use must be accurately determined.

Wetzel (1978) and Hirshleifer et al. (1960) suggest that a quota is simpler and, thus, a more attractive alternative from an administrative point of view since there are no tax revenues to redistribute. However, enforcement needs are more complex in that greater monitoring is necessary to insure pumpers limit their use to that established by the quota. Under a tax system the tax itself serves as a monitoring device to a certain extent. Unless quotas are tradeable they suffer from the same limitations as strict priority and preference management schemes -- they lock water use into certain patterns. Like the tax, however, quotas must be periodically re-evaluated, and thus offer potentially more flexibility than the other two systems. In addition, quotas are likely to be more favorably received than use taxes.

The relative superiority of a tax/subsidy scheme over the quota or other regulatory policies has been much debated in the literature. Burt (1970) suggests that a tax/subsidy approach provides an internal check on the results derived in the empirical optimization model. That is, the observed rates of groundwater use under the specified tax scheme should be consistent with the implied quotas and shadow prices of the model. A divergence between the actual and implied rates of use would suggest that some adjustment in the optimization model is necessary. Such a validation mechanism for a quota system is not readily apparent. However Whitcomb (1972) suggests the relative superiority issue is a moot one: "No claim should be made as to the relative robustness of corrective taxes versus output directives in the face of changing states of the world; static analysis as well as the second-best theorem permits no such comparison" (Whitcomb, 1972, p. 89).

Appropriate Management Entity

By its very nature a centralized approach to groundwater management requires some entity or "center" to determine how this resource is to be used. As discussed in the previous section, it is the center which regulates the timing and quantity of groundwater extractions, stipulates special use conditions and assesses fees. While theoretically this entity can be public or private, most of the literature has focused on public management organizations or, at the very minimum, ones subject to state supervision.

Corker (1972) and others emphasize the need for management on a local level given the extreme variation in groundwater conditions from basin to basin. Jaquette and Moore (1978) conclude that basin or subbasin level control is more desirable than centralized state control for both political and economic reasons. They suggest that state input is best utilized for determining the boundaries of these basins (based on hydrologic conditions) for which local management plans can then be established. In addition, they emphasize that management powers should be broad to provide maximum flexibility:

Groundwater basin management should include a management plan and a management entity to negotiate for terms and rents of storage in the basin, to sell groundwater, to redistribute profits or taxes, as well as to correct the common pool inequities and inefficiency (Jaquette and Moore, 1978, p. v).

Corker identifies the critical management powers as the authority to buy and sell water and water rights, impose pumping taxes and extraction taxes, store water, finance operations by general obligation and revenue bonds, enter contracts, sue in the name of the water district, and be liable for injuries.

There are a variety of organizational structures suited to water resources management on a local level. Hartman and Seastone (1965) contrast mutual ditch companies, water users' associations and public conservancy districts, and conclude the the public district is the superior management entity:

The public district serves both water resources development objectives and allocation objectives ... this form of organization at least has the potential for structuring economic interests to achieve efficient transfers and is deserving of continued study (Hartman and Seastone, 1965, p. 30).

Smith (1956) voices similar support for the use of the public district in groundwater management. "Its geographic flexibility, inter-temporal flexibility, concentration upon a single problem, ability to reflect local interests to obtain program adjustments, and ability to relate project costs to benefits commend the district as a groundwater management agency" (Smith, 1956, p. 269). However, he cautions that when districts are focused around special interests or single purposes, they can further fragment the problem, inhibit changes from the status quo and make the task of integrated water management impossible. According to Smith, these undesirable side-effects can be avoided by the selection of adequate enabling legislation so that management attention is focused upon the "totality" of the water problem. One important step, he suggests, is an active role for a technical state agency -- such as the state water resources department -- in the organizational process. This agency would provide the engineering, economic and hydrologic data necessary for developing integrated management programs.

Montana law allows for the creation of a variety of multi- and single-purpose public districts related to water resource management, including irrigation districts, county water and sewer districts, water users' associations, drainage districts, soil and water conservation districts, and water conservancy districts. Although the Water Use Act calls for the establishment of special controlled groundwater areas, it seems that actual management of these areas could be carried out by an existing district organization. This would help eliminate jurisdictional overlap between agencies and the concomitant problems of interagency rivalry as well as provide the structural basis for a truly integrated water management program. A logical candidate for this is the multi-purpose water conservancy district (WCD). As defined under its enabling legislation, a WCD is designed "to provide for conservation and development of the water and land resources of the state of Montana, conserve Montana's water for utilization for beneficial purposes within the state, and provide for the greatest beneficial use of water within this state. . . " (MCA§85-9-101). In addition, a WCD is authorized to borrow money, incur indebtedness, issue bonds, acquire water and water rights, undertake, construct, maintain and operate project works, set and collect fees and other charges, exercise the right of eminent domain, and enter into agreements with state and federal agencies.

Despite the apparent suitability of the WCD as a basinwide water resource management entity, none have been established in the state since the passage of the Water Conservancy District Act in 1969. Thus the actual usefulness of this management mechanism is difficult to determine. In her assessment of WCDs as a means for establishing and implementing basinwide water resource management plans, Anderson (1980) concludes that the political attitude of the state is not favorable to WCD formation. One key reason cited for this negative attitude is that WCDs are viewed as simply another layer of government granted with taxing authority -- certainly not a popular position in light of the current political climate. In contrasting the operation of WCDs in Colorado and South Dakota, Anderson suggests that Colorado has enjoyed much greater success with its WCDs (primarily concerned with groundwater resources) due to the state's higher tax base and the slowdown of special purpose district growth since the establishment of a WCD Act in 1937. In terms of Montana, Anderson concludes that the WCD does not represent the best jurisdictional alternative:

> In a state where rural densities do not create a high tax base, where the greatest water use is agriculturally oriented, and where rural values do not generally support planning except for pragmatic purposes, the effort required to promote and initiate water conservancy districts would probably not be warranted" (Anderson, 1980, p.35).

In an effort to slow the explosive growth of new districts and coordinate basinwide natural resource management, Nebraska has consolidated various districts into comprehensive Natural Resource Districts. From the standpoint of integrated resource management this represents the best of all worlds. Such consolidation also can be expected to meet with greater public support.

Rather than create a new district system, however, Anderson recommends that the powers of Montana's Soil and Water Conservation Districts (SWCDs) be expanded to incorporate the role of WCDs. Like WCDs, SWCDs perform a variety of administrative, planning and management functions. Although SWCDs in the past have often coincided with county boundaries, the enabling legislation could be modified so that they can extend across the natural boundaries of a watershed or drainage basin. In cases where groundwater basins do not coincide with these boundaries, special sub-basins could be established with management programs designed to meet the needs of that particular hydrologic setting. Anderson cautions that "soil and water conservation district have emerged as the bastions of agricultural interests" (Anderson, 1980, pp. 48-49). Thus, various aspects of the SWCD Act would have to be modified to ensure that other interests -- industry, municipal, fish, wildlife, and recreation -- are equitably represented.

Centralized groundwater management need not be limited to a public agency. However, at the present time it appears that public entities already exist in Montana which have the legal structure and technical expertise necessary for comprehensive water resource management. In light of this, it appears that the state's groundwater management needs may best be served by a basinwide district (such as the soil and water conservation district) with direct technical input from the Water Resources Division of the DNRC. Thus, the concept of a controlled groundwater zone would be incorporated under whatever management activities deemed necessary by the appropriate management district.

DECENTRALIZED MANAGEMENT - A BARGAINING APPROACH

The cost and complexity of intervention solutions as well as the questionable motives of central managers (Burton, 1980) have firmly established the decentralized bargaining approach to externality problems in economic literature. Within the context of water, numerous articles identify the competitive market as the most effective mechanism for the efficient allocation of resources. "Given clearly defined and freely transferable rights and the presence of competitive markets composed of willing buyers and sellers, the apportionment of rights to water would, over time, reflect the pressures of supply and demand" (Oeltjen and Fischer, 1978, pp. 269-270). McKeachnie (1970) observes that with individual property rights in water freely transferable, the profit motive can be relied upon to effect a smooth reallocation to higher valued uses.

The assumption of zero transaction costs in Coase's analysis (1960) has been recognized as a serious deficiency by many (Dahlman, 1979; Demsetz, 1964; Randall, 1972). Transaction costs have been singled out as the source of the market's failure to internalize externalities. Broadly defined, transaction costs include the costs of acquiring information, negotiating prices, charging for the use of resources, and excluding free riders (Burton, 1980). According to Cheung (1980) it is the absence of well-defined property rights which results in positive transaction costs. Burton (1980) adds that high transaction costs prevent the emergence of a bargaining solution. Thus much of the literature on water use has focused on improvement in the definition of water rights (Milliman, 1959). A summary of this literature is contained in Chapter 4.

While several specific recommendations for decentralized approaches to groundwater management have been made, none have actually been implemented. Smith (1977) suggests a water deeds approach to groundwater.

Under his proposed system, groundwater property rights are composed of two deeds. The first deed establishes a right to withdraw a certain quantity of groundwater on an annual basis in perpetuity. The actual quantity allocated is some fixed percentage (based on historical use) of natural recharge to the basin. The second deed establishes a lump sum right to some portion of the groundwater stored in the basin. The total allocation of stored water is limited to an estimated recoverable level. Presumably this level is established to prevent "excessive" overdraft problems such as land subsidence, water quality degradation and loss of recharge capacity. This "stock" right can be exercised at any time, either fully or only partially. A critical element to Smith's proposal is that all deeds can be sold, purchased, re-assigned or bequeathed. While no restrictions are placed on who can buy the rights (i.e. city residents can purchase from mining companies and vice-versa), it is not clear from Smith's article whether groundwater can be transferred out of the basin. Given the "recoverable" nature of the water allocated, it is assumed that inter-basin transfers would be permitted. At 10-to-20-year intervals, the program would be reviewed with possible modification of outstanding rights to account for changes in natural recharge.

The advantages of this system are obvious. From an efficiency standpoint, transferability enables groundwater to be allocated to its most valued use, exhausting the gains from trade and increasing total welfare in the area. New or enlarged wells are permitted as long as deed payments are made for the water used. Individual users are free to decide how much groundwater to use at any given time. For example, if a farmer believes the irrigation season will be unusually dry, he can exercise his stock right or purchase additional deeds. Thus, each user selects the level of risk-aversion most appropriate for him.

However, there are some serious limitations to the deeds approach. It is not purely a "private" market solution. Significant technical data are required to determine recharge rates and the "safe" stock level. Presumably only a public agency such as a state water resources department has the technical expertise to conduct the necessary hydrologic studies. These studies are costly and may take many years to complete depending on the complexity of the hydrologic system. An enforcement mechanism is also necessary not only to monitor annual groundwater use but to maintain records on stock use and transfers. Meters would be required on all wells. Conflicts will undoubtedly arise over the initial allocation of the deeds. Deed-holders are still not protected from third party effects which may arise once rights are transferred. Congestion externalities in the form of localized drawdown may occur, for example, if pumping activities become concentrated over one section of the basin or if neighboring pumpers simultaneously decide to exercise their stock rights in full.

Theoretically under a bargaining solution parties involved in the externality could bribe each other either to accept the externality or to prevent it from happening. However, Randall (1972) and others have argued that the actual outcome depends on the liability rule in force. Still others (Wellisz, 1964) assert that bargaining solutions break down when large groups are involved or when externalities are mutual. Notes Whitcomb:

> If we were to allow the assumptions the 'private bargain' people make for externalities to hold everywhere in price theory, we would have no monopoly or imperfect competition theory, and, in fact, no situations anywhere that are not Pareto optimal. After all, the victims of a monopoly could pay the monopolist to act as if he were a perfect competitor and still be better off (by the definition of Pareto optimum). They don't do so, of course, only because bargaining is difficult and breaks down owing to the size of the coalition and/or the issue of division of spoils (Whitcomb, 1972, p. 123).

Water banking is another allocation system that has been suggested as a means of improving the efficiency of water use (Angelides and Bardach, 1978). It has been used on a limited scale in California and Idaho. Under the basic system, individuals not wishing to use their water can deposit it in a "bank" and receive a rental or use fee. Those wishing more water can, for a fee, withdraw it from the bank. Like any institution, the agency operating the bank arranges transactions, handles the flow of money (and water), and maintains all records. The bank can be either a public or private entity, although Angelides and Bardach suggest that it may be easier if public water agencies initiate the system. In the past water banking proposals have focused on surface water allocation, but the concept theoretically could be extended to groundwater. Like transferable deeds, water transfers under a banking system promote economic efficiency in that those who value water the most are able to obtain it. In equilibrium there is equimarginal value in use and a Pareto-optimal allocation. As with any transfer mechanism, water rights must be well-defined for banking to be successful. Third-parties harmed by transfers must also be protected. Banks could authorize compensation payments to be added to the price charged for withdrawals from the bank. Johnson et al. (1979) suggest that third-party impacts could be minimized by limiting transfers to the amount of water actually consumed in the original right holder's use rather than the total diversion or extraction. While banks are not necessary for transfers to be effective, Angelides and Bardach (1978) emphasize their role in reducing transaction costs.

Third-party effects are more complex with groundwater use than with surface water due to the technical interdependence of extraction activities. This complicating factor may limit the success of a purely decentralized management scheme. In an article exploring the role of regulation in the efficiency of ocean exploitation, Sweeney et al. (1974) single out two key characteristics of oil which, unlike magnesium nodules, make negotiation and enforcement of rights prohibitively expensive: 1) the difficulty in identifying one producer's oil; 2) the pumping by one oil producer interferes with the other's efficiency. Burton (1980) arrives at a similar conclusion. "It is always possible in principle to define (i.e. set up) a system of private rights in property. But in some cases it would still be prohibitively expensive for the owners to police and enforce their rights, given the technical difficulties . . ." (Burton, 1980, p. 69). Whitcomb (1972) carries the conclusion one step further: "Since externalities continue to exist in all kinds of real world situations, it seems impossible to sustain the conviction that private bargains among firms affected by externalities can eliminate all need for corrective action by a central authority" (Whitcomb, 1972, p. 17).

In theory private bargaining is capable of providing the most efficient and flexible means for improving the allocation of groundwater. As a result it comes closest to meeting the goal of maximized social welfare. Whether it actually can achieve this goal depends upon the costs of bargaining relative to the benefits it produces.

Chapter 6

OPTIMAL GROUNDWATER USE: A CASE STUDY

In the previous chapter considerable attention was focused on centralized approaches to groundwater management. As was pointed out, these management alternatives require that an optimal use rate be established for the basin before the appropriate tax-subsidy, quota, rotation or spacing scheme can be determined. The primary intent of this chapter is to demonstrate how such a rate can be estimated. It should be recognized, however, that this rate is not optimal in any absolute sense of the word. Rather, it is optimal given the assumptions and structure of the model employed. Thus, the rate established here should be viewed as <u>conditionally</u> optimal.

In essence, an optimal use rate is selected which maximizes expected net returns to the study area over an infinite planning (decision) horizon. The selection of this rate is a multi-stage decision process (Bellman, 1957); that is at every physical state or condition of the groundwater system at a point in time, a level of use transforming the system into another state in the next time period is chosen which maximizes net returns to the area. This decision process continues until, given a sufficiently large number of time periods, the use rate selected converges to some constant decision rule (Howard, 1960; Burt and Allison, 1963). In practice this relationship is a recursive one; decisions are made backward from some future time to the present.

In this study both linear and dynamic programming are used to derive the optimal decision rule. The methodology used here draws heavily on the work of Burt (1964 a, g) as well as some of the general principles established by Brown and McGuire (1967), Domenico et al. (1968) and Brown and Deacon (1972) in their work on groundwater.

While much of the information used in deriving this rate is based on actual physical and economic data from the Crow Creek Valley area of Montana, in many instances assumptions were made to simplify the model or to fill informational voids. Thus the results from this study do not necessarily provide a management prescription for the area, but are suggestive of the important considerations involved. They are intended to serve as a guide as to how an optimal rate can be derived _in general_, its interpretation, the information required and the impact of changes in various arguments of the model on the decision rule established.

The model and its results are couched in terms of an actual groundwater basin in Montana rather than some hypothetical area for two reasons. First, it helped to structure the problem for the analyst and thereby provide direction to the overall study. Secondly, the analyst felt that those ultimately using the report could better relate to "actual" results rather than hypothetical ones. An important aspect of this is that it was necessary to work with data as it actually exists (often in a less than desirable form) rather than hypothetical, "text-book" conditions that are free from the complications of reality. Thus data problems associated with empirical modeling are addressed in the study.

The chapter is divided into four basic sections, following the organization of the model used in developing an optimal decision rule. An optimal decision rule is defined here as a policy guide which establishes the optimal level of groundwater use for a basin (that which maximizes net returns to the area over the appropriate planning horizon) given an initial quantity of groundwater in storage. Thus the rule establishes optimal use levels for all possible quantities of groundwater in storage. In this study the primary concern is with the general structure (shape) of the decision rule rather than the implied level of use. The first section describes the study area, the reason it was selected, its physical characteristics, its economic setting and the role of groundwater in the area's water profile. The second section describes the linear programming (LP) model used in deriving the gross returns associated with groundwater use. Literature associated with the use of LP as an optimization routine for agricultural and water resource management decision making is briefly reviewed. Data sources and assumptions are detailed. Finally, the results of the LP model are presented. The third section describes the dynamic programming (DP) portion of the overall model and how the results from the LP model are incorporated. The use of DP in previous groundwater studies is briefly reviewed. Data sources, assumptions and empirical results are summarized. Finally, the results are interpreted in terms of their implication for groundwater use and management in the area. The sensitivity of these results with respect to energy costs, the discount rate, land productivity and the areal extent of the aquifer are explored in the fourth section.

THE STUDY AREA

The Crow Creek Valley located in southcentral Broadwater County, Montana (Figure 6.1) was selected as a study site for several reasons. The most important reason was the fact that it was one of the few basins in Montana where some physical data were available on the aquifer system underlying it (Lorenz and McMurtrey, 1956; Wyatt, 1981). Little is known about the hydrogeologic characteristics of groundwater occurences in Montana. Availability of such data proved to be the most stringent limitation faced in selecting a potential study area. As demonstrated in the remaining sections of this chapter, a certain minimal level of physical data is needed before an optimal groundwater withdrawal rate can be estimated. Thus if active groundwater management programs are to be pursued in Montana, a far greater commitment must be made to obtaining basic hydrologic information. It is hoped that this portion of the study will highlight the kinds of data needed.

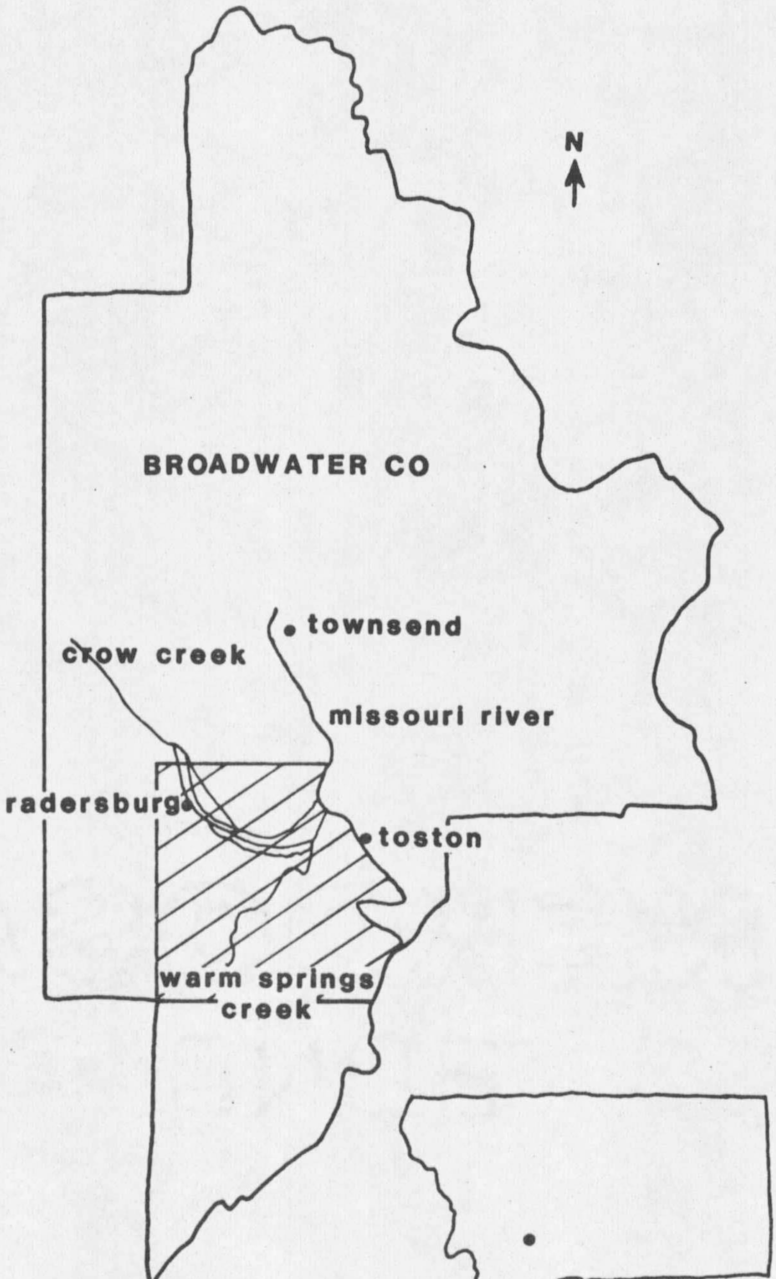

Figure 6.1. Crow Creek Valley (Shaded Region).

The valley also was chosen as a study site because of its relatively small size and agrarian setting. Both characteristics simplified the data requirements of the economic model used. Finally, the area was chosen due to the increasing reliance on groundwater for irrigation in the region. Currently 30 high-capacity (greater than 1,000 gpm) irrigation wells are located within a 16 square-mile section of the valley.

Physical Setting

Crow Creek Valley occupies approximately 150 square miles of an alluvial plain bordered by the Elkhorn Mountains on the west and the Missouri River to the east. Outcroppings and rolling hills roughly form a northern and southern boundary to the area. Elevations within the valley itself range between 3800 and 4600 feet with local relief in the valley floor less than 150 feet (Wyatt, 1981). The only exception is Lone Mountain (5,024 feet high) which rises some 600 feet above the surrounding valley. Soils in the area range from silty alluvium deposited by the Missouri River to weathered volcanic sediments eroded from the Elkhorn Mountains. The majority of the soils in the study area have been classified in capability groups II, III and VI (DNRC Land Classification Survey, 1975). (See page 118 for a description of the capability classification system.) Class II and III soils are suitable for cultivation subject to certain limitations.

Class VI soils generally are unsuited to cultivation and are largely limited to pasture, range,woodland or wildlife habitat (SCS Soil Survey of Broadwater County Area, Montana, 1977, p. 36).

Climatic conditions in the area are relatively dry. Natural vegetation in the valley is primarily composed of sagebrush and grasses except for coniferous and deciduous tree growth along streams and creeks. Although the mountains to the west of the valley receive 40 inches of precipitation annually, they create a rain shadow effect and less than 12 inches per year actually fall on the lowlands (Wyatt, 1981). The SCS has classified the region as a moderate consumptive use climate area for irrigation.

The primary sources of irrigation water in the area are two tributary streams of the Missouri River, Crow Creek and Warm Springs Creek, the Missouri River itself via the Toston Irrigation Canal Project and groundwater underlying the valley floor.

Wyatt (1981) in his hydrogeologic study of the valley notes that the primary source of groundwater for irrigation wells is not well defined and suggests several sources: direct recharge from precipitation in the Elkhorn Mountains to the west; and, possibly upward leakage from an underlying deep flow system. All of the irrigation wells in the study area are under artesian pressure, suggesting the presence of some confining or relatively impermeable overlying stratum such as a tight clay or hardpan (Figure 6.2). Where a series of clay lenses or

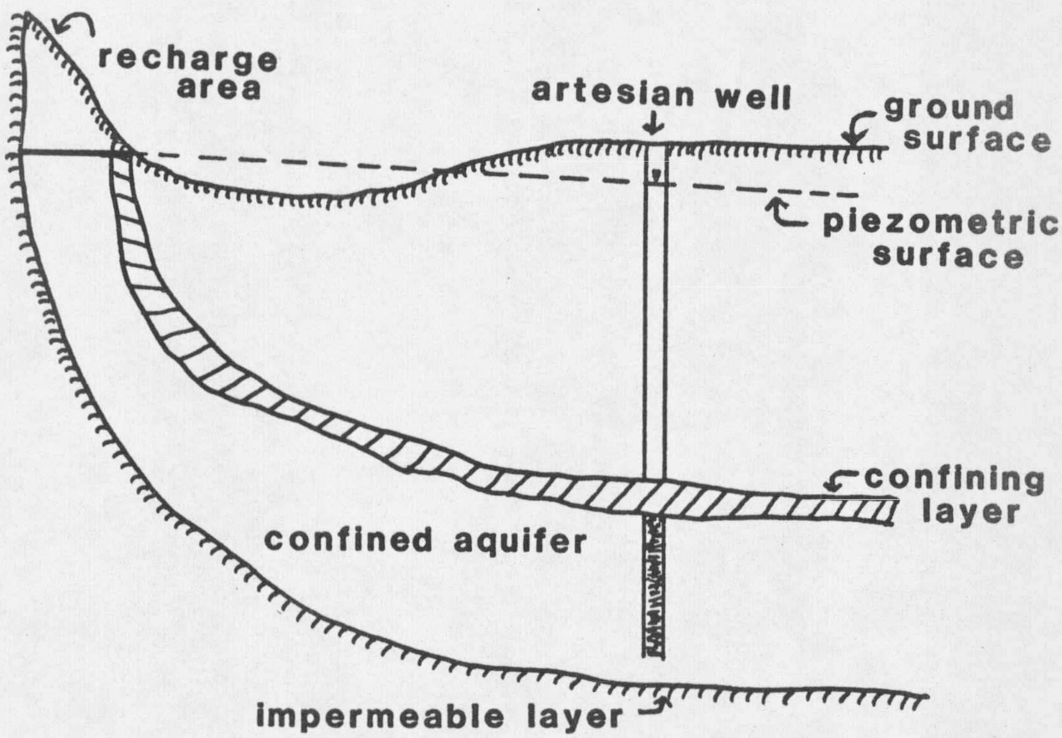

Figure 6.2. Cross-section of a hypothetical confined aquifer.

layers are present, a variety of confined aquifers may exist at different depths. However, for purposes of this study it was assumed that there is a single confined aquifer underlying the basin which provides water to all of the irrigation wells. This assumption greatly simplifies the calculations required in deriving an optimal ground-water withdrawal rate. Well elevations were adjusted to a common datum (4110 feet above sea level) and, on the basis of well log data, static water levels (piezometric surfaces prior to pumping) were found to have an average depth of 55 feet below the ground surface. On the basis of well log drilling descriptions it was determined that the clay stratum which confines the aquifer occurs at an average depth of 215 feet. Wyatt (1981) refers to this aquifer as the "Tertiary-Quaternary" aquifer because of the sediments from which the water is extracted.

The methodology established in this study could be adapted to basins where more than one confined aquifer is relevant. In such a setting each aquifer would be treated as a separate sub-basin (assuming there is no leakage between the aquifers) and an optimal decision rule calculated for each. From this, an aggregate policy could be formulated, recognizing the rules established for each sub-basin. In such cases much more detailed physical data are required to accurately define the conditions and extent of each sub-basin.

The actual areal extent of the confined aquifer examined in this study is not precisely known. Rarely is such information ever known about a natural groundwater system. Instead hydrologists and geologists draw on available physical data to estimate where aquifer boundaries, in theory, should occur. Estimated boundaries for the "Tertiary-Quaternary" aquifer are depicted in Figure 6.3.

On the basis of pumping test results reported by Wyatt (1981), the storage coefficient used in calculating the volume of groundwater in storage in the aquifer was .0016. The storage coefficient is a unitless measured defined as:

> . . . the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer per unit change in the component of head normal to that surface (Todd, 1980, p. 45).

Recharge was assumed to be 30,000 acre feet per year (as estimated by Wyatt, 1981). Given the dearth of information on frequency distributions associated with this estimate, recharge was assumed to be constant. Also no information was available on how either the amount of groundwater in storage or quantity used affects recharge. Thus recharge was assumed to be unaffected by pumping, and a deterministic model was used in the dynamic programming portion of the analysis. The details of this model are enumerated in a subsequent section of this chapter.

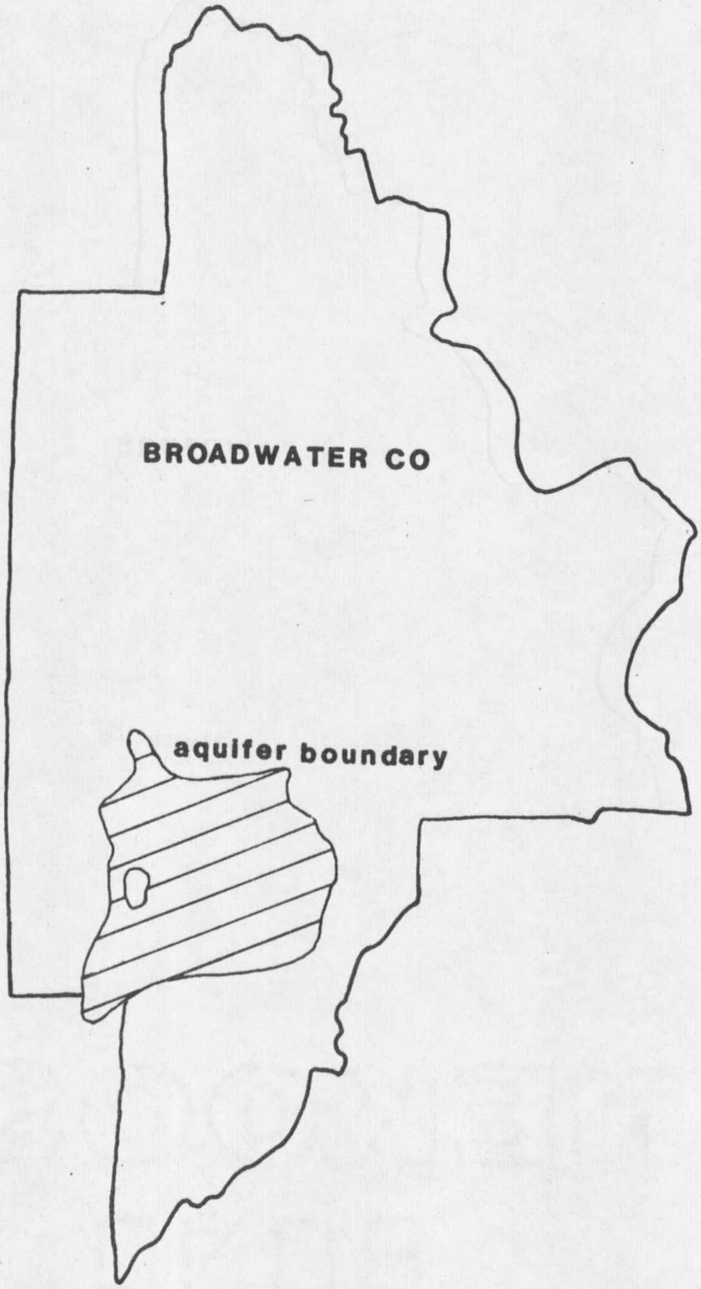

Figure 6.3. Hypothetical boundaries for the "Tertiary-Quaternary" aquifer underlying Crow Creek Valley as estimated by W yatt (1981).

Economic Setting

Water has played a vital role in the economy of the Crow Creek Valley since its first settlement. Both early mining and cattle ranching activities depended on the availability of water. Radersburg, 20 miles southwest of Townsend, was the site of placer gold mining as early as 1863. Later, lode mining of gold and quartz became an important activity. Toston, 11 miles southeast of Townsend, served as a shipping point for the Radersburg mining camp (Water Resources Survey - Broadwater County, Montana, 1956). At the same time ranching and farming became firmly established, eventually dominating as mining activities began to play out. Severe droughts in the late 1910s and early 1920s reminded area farmers and ranchers of the importance of reliable sources of irrigation water.

The Crow Creek Pumping Project near Toston was built in the early 1950s by the U.S. Bureau of Reclamation to provide irrigation water for new lands brought under cultivation to replace those flooded by the Canyon Ferry Reservoir. In 1955 the Toston Irrigation District was formed and took over operation of the pumping project. Today approximately 24,000 acre feet of water are pumped out of the Missouri River and delivered by gravity flow through the Toston and Lombard Canals and associated lateral system to some 6,000 acres of irrigated farmland in the valley (Kolberg, 1981).

Over the last 40 years agriculture has become the valley's primary source of revenue while mining has all but died out. Today cattle and hog production as well as irrigated and dryland farming are the main agricultural activities. Winter wheat and barley are the primary dry-land crops. Irrigated crops include: alfalfa hay, spring wheat, barley and seed potatoes. Corn, oats, grass seed and triticale comprise less than one percent of the total irrigated acreage. Sugar beets have not been grown since 1978 when the area lost its sugar beet contract.

The Role of Groundwater

As is characteristic throughout much of Montana, groundwater played only a minor role in the water profile of the Crow Creek Valley until the 1950s (see Figure 6.4). Prior to this time, groundwater was used almost exclusively for domestic and stock water purposes. Surface water from the Missouri River, Crow Creek and Warm Springs Creek was used for irrigation. But by the early 1950s these tributary sources were completely utilized. Note Lorenz and McMurtrey (1956), "During the summer months the entire flow from these perennial streams [Crow Creek and Warm Springs Creek] is diverted for irrigation" (p. 209). As a result, area farmers and ranchers began to turn to groundwater as an additional source of water.

SCS records indicate that the first high-capacity irrigation well was drilled in the study area in 1958. Today 30 such wells have been

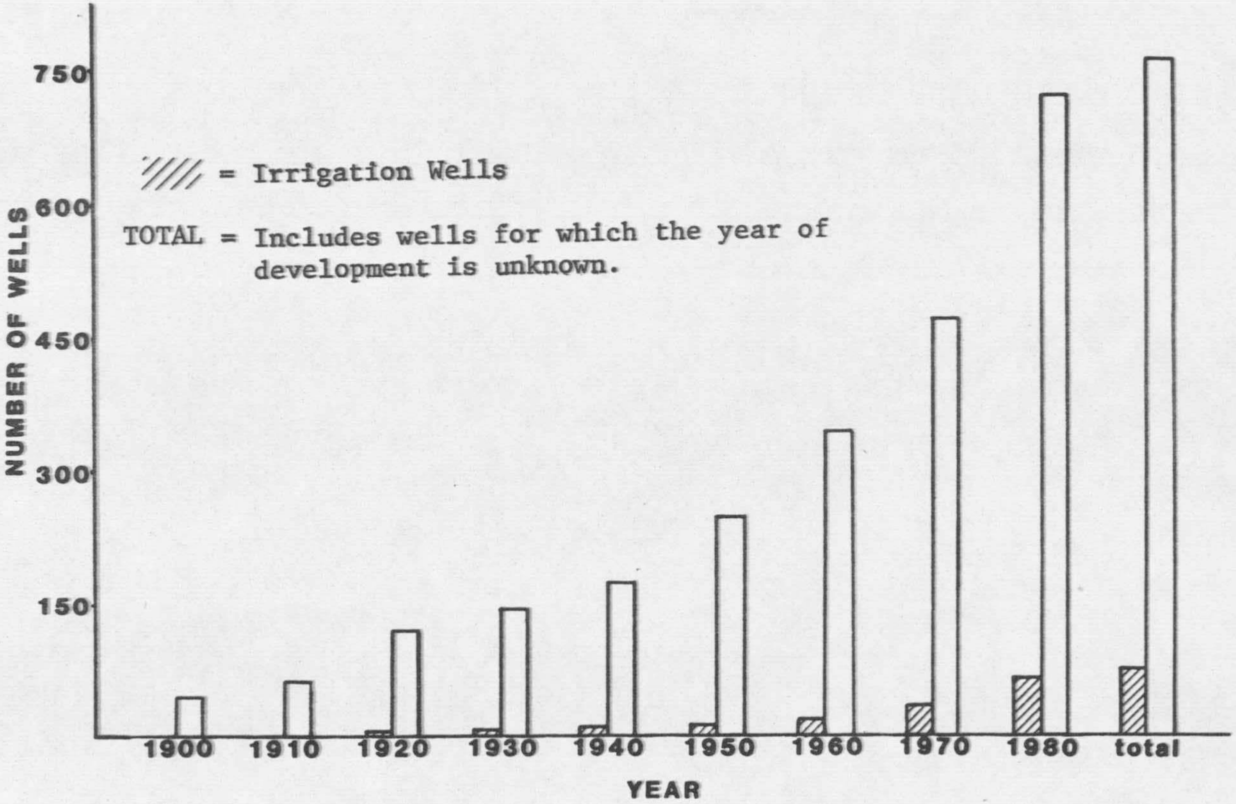

Figure 6.4. Well Number for Broadwater County at 10-year Intervals.

Source: Montana Bureau of Mines and Geology Well Log Inventory Records.

installed, providing water to approximately 25 percent of the area's irrigated cropland (Crowell, 1981). Wyatt (1981) estimates that 7,368 acre feet of groundwater are withdrawn from these wells during the irrigation season, with pumping rates ranging from 600 to 3420 gpm and an average application rate of 1.8 acre feet per acre per season. From casual discussions with ten area ranchers and farmers it appears that these individuals have turned to groundwater despite its high initial investment costs for three basic reasons: 1) it enables new lands to be brought under irrigation; 2) it is a more dependable source of water; and 3) it is less labor-intensive than surface water irrigation.

RETURNS FROM GROUNDWATER USE

Background

An important step in developing an optimal decision rule for groundwater extraction in the study area is calculation of expected returns or net benefits associated with various quantities of groundwater availability per unit of time. For purposes of this study, a year is defined as the appropriate time period. The linear programming methodology used here is virtually identical to that used by Burt 1964a). Given the small geographic scope of the study and the types of crops grown, the purely competitive model seems entirely appropriate. That is, area farmers are price takers in both the factor and product markets.

Parametric programming was applied whereby the fixed level of groundwater available was systematically increased from zero acre feet per year to some upper limit. By changing this resource constraint it was possible to determine how groundwater availability and use affect not only the optimal activity (crop) combination but the level of farm profit (the objective function value) and resource use. From this, a marginal value product function for groundwater use was derived, enabling the calculation of expected immediate returns under various rates of use given a particular quantity of groundwater in storage in the aquifer. As is described in greater detail later in this chapter, such information is a key component of the dynamic model used in developing a decision rule for groundwater withdrawal over a long or even infinite planning horizon.

Optimization routines using linear programming algorithms have been used extensively for agricultural planning and other decision making activities (Heady and Candler, 1958; Agrawal and Heady, 1972; Beneke and Winterboer, 1973; Baumol, 1977). Both Moore and Hedges (1963) and Gisser (1970) use parametric linear programming to estimate demand for irrigation water. While in these studies the cost of irrigation water is varied parametrically to generate a demand function, Moore and Hedges note that the same information could have been obtained by varying the water resouce constraint rather than cost. Linear programming also has been frequently applied in groundwater management studies. Bredehoeft and Young (1970), McConnen and Menon (1968), Hardin and Lacewell (1980) and others use linear programming formulations in their analyses. Burt (1964a) uses linear programming as an initial step in deriving an optimal decision rule.

Model Description

The linear programming problem used in this study can be defined as follows:

objective function: $\text{Max} \sum_{i=1}^{n} C_i X_i \quad i = 1, 2, \ldots n$

Subject to: $\sum_{j=1}^{m} a_{ij} X_i \leq b_j \quad j = 1, 2, \ldots m$

and: $X_i \geq 0$ for all i,

where: X_i = acreage of the ith crop grown.

C_i = net revenue or return over variable cost per acre of the ith crop.

a_{ij} = the amount of the jth resource required to produce an acre of the ith crop.

b_j = the total level of the jth resource available for use by the n crop activities. There are a total of m resources which are constraining to the crop activities. These include: total irrigated and potentially irrigable acres, quantity of groundwater available and various crop acreage limitations designed to reflect rotational patterns or other practices and habits which would not be suggested in a purely economic analysis. These constraints are explored in greater detail in a subsequent section.

The non-negativity requirement, $X_i \geq 0$, simply precludes the mathematical possibility of negative acreage. While labor is not treated as a resource constraint, a non-restrictive labor balance equation is incorporated into the model so that total labor requirements can be accounted for. Such information may be valuable to others analyzing the results of this study or those interested in expanding its scope.

As noted above, the use of parametric programming enabled the b_j associated with groundwater availability to be varied so that a value function for groundwater use could be derived. For computational ease and to minimize the number of computer runs necessary, the groundwater resource was arbitrarily increased by increments of 2,500 acre feet to a total level of 50,000 acre feet. This upper limit represented a level of water more than sufficient to deliver 2.14 acre feet of water per year to all the potentially irrigable land in the study area. As is explained below, the 2.14 acre feet figure represents a gross irrigation requirement for the most water intensive crop grown in the Crow Creek Valley (alfalfa). The linear programming matrix used in the study is presented in Appendix A. A standard mixed integer computer programming package (NHILP) developed by Verner G. Hurt of Mississippi State University was used in performing the optimization analysis.

Assumptions and Data Sources

As with any empirical study it was necessary to make certain assumptions about the data used and the overall structure of the model. In some instances assumptions were made when no other information was available. In other cases they were made to simplify some of the computational demands or limit the complexity of the program design. It should be reemphasized that this study is not intended to represent the final word on how groundwater resources in the Crow Creek Valley should be managed. Rather, it is intended to demonstrate how an optimal decision rule can be estimated, what sorts of information are required and the implications of the rule for aquifer management. In many respects the study is a hypothetical one except that wherever possible "real" data relating to the physical and economic conditions of the Crow Creek Valley have been used. This cautionary note should be kept in mind throughout the remainder of this paper.

One of the most important assumptions of this model is that the entire area was treated as a single farm. Thus the optimal activity pattern is for the entire area and not for individual farms. Miller (1966) provides a theoretical justification for aggregating an area into a single linear programming model. Moore and Hedges (1963) and Gisser (1970) treat their respective study areas with an aggregate model in generating demand functions for irrigation water. Similar assumptions are used by Burt (1964 a, b), Brown and McGuire (1967) and

Brown and Deacon (1972) in their work on groundwater. This assumption is consistent with our objective of deriving an optimal decision rule for the entire basin. It is our ultimate intent to specify a groundwater policy which maximizes the present value of expected returns to the area, irrespective of the distributional implications. (For a detailed explanation of why this objective is chosen, see Chapter 3.) Hence treating the area in aggregate appears to be justifiable given the objective of the study.

The objective function used in the LP model assumes that the farm seeks to maximize returns or profits. Although this is consistent with the rationality assumption of neoclassical microeconomic theory, a growing segment of the literature emphasizes the incorporation of risk in economic models. Uncertainty in terms of income variability, resource availability and the technical coefficients used in constraint equations can have an important impact on the optimal activity mix and level of resource use (Anderson et al. 1977). Risk and uncertainty can be incorporated into a model through the use of an alternative algorithm such as quadratic risk programming or with linear risk programs which place a constraint on the maximum allowable loss or which minimize the total absolute deviation (MOTAD) of the objective function value. Other programming formulations incorporate game theory in the decision criteria or utilize Monte Carlo studies. Anderson et al. (1977) provide an overview of the various programming techniques available. For this particular study risk was ignored in order to simplify the computational work. Subsequent studies might consider its inclusion.

Associated with the objective function of profit maximization is the assumption that net farm income (and the related market values of the crops) is an adequate measure of area net benefit. Again, deferring to Chapter 3 in lieu of some alternative measure farm income appears to be the only available welfare index.

As mentioned earlier the assumption of perfect competition in both the product and factor markets in the study area appears to be relatively accurate. Thus the level of output or input usage does not affect the price of either, and a single set of prices are used in the analysis. For purposes of this study it was assumed that the prices will not change in real terms or will all change by the same relative increment, cancelling out any impact on the results. This assumption may not be strictly valid for electricity used for irrigation. The impact of changing energy costs is explored through sensitivity analysis later in this chapter. Technology and the irrigation requirements of the crops also were assumed to be unchanging.

By using linear objective functions and linear production coefficients it was further assumed that there are no diminishing marginal returns, i.e. each additional unit of output requires the same level of inputs and costs are constant. Thus, economies of scale are not possible (Beneke and Winterboer, 1973).

Both capital and labor were treated as unlimited and valued at their market price during the 1980 base year period. Thus only land and water served as limiting or constraining resources.

A 1975 land classification survey of Broadwater County by the DNRC indicates that some 18,437 acres are currently under irrigation in the Crow Creek Valley area. Since the primary concern at this stage of the study was to determine returns to irrigation water, only crop activities were considered in the LP analysis. Thus land used solely for irrigated pasture was subtracted out of the irrigated land base. A four-year historical average (1978-1981) based on U.S. Agricultural Stabilization and Conservation Service (ASCS) records indicate that some 1,347 acres are used for irrigated pasture annually in the study area. Thus total currently irrigated cropland is estimated at 17,090 acres. The same land classification survey estimates that an additional 31,961 acres in the study area are physically suited for irrigation in terms of soil and topographic conditions and drainage. This classification does not consider economics or water availability. For purposes of this analysis the 31,961 acre figure was used as an estimate of potentially irrigable land.

Most of the currently irrigated land falls under capability classes II and III, while 80 percent of the potentially irrigable land is considered to be class III. Capability groupings are a classification system used by the U.S. Soil Conservation Service (SCS) to indicate in very general terms the suitability of soils for most types of field crops. From a technical standpoint class II lands have soils with moderate limitations in terms of the plants that can be grown and the conservation practices required. Class III lands have soils with severe limitations. By contrast class I lands have soils with few limitations that restrict their use. Unfortunately no information was available in the study area on differences in productivity associated with these land classes. Deriving such data would require sophisticated studies beyond the technical expertise of this analyst. Thus the problem of differences in land productivity was addressed in several ways. Initially all the irrigated and potentially irrigable land was treated as homogeneous; that is, equal yields are produced from the same input levels. This is an admittedly unrealistic assumption and, as expected, results in the generation of a nearly linear returns function (see p. 140). Anderson et al. (1982) emphasize that the shape of this returns function is critical in determining the extent of the externality problem and, thus, how groundwater use under an optimal decision rule differs from that under an open access situation. With a linear returns function, the difference is minimal. Recognizing this limitation, the returns function was then modified to account for differences in land productivity. Specifically an exponential decay function in the form Ae^{-bq} was applied to the marginal returns function, where b represents the rate of decay, q is the level of groundwater use and A is a constant. Integrating this, a new total returns function was derived exhibiting a more concave shape (see p. 140). This shape reflects the diminishing marginal productivity of additional lands brought under irrigation as more groundwater is available. That is, the most productive class I lands are used first followed by progressively lower quality lands. Associated with these less productive lands are lower yields, greater input requirements and, hence, lower returns. Since class I soils are well suited to a wide variety of crops, it was assumed that declining land productivity did not occur until <u>after</u> all class I lands had been utilized (estimated at a level of groundwater use greater than 667.85 acre feet). The decay rate, b, was selected such that at this rate of groundwater use an elasticity (η) representing the proportionate change in returns for a proportionate change in groundwater use was equal to some arbitrary level. In essence the elasticity figure simply provided a "kick off" point for the function since it increases with the level of groundwater use. Thus, $b = \frac{\eta}{667.85}$ while A was chosen such that the decay function was equal to one when $q = 667.85$. Several elasticity values were examined and their impacts on the optimal decision rule are explored in the sensitivity analysis section of this chapter.

Obviously many assumptions were made in applying the decay function. Specific information on yield variations and cost differences would provide a superior method for incorporating productivity differences into the model. For example, land constraints could be further broken down by class category and additional activities included in the objective function to reflect the different returns over variable costs associated with each crop on each class of land. However, in lieu of this information, application of the decay function seems to be one method for recognizing the role of land productivity in determining the optimal rate of groundwater use.

Water is the other major resource constraint. Since 17,090 acres of cropland are currently under irrigation, it was assumed that sufficient water is already available for this land even for the most water-intensive crops, and that water conveyance and irrigation distribution systems already exist. Thus investment costs for irrigation equipment serving the currently irrigated acreage were ignored in the returns over variable cost calculations and water was not treated as a constraint.

This was not the case for the 31,961 potentially irrigable acres, however. For these acres additional water and new irrigation equipment are required. Thus a decision to grow irrigated crops on this land also represents a decision to obtain additional water and invest in capital equipment. As a result, ownership costs for new irrigation distribution systems were converted into an annual cost per acre (amortized) and treated as a variable cost, though technically a fixed cost.

It was further assumed that groundwater is the only source of irrigation water for the potentially irrigable acreage. Groundwater quality was assumed to be uniform and suitable for irrigation. The first assumption was made for two reasons. First, the study is concerned with groundwater and this assumption made it possible to derive a net benefit function associated with groundwater use in the area. Secondly, the assumption, to a large degree, reflects the reality of the situation. As mentioned previously flows from both Crow Creek and Warm Springs Creek are entirely diverted during the summer months, virtually precluding them as sources of new irrigation water. The Toston Irrigation District is limited to a total withdrawal of 24,000 acre feet per year from the Missouri River. Arnold Kolberg, project manager for the district, reports that additional appropriations are not possible given the senior claims of the U.S. Bureau of Reclamation (BuRec) and Montana Power Company (MPC) on the Upper Missouri River.

These existing claims have sparked a great deal of controversy regarding additional appropriations of Upper Missouri River water. Almost without exception, BuRec and MPC have objected to all applications to appropriate water from the Missouri River upstream from Canyon Ferry Reservoir. MPC in its objections, citing an 1898 water right, asserts that no unappropriated water exists above the reservoir and that new appropriations would deplete water needed for its hydroelectric generation activities. Similarly BuRec claims that additional appropriations would deplete water needed for irrigation in the Helena Valley and energy production. According to Fitz (1981) in a report by DNRC, "In order for water in the Upper Missouri River to be considered available for appropriation, it must be water that is in excess of the water used by WPRS [BuRec] at Canyon Ferry. WPRS [BuRec] claims that no such water is available on a reliable basis and that water is never available throughout the entire irrigation season" (Fitz, 1981, p. 6). In an effort to determine whether water is available on the Upper Missouri River above Canyon Ferry, the Water Science Bureau of DNRC conducted a hydrologic study of water flows on the Upper Missouri based on time series data. The following is the conclusion of their analysis: "Since no spill (no available water) is expected in 40% of the years, water for appropriation probably will be available in only 60% of the years. As the run-off season progresses the probability of available water decreases. After August 9, water is essentially never available for appropriation" (Fitz, 1981, p. 19).

Given the conclusions of this analysis and assuming a rather high degree of risk aversion on the part of the individual entrepreneur, it seems unlikely that: 1) a permit for new appropriations of surface water can be obtained; and, 2) an entrepreneur would be willing to take the risk of an uncertain water supply in light of the fact that this uncertainty increases as the irrigation season progresses and <u>after</u> a commitment has been made as to what crop is grown. For these reasons it appears that the assumption that groundwater will be the primary source of water for irrigating new land in the Crow Creek Valley is not that far astray from reality.

As mentioned above, investment costs of irrigation systems for this new land are incorporated into the variable cost calculation. Obviously there are myriad irrigation systems that can be used. Thus in calculating these costs certain assumptions had to be made.

For well costs, a synthesis approach was taken whereby construction characteristics, designs and depths of existing wells in the area were averaged to determine a "typical" irrigation well. It could be successfully argued that no such well exists and that each must be customized to meet the needs of the immediate soil conditions. Recognizing this criticism, it should be remembered that for purposes of this study the well used for cost estimation is purely synthetic.

The "typical" well was assumed to be drilled to a depth of 260 feet, using a 16-inch diameter casing of 1/4 inch prime steel. A typical pumping capacity was estimated at 1500 gallons per minute. The majority of the wells in the study area have perforated casings rather than screens in addition to the casing. Screening material is extremely expensive. Although many drillers argue that screens extend the useful life of the well and pump because they do not clog as easily as the perforations and do a better job of keeping fine material and sands out of the water, cost calculations used in the study are based on the use of a perforated casing with gravel packing around the casing. It was further assumed that water is pumped directly from the well into the mainline of the distribution system rather than into a ditch first, and that a single pump is used to bring the water to the surface and pressurize the distribution system. Both of these conditions are typical of the current trend in irrigation well system design.

The costs of the well pump, motor, electric panel and wiring are considered in the dynamic programming portion of the analysis and are detailed later on in the chapter. Thus well investment costs used for calculating returns over variable costs for the various crop activities are for the well only.

The vast majority of the farmers in the Crow Creek Valley use sprinkler systems for distributing irrigation water. Mike Crowell, SCS District Office for Broadwater County, estimates that 80 percent of the irrigated acres in the valley are served by sprinkler systems. Currently the majority (55 percent) of these sytems are wheel lines; however, irrigation equipment suppliers in the area suggest that there is an increasing trend toward the use of center pivot systems. To reflect this trend, investment costs were averaged for a wheel line system servicing 160 acres and a center pivot system delivering water to 133 acres (a combined average of 146.5 acres). For both systems an application rate of seven gallons per minute per acre was used.

The useful life of the distribution systems were estimated at 15 years and 25 years for the well. Obviously actual life varies tremendously depending on how well an individual operator maintains the equipment, weather conditions (freak wind storms or lightening can destroy a system) and on water quality. For example, highly corrosive water can rust out the casing in a well in a relatively short period of time. Problems such as these were ignored. Useful life estimates used in this study were based on information contained in The Economics of Sprinkler Irrigation, Circular 1255, Cooperative Extension Service, Montana State University and Cost of Operating Center Pivot Systems on Irrigated Pastures 1972-74 & Projected Costs for 1975-76, Report No. 68, Agricultural Experiment Station, University of Nebraska - Lincoln.

Actual cost information for the well and sprinkler systems was obtained by contacting several well drillers and irrigation equipment suppliers. In general, well drillers charge by the foot for drilling and casing and on an hourly basis for testing and developing the well and perforating the casing. However, for purposes of this study, all well investment costs were estimated on a per foot basis. Cost figures for the irrigation sprinkler systems ultimately used in the study represent the high range of the estimates received but were judged to be the most reliable. Table 6.1 summarizes the cost data and Table 6.2 summarizes them on an annualized basis.

Irrigation requirements for the crops were based on estimates reported in the Soil Conservation Service's Irrigation Guide for Montana

Table 6.1. Irrigation well[1] and distribution system investment costs (1980 dollars).

System Description	System Cost	Cost Per Acre
Irrigation Well[1] (146.5 acres)	$19,500 @ $75/foot	$133.11
260 foot depth 16" diameter, ¼" steel casing Perforated (slotted) casing testing and developing 1500 gpm pumping rate		
Center Pivot (133 acres)	$46,281	$347.98
7 towers 30 psi operating pressure Application rate = 7 gpm/acre Buried mainline Assumes well at edge of field		
Wheel line (160 acres)	$38,108	$238.18
4 ¼-mile wheel line laterals 2640 feet of buried mainline 50 psi operating pressure Application rate = 7 gpm/acre Assumes well at edge of field		

[1] Well only, does not include cost of pump, motor, electric panel or wiring. Acreage is based on a simple average of that served by center pivot and wheel line distribution systems.

Table 6.2. Annual investment costs of irrigation well and distribution systems. Assumes zero salvage value and a six (6) percent real rate of interest (1980 dollars).

System

1. Center Pivot & Well

   Capital recovery factor: 15 years, 6% = .10296[1]
   Capital recovery factor: 25 years, 6% = .07823[1]
   Annual Cost/acre = (46,281) (.10296)/133 + (19,500)(.07823)/133
   Annual Cost/acre = $47.30

2. Wheel line & Well

   Annual Cost/acre = (38,108)(.10296)/160 + (19,500)(.07823)/ 160
   Annual Cost/acre = $34.06

3. Average annual investment cost/acre = $40.68

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1 From Managerial & Engineering Economy by George A. Taylor, D. Van Nostrand Co., Inc., Princeton, N.J. 1968.

for climate area III (moderately consumptive use). These annual net consumption irrigation requirements are based on a 50 percent effective rainfall. The net irrigation requirements were then modified to account for overall irrigation system efficiency to determine the gross irrigation requirement:

$$\frac{\text{Net Annual Irrigation Requirement}}{\text{Overall System Efficiency(\%)}} = \text{Gross Annual Irrigation Requirement}$$

Since it was assumed that groundwater was pumped directly from the well into the mainline of the distribution system, conveyance efficiency was 100 percent. Field efficiencies for the center pivot and wheel line systems were averaged at 70 percent. Thus overall system efficiency (conveyance efficiency x field efficiency) was estimated at 70 percent. Table 6.3 summarizes the gross irrigation requirements for each crop included in this study.

Table 6.3. Gross irrigation requirements (acre feet/season).[1] Based on a 70 percent overall system efficiency in climate area III.

Crop	Gross Irrigation Requirement (acre feet/season)
Alfalfa	2.14
Small Grains (wheat and barley)	1.29
Potatoes	1.85

[1]Adapted from USDA-SCS Irrigation Guide for Montana.

Unlike alfalfa hay, barley and wheat, seed potatoes have more restrictive soil requirements. They cannot be grown in tight soils such as heavy clays which restrict tuber growth or in rocky, cobbly soils which also limit growth and make harvest more difficult. For purposes of this study potatoes were limited to class I lands only in the model -- estimated at five percent of the currently irrigated lands and one percent of the potentially irrigable lands -- to account for these restrictive soil needs.

Additional constraints were added to reflect historical cropping patterns that a model solely maximizing returns would fail to reflect. These patterns may exist for a number of reasons: agronomic, institutional, custom or even inertia. For example, second to seed potatoes, alfalfa hay produces the largest return. Thus to maximize profits we would expect a farmer to grow as much seed potato as his land would permit and then plant the rest in alfalfa hay. But in the real world this does not happen, and we observe the farmer devoting some of his land to grain crops as well. The key feature of these cropping patterns is that they cannot be explained by economics alone, and hence, must be incorporated into the model vis-a-vis constraint and balance equations. Caution must be exercised, however, when introducing these additional constraints. While the analyst would like the model to reflect the real world as much as possible, the constraints cannot be so inflexible that they prevent the optimization part of the model from operating and instead force a solution which simply represents the status quo. Thus careful decisions must be made when structuring the LP model so that the solution is both optimal and consistent with reality.

ASCS records of crop acreages in the Crow Creek Valley over the last four years indicate that alfalfa hay accounted for less than 40 percent of the irrigated crops grown each year. Similarly irrigated spring wheat and barley, combined, averaged around 60 percent. To reflect these sorts of patterns, constraints were imposed such that alfalfa hay could not be grown on more than 50 percent of the total irrigated cropland and irrigated grain on not more than 75 percent of the land. A minimum of 12 percent of the irrigated cropland had to be grown in barley. Even though Crow Creek Valley farmers grow irrigated barley every year, without this constraint the activity would not appear in the final solution due to its relatively low return.

Finally an additional constraint was imposed that dry wheat and barley acreage equal summer fallow acreage. Summer fallow has a negative return over variable cost, however, farmers alternate fallow with winter wheat and dry barley to control weeds and build up soil moisture for the dry grain crops. Thus the constraint was incorporated to reflect this rotational pattern.

Variable cost data used in the analysis were based on calculations contained in a series of enterprise cost studies published by the Montana Cooperative Extensive Service. These costs are presented in Appendices B - H. Costs for irrigated spring wheat, barley, and alfalfa hay were updated from a 1978 enterprise study for Broadwater County. Seed potato data were taken from a 1980 enterprise study for Lake County. Where necessary all costs were converted to 1980 dollars by using the Index of Prices Paid by Farmers for Production Inputs (total). Since Lake and Gallatin Counties receive slightly more rainfall than Broadwater County (on average 16.36 and 18.66 inches, respectively, Montana Agricultural Statistics), yields for seed potatoes and the dryland crops were adjusted downward from those reported in the studies. A simple average of annual yields for each of these crops between 1970 to 1979 in Broadwater County was used, arbitrarily inflated by five percent to represent the above average level of management assumed in the enterprise studies.

Prices used in calculating gross revenue were based on an eleven year average of state average annual prices from 1970 through 1980. All prices were converted to 1980 dollars before averaging. An eleven-year series was selected because it coincided with the length of a typical cattle cycle and thus problems with placing undue weight on intra-cycle price fluctuations were hopefully avoided. Table 6.4 summarizes yield and price data by crop used in the revenue calculations.

The enterprise cost studies were modified in several other areas.

Table 6.4. Price and yield data used in calculating gross returns. (1980 dollars).[1]

Crop	Yield/Acre	Price/Unit	Gross Returns/Acre
Alfalfa Hay	4 tons	68.22	272.88
Spring Wheat	60 bu.	4.43	265.80
Irrigated Barley[2]	75 bu.	2.64[2]	198.00
Seed Potatoes[3]	190.05 cwt.	5.21	990.16
Winter Wheat	26.25 bu.	4.08	107.10
Dryland Barley[2]	29.4 bu.	2.64[2]	77.62

[1]Sources: The Reporter and Montana Agricultural Statistics 1970-1980, Montana Department of Agriculture and Montana Crop and Livestock Reporting Service.

[2]Represents a composite figure for feed and malting barley.

[3]Price based on a 10-year state average of seed and commercial potato prices/cwt.

Variable costs associated with management were ignored. Thus the returns to variable costs represent a return to management as well. Only 50 percent of the labor requirements were assumed to be supplied by hired workers at a cost estimated at five dollars per hour. The remaining 50 percent was assumed to be supplied by management. Irrigation labor requirements reported in the studies were felt to be too high for sprinkler irrigation systems and were revised downward based on the findings of studies in Idaho and Washington (Irrigation Costs for Southern Idaho, Progress Report No. 213, Agricultural Experiment Station, University of Idaho and The Cost of Owning and Operating Sprinkler Irrigation Systems in the Columbia Basin, Cooperative Extension Service, Washington State University). Wheel lines were estimated to require 2.7 hours per acre per season while a center pivot system required .6 hours per acre per season, giving an overall average labor requirement of 1.4 hours per acre per season. Again, 50 percent of this was assumed to be supplied by management.

Irrigation water costs per se were ignored since the majority of the land is served by private ditches or wells. Only 6,000 acres are irrigated by water purchased from the Toston Irrigation District.

For acres already under irrigation (17,090), only maintenance, insurance and power costs for the sprinkler distribution systems were included as variable costs. Maintenance costs were estimated on the basis of information provided by irrigation equipment suppliers.

Following the methodology of Luft (1981), insurance costs were calculated at six-tenths of a percent of the average value of the distribution equipment. As previously explained, variable cost calculations for irrigated crops grown on the potentially irrigable lands also included an annualized investment cost for the irrigation well and distribution equipment as well as insurance and maintenance costs for the well. Irrigation wells are basically maintenance free except for the oil used in lubricating the shaft -- estimated at 20 gallons per season at $4 per gallon. Table 6.5 summarized these cost calculations.

Power cost calculations for the irrigation systems varied according to the irrigation requirement of the crop. In addition, certain assumptions had to be made regarding the average lift required, operating pressures, friction pressure losses, elevation of the field, pump and motor efficiencies and average water application. For purposes of this study it was assumed that only sprinkler systems were used for irrigation. (Only a small percentage of the farmers in the area use contour flooding and furrow systems.) Average water applications were assumed to be seven gallons per minute per acre for both the pivot and wheel line systems. Pump efficiences were assumed to be 70 percent and motor efficiencies 90 percent. The center pivot system was assumed to have an operating pressure of 30 pounds per square inch (psi) with pivot, mainline and miscellaneous frictional

Table 6.5. Variable Cost Calculations for irrigation equipment — maintenance, insurance and annualized investment[1] (1980 dollars).

Variable Cost Category	Cost Per Acre
A. Maintenance	
Center Pivot System	3.21
Wheel line System	4.13
Average[2]	3.67
Well[3]	.55
B. Insurance[4]	
Center Pivot System	1.04
Wheel line System	.72
Average[2]	.88
Well[3]	.40
C. Annualized Investment	
Center Pivot & Well	47.30
Wheel line & Well	34.06
Average[1]	40.68

1 Included as a variable cost for potentially irrigable lands only.

2 Figure used in variable cost calculations for crops grown on lands currently under irrigation.

3 Additional variable cost for irrigated crops grown on potentially irrigable lands.

4 $\frac{\text{New cost}}{2} \times .006 \div$ number of acres = per acre insurance cost.

losses of 17 psi. The wheel line system was assumed to operate at 50 psi with mainline, lateral line and miscellaneous pressure losses of 20 psi. In all cases it was assumed that there were no elevation changes in the field.

To estimate total power costs, the number of kilowatt hours per season had to be calculated for each crop. For all lands the kilowatt requirement under a center pivot and wheel line system were averaged. It was assumed that the water was already at the mainline of the distribution system and, thus, no lift was required. Power costs per acre foot of water associated with varying levels of pumping depth are considered in the dynamic portion of the study. In calculating kilowatt hours, the following formulas were used:

$$\text{Hours} = \frac{\text{Area in square feet x gross irrigation requirement of crop (depth in inches)}}{\text{Total head x water application x number of acres x 96.3}}$$

$$\text{Brake Horsepower Hours} = \frac{\text{Hours x brake horsepower of motor}}{\text{Motor efficiency (\%)}}$$

Kilowatt Hours = (.746) Brake horsepower hours.

Table 6.6 provides a step-by-step example of how power requirements were calculated for alfalfa hay with a center pivot system.

Two utility companies, Montana Power Company and Vigilante Rural Power Cooperative, provide electric power to the Crow Creek Valley area. Information was not available as to what portion of the irrigation power comes from each source. Hence the two companies' rates

Table 6.6. Power requirement calculations[1] for alfalfa hay with a center pivot distribution system.

Assumptions:

- 30 psi operating pressure
- 17 psi pressure loss
- 70% pump and 90% motor efficiencies
- 7 gpm/acre water application
- 133 acres
- flat field with water already at head of mainline

Flow rate (q) = 133 x 7 = 931

Head, in feet (h) = (30+17)(2.3)=108.1

Water horsepower (Whp) = $\frac{108.1 \times 931}{3960}$ = 75.414419

Brake horsepower (Bhp) = $\frac{75.414419}{.7}$ = 36.306313 ≐ 40 hp

Gross irrigation requirement for alfalfa = 2.14 acre-feet/year
= 25.68 inches/year

Operating hours = $\frac{(25.68)(133)(43560)}{(931)(96.3)}$ = 1659.4286 hrs.

Bhp hours = $\frac{(1659.4286)(36.306313)}{.9}$ = 66941.927

Kilowatt hours = (66941.927)(.746) = 49,939 kwh

1 Based on information provided by Dr. Gerald L. Westesen, Agricultural Engineer, Montana Cooperative Extension Service and contained in Sprinkler Irrigation, 4th Edition, Claude H. Pair (Ed.), Sprinkler Irrigation Association, Silver Spring, MD, 1975.

were simply averaged in calculating irrigation power costs. The companies' current irrigation power rate structures are presented in Appendix I.

MPC currently has a proposal before the state's Public Service Commission to revise their irrigation electricity rate schedule. The revision, if accepted in full, would increase irrigation power costs by more than 300 percent. As discussed in the first chapter of this study, power costs are likely to have a very critical impact on the use of groundwater for irrigation in the future. The impact of varying rate schedules are explored through sensitivity analysis later in this chapter.

LP Results

The results of the LP analysis used in determining the returns associated with groundwater use are presented graphically in Figure 6.5. These returns are gross in that they are not net of well pumping costs. A comparison of these results and those obtained where an exponential decaly function was applied to account for diminishing land productivity is depicted in the same figure.

Regression analysis using a general econometric computer program (SHAZAM) developed by White (1978) was used to estimate the functional form of the returns function. A quadratic function was judged to provide the best fit, where gross returns = $a_0 + a_1U + a_2U^2$. The regression

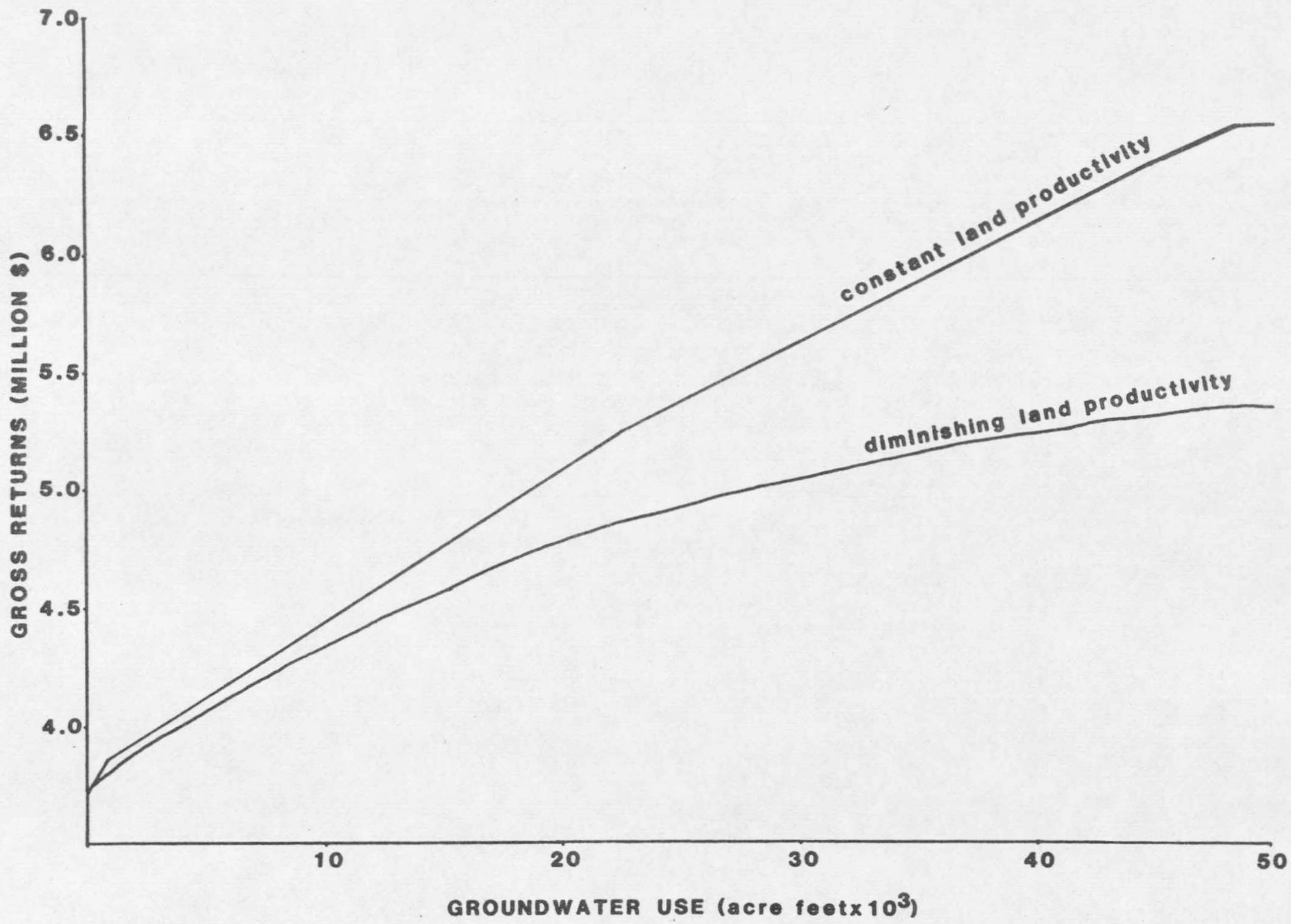

Figure 6.5. Gross Returns to Groundwater Use. Functions are Derived for Constant and Diminishing Marginal Land Productivity.

model and summary statistics are presented in Table 6.7.

OPTIMAL USE OVER TIME

Background

In this section the concept of time is introduced into the decision making process. As noted in an earlier chapter on the commonality problem, with an open access resource such as groundwater future returns from the use of that resource are discounted at an infinitely large rate -- in essence, the present value of returns from future resource use are zero and the time dimension is irrelevant. However, by applying an optimization technique these future returns and the associated value of resource stocks are evaluated in a more realistic framework.

The optimal allocation of groundwater is a multi-stage decision process. At each stage, in this case each year, a decision must be made regarding the level of groundwater use which will maximize economic returns to the basin. The structure of this decision process makes it well suited to the use of dynamic programming for obtaining numeric solutions to the problem.

In an extensive series of articles on groundwater, Burt (1964a, b, 1966, 1967, 1970) examines the optimal use of groundwater within the context of inventory control using dynamic programming. Corresponding to an optimal level of groundwater use at a particular stage is some

Table 6.7. Statistical Summary[1] of Gross Returns Equations.

1. Base model: $\overline{R}^2 = .9994 \quad s = 14133 \quad df = 58$

$$\hat{R} = \underset{(5638.0)}{3,814,900} + \underset{(.50728)}{65.678U} - \underset{(.95700\text{ E-05})}{.00051011U^2}$$

2. 100% Electric Rate Increase:

$\overline{R}^2 = .9993 \quad s = 13930 \quad df = 58$

$$\hat{R} = \underset{(5556.7)}{3,692,200} + \underset{(.49997)}{59.986U} - \underset{(.94322\text{ E-05})}{.00046546U^2}$$

3. 300 % Electric Rate Increase:

$\overline{R}^2 = .9991 \quad s = 13377 \quad df = 58$

$$\hat{R} = \underset{(5336.1)}{3,446,000} + \underset{(.48012)}{48.661U} - \underset{(.90577\text{ E-05})}{.00037691U^2}$$

4. Constant Land Productivity:

$\overline{R}^2 = .9998 \quad s = 13246 \quad df = 18$

$$\hat{R} = \underset{(8107.8)}{3,794,300} + \underset{(.76191)}{70.588U} - \underset{(.14816\text{ E-04})}{.00029161U^2}$$

5. Greater Diminishing Land Productivity:

$\overline{R}^2 = .9980 \quad s = 19771 \quad df = 58$

$$\hat{R} = \underset{(7886.7)}{3,844,500} + \underset{(.70961)}{58.628U} - \underset{(.13387\text{ E-04})}{.00057799U^2}$$

[1] Estimates represent simple curve fitting and not statistical data. Standard errors in parentheses below coefficients.

optimal level of groundwater storage or "inventory" to be maintained in the basin.

An entire body of economic and mathematical theory has developed with regards to inventory control analysis. While it is just one of several techniques available, dynamic programming offers a particularly practical method for actually solving such problems. Within the context of DP, an optimal decision "is one that properly balances the current cost of the decision against the future value of the new state resulting from the decision." (Dreyfus, 1962, p. 216.) A state describes or summarizes all relevant information regarding the condition of the particular system under consideration. The quantity of water in storage (stocks) frequently is treated as a state variable in groundwater analysis since it can be used to evaluate pumping costs.

The optimization condition with respect to groundwater has a very neat and intuitive interpretation: use groundwater up to the point where marginal returns from current use equals the marginal value of groundwater in storage (Burt 1964a, b; 1967). Similar results have been obtained with the use of control theory and linear optimization. Renshaw (1963) notes that a critical element in the optimal allocation of groundwater is consideration of the marginal value of water retained in the ground (stocks) as a substitute for pumping inputs. Domenico et al. (1968) in their analysis of optimal groundwater mining conclude that when recharge and profit per unit pumped are constant, mining is desirable as long as "annual net revenue generated from mining exceeds the capitalized annual loss in value of recharge. As in the general case, loss in value of recharge is interpreted in terms of greater lift required for its extraction" (p. 250). Brown and McGuire (1968) establish the following rule for a centrally managed basin: "Pump that amount of groundwater that equates value of marginal product with the sum of direct marginal pumping costs at current lift and discounted marginal effects of current pumping on future pumping costs" (p. 37).

The use of DP as an optimization technique has a further advantage in that the derived solution has significance for a host of related problems (Burt and Allison, 1963). As is demonstrated later in this chapter, the decision policy can be used to determine the extent of losses to the basin under a one-year planning horizon (open access setting) versus an infinite time frame (optimal allocation). Similarly it is possible to examine the stability of the decision rule as the planning horizon changes and the point where it converges to some constant policy invariant with state.

Pumping Cost Calculations

In the previous section LP was used to generate a gross returns function associated with groundwater use in the study area. However, this function ignores the costs of groundwater extraction and, thus, must be modified before an optimal decision rule can be derived. Specifically a function must be calculated such that the expected returns from groundwater use in a particular state are net of pumping costs. In this section the generation of such a function is described.

In theory a net returns function can be summarized by the relatively simple transformation, G(u) - C(u) = R(u); where G(u) is the gross returns associated with a particular level of groundwater use, C(u) is the cost associated with pumping that volume of groundwater and R(u) is the resulting net return. In reality, however, this calculation is somewhat more complicated since the cost of extraction is a function not only of use but of pumping depth. Pumping depth, in turn, is determined by the level of the water table (unconfined aquifer) or piezometric surface (confined aquifer) in a well. It is the distance between this level and the ground surface which determines the power and well pump accessories required to extract the groundwater.

Calculation of a pumping cost function proved to be one of the more difficult aspects of the study. In part this was due to the complex physical nature of the confined groundwater setting. The lack of detailed and consistent physical data also hindered its calculation. As a result, numerous assumptions were employed in deriving a groundwater pumping cost function.

The drawdown in a particular well describes how the water table or piezometric surface drops from its initial position over time as groundwater is pumped from the well. It is a function of the geohydrologic characteristics of the aquifer as well as the efficiency of the well, its construction characteristics, and the turbulence of flow through the well screen or perforations.

For purposes of this study a nonequilibrium flow equation was used in calculating drawdown for the confined system. The equation is based on methodology established by Jacob (Todd, 1980):

$$D_w = \left[\left(\frac{2.30Q}{4 \pi T} \right) \left(\log \frac{2.25\ Tt}{r_w^2\ S} \right) \right] + cQ^n$$

where D_w = total drawdown within a well (ft),

Q = the volume of water discharged from the well per unit time (ft^3/day),

S = storage coefficient (unitless),

T = transmissivity (ft^2/day),

t = time (days),

r_w^2 = radius of well or borehole (ft),

c = well loss coefficient ($days^2/ft^5$),

n = flow turbulence measure (unitless).

Since this study is concerned with inter-seasonal rather than intra-seasonal groundwater use, the drawdown measurement used in calculating pumping lifts is based on that experienced at the end of the irrigation season. Thus t was estimated by the number of days farmers and ranchers in the study area typically run their wells during the irrigation season. Based on personal interviews with several well owners and data reported by Wyatt (1981), t was estimated at 35 days. It was further assumed that the wells are pumped constantly during the 35-day period rather than at scattered intervals throughout the growing season. While this assumption is true for such irrigated crops as wheat and barley, it is not strictly valid for alfalfa where more than one crop is harvested during a season. The assumption was made, however, to avoid the problem of determining how the drawdown might recover between pumping intervals during a single season. No information was available for deriving such an estimate.

Other simplifying assumptions were made where detailed information was not available. To be consistent with the assumptions used in calculating irrigation equipment costs on a per acre-foot basis (see p. 153), it was assumed that each well serves 146.5 acres and that 1.8 acre feet of water are delivered to each acre during the season. Hence discharge (Q) = (1.8 X 146.5)/35 or 7.534 acre feet per day (328,194 ft^3/day). On the basis of well efficiency tests conducted by Wyatt (1981), a value of .27 was used for c. Following the suggestion of Jacob as reported by Todd (1980), a flow turbulence measure (n) of 2 was used. It was further assumed that wells have a radius of 1.33 feet (allowing for a 32-inch borehole with gravel packing). This assumption is consistent with the construction characteristics reported in existing well logs.

Storage coefficient and transmissivity measurements were based on data provided by Wyatt (1981). A storage coefficient of .0016 was used for the confined aquifer with a transmissivity estimate of 100,000 gallons per day per foot (13,369 ft^2/day). While the transmissivity figure is smaller than test results reported by Wyatt at a single well location, the smaller figure was suggested as being more representative for the entire basin (personal communication with Wyatt, 1981). The data appear consistent when an average drawdown is calculated using the above formula with information contained in well logs for many of the existing wells. The calculated drawdown is virtually identical to an average of those reported in the logs.

Drawdown itself is not a perfectly horizontal drop in the piezometric surface or water table, but rather a cone-shaped depression fanning out from the well. Thus the greater the radial distance from the pumping well, the less the actual drawdown. When cones of depression from adjacent wells overlap, total drawdown is the sum of the component drawdowns (Freeze and Cherry, 1979). While the drawdown estimate used in this study is believed to be reliable given the limited data base, readers should be aware of the assumptions implicit in its calculation and use. A single figure, as such, assumes that all wells are identical in their construction, pumping and efficiency. It also assumes that hydrologic conditions and responses are uniform throughout the basin. Neither assumption is very realistic. The nonequilibrium flow equation itself implies some rather heroic assumptions, as well. Underlying its calculation is the assumption that a well completely penetrates the aquifer and is perforated or screened along the entire height of the aquifer. Similarly it is assumed that flow in the aquifer is in a horizontal direction only and that the aquifer is homogeneous and isotropic. For a more complete explanation of the assumptions associated with transient pumping tests see Bouwer (1978).

Assumptions such as the above are always disturbing to an investigator. However, without more detailed physical data and additional testing it is unlikely that more accurate estimates of drawdown and its variability across the basin are possible. To attempt such an estimation given the current data base would suggest a level of precision and reliability far greater than is the case.

Given the above data assumptions, drawdown in the confined aquifer was estimated from the equation on page 146 at 75 feet from the initial position of the piezometric surface at the beginning of the season. However, once the piezometric surface is drawn below the confining layer (estimated at a 215 foot depth), the aquifer is no longer confined and the water bearing formation is no longer fully saturated. When this occurs transmissivity is no longer a constant but varies with the saturated thickness of the water table. Thus drawdown may vary considerably depending on the thickness of the aquifer below the confining layer. Unfortunately no information was available on this thickness. Rather than treat the aquifer as "bottomless," an artificial cut-off or bottom was established at 100 feet below the confining layer. This 100-foot figure seems reasonable as a lower bound for a depth estimate since existing wells in the area have been drilled to an average depth of 260 feet -- 45 feet below the assumed location of the confining layer. To avoid problems of estimating how drawdown changes with the saturated thickness of the water table once the piezometric surface falls below the confining layer, an average drawdown of 30 feet was assumed once the aquifer becomes unconfined. While this figure is arbitrary, it is based on the assumption that well drawdown is substantially less when the aquifer is unconfined and conductivity is high. Unfortunately no estimates of hydraulic conductivity were available, however, well log reports of materials encountered in the aquifer during drilling (clean sands and gravels) indicate high conductivity (Todd, p. 72, 1980).

A linear interpolation scheme was used for the transition in drawdown between the confined and unconfined setting. For example, if the static head or piezometric surface is less than 75 feet above the confining layer at the beginning of the irrigation season, the aquifer will be confined for the initial part of the season and unconfined for the later portion. Interpolation of drawdown simply permits a smooth transition between the two states. Table 6.8 summarizes the drawdown calculations at 10-foot intervals in

Table 6.8. Estimated Drawdown During the Irrigation Season Associated with Depth to Piezometric Surface.

Depth of Piezometric Surface (Confined) or Water Table (Unconfined) Below Ground Surface at Beginning of Season	Associated Drawdown	
-ft.-	-ft.-	
0 - 140	75[1]	
150	69	Based on a linear interpolation scheme (150–210)
160	63	
170	57	
180	51	
190	45	
200	39	
210	33	
215+ (unconfined)	30[2]	

[1]Estimated from the equation on p. 146.

[2]Assumed drawdown once the piezometric surface remains below the confining stratum and the aquifer becomes unconfined (see p. 150).

piezometric surface depth.

Once these drawdown estimates were computed, pumping costs were then calculated on the basis of pumping lift. Pumping costs are comprised of two basic components -- power costs for bringing groundwater to the surface and through the distribution system, and capital equipment costs. Irrigation electric rates for Montana Power Company and Vigilante Rural Cooperative were averaged to calculate an average power cost per acre-foot of water as total pumping lift increases. (I am indebted to Mr. Vern Fogle, Extension Economist with the Montana Cooperative Extension Service, for devising a computer program which enabled me to accurately calculate these costs.) These electric rates were increased by 100 and 300 percent in the sensitivity analysis section of the study.

Capital costs include a variety of items primarily involved with motor and pumping components of the well system as lift increases. Brake horsepower requirements for the complete irrigation system were calculated for increasing depths to the groundwater (pump lift). These requirements were then translated into motor horsepower requirements allowing for an additional five percent service factor above the nameplate rating. For example, a 60 hp motor is sufficient to handle a 61.5 brake horsepower requirement, while a 150 hp motor would be necessary for a 131.7 brake horsepower requirement.

Once motor horsepower requirements were calculated, it was possible to determine the additional cost of pumping from a particular depth. An initial cost was calculated for the basic pump, associated fittings and 20 feet of column pipe. As pumping lift increases, the cost of additional column pipe length and, if necessary, more powerful motor and associated electric panel and wiring are added to the base cost. Also, at every 60-foot increase in lift, the cost of an additional bowl or stage on the turbine pump is added. Table 6.9 provides an itemized summary of the capital components used in the analysis of pumping costs.

These costs were then summed and averaged for the two distribution systems (center pivot and wheel line) and converted to 1980 dollars using the Index of Prices Paid by Farmers for Production Inputs (Total). Per acre-foot pumping costs were calculated by dividing the total cost by an assumed application rate of 1.8 acre feet. These costs were then amortized assuming a useful life of 15 years and a six percent real rate of interest.

An additional component of the capital cost associated with pumping lift involves the well itself. It is initially assumed that all wells are drilled to a minimum depth of 260 feet, and that a well must be 20 feet deeper than the maximum drawdown to provide a safety margin in the event of excess surging. Given these assumptions, the wells are adequately deep unless actual lift increases to more

Table 6.9. Itemized Cost Summary of Capital Equipment Associated with Increased Pumping Lift.[1]

Item	1981 Dollars	1980 Dollars
Basic pump, fittings and 20 feet of column pipe		
For well with center pivot system	5725.00	5247.92
For well with wheel line system	7739.00	7094.08
Column Pipe		
8" diameter - for well with center pivot system	808.00/20' or 40.40/foot	740.67/20' or 37.03/foot
10" diameter - for well with wheel line system	933.00/20' or 46.65/foot	855.25/20' or 42.76/foot
Wiring	10.00/hp	9.17
Motors		
40 hp	2550.00	2337.50
50 hp	3026.00	2773.83
60 hp	3494.00	3202.83
75 hp	4254.00	3899.50
100 hp	5374.00	4926.17
125 hp	6492.00	5951.00
150 hp	7810.00	7159.17
200 hp	10612.00	9727.67
Panels		
40, 50 hp	810.00	742.50
60, 75, 100 hp	1160.00	1063.33
125,150,200 hp	2464.00	2258.67
Bowl		
Every 60 feet of lift	500.00/bowl	458.33/bowl

[1]Costs have been deflated to 1980 dollars and are based on information provided by Mr. Wayne Brewer of VanDyke Irrigation, Bozeman, MT.

than 240 feet. If lift extends beyond this level, the wells must be deepened or new ones drilled. Obviously this adjustment for well depth will not be an abrupt one. Rather there will be a continual adjustment over time as new wells are drilled deeper in anticipation of the increasing lifts. However, to account for the fact that beyond a pumping lift of 240 feet wells must be deeper, the cost of additional well depth is incorporated into the capital cost calculation on a per acre-foot basis amortized for a useful life of 25 years.

Total pumping costs were calculated by adding the appropriate electric and capital costs together. While pumping costs were derived in terms of lift, the actual cost function was estimated with respect to the amount of groundwater in storage. Since lift represents the depth to the piezometric surface (or water table in the unconfined setting), it can be translated into a change in groundwater storage via a relatively simple transformation. In general, total storage (S) is equal to the surface area of the basin multiplied by the product of the storage coefficient (SC) and the saturated thickness of the aquifer (b):

$$S = (\text{area})(SC)(b).$$

For a confined aquifer, the distance between the piezometric surface and confining layer is used rather than b since the saturated thickness of the aquifer remains unchanged. As lift increases this distance declines; or, as in the case of the unconfined aquifer, the saturated thickness shrinks. Thus the change in storage is represented by the area of the aquifer multiplied by the storage coefficient and the change in lift (ΔL):

$$\Delta S = (\text{Area})(\text{SC})\ (\Delta L).$$

The resulting quantity of storage is calculated by replacing b with the new thickness or depth (b - L):

$$S = (\text{Area})(\text{SC})(b-L).$$

In terms of the groundwater system examined in this study, calculation of total storage is somewhat complicated in that separate storage quantities must be computed for the confined and unconfined portions of the aquifer. The two estimates then must be added together to determine total storage. No data was available on the storage coefficient (specific yield) associated with the aquifer system when it is unconfined. In general this parameter is several orders of magnitude larger than that found in a confined setting, ranging from 0.01 - 0.3 as opposed to 0.005 - 0.00005 (Freeze and Cherry, 1979). For purposes of this study, an average of this range (.16) was used as an estimate of the storage coefficient for the unconfined portion of the aquifer. Based on information from well logs for the area, it was assumed that the piezometric surface currently is 55 feet below the surface. Wyatt (1981) estimates that the basin underlies an area of approximately 60,160 acres. Thus, current total storage (S_{total}) is calculated at approximately 978,000 acre-feet:

$$S_{total} = S_{confined} + S_{unconfined}$$

$$S_{total} = (60160)(.0016)(215\text{-}55) + (60160)(.16)(100),$$

where 215 feet is the estimated depth to the confining layer and 100 feet is the assumed "bottom" of the aquifer below this layer (see p. 150), corresponding to the saturated thickness of the water table when the system is confined. The size of the basin was increased and decreased by 20 percent in the sensitivity analysis section of the study.

The resulting relationship between pumping cost and groundwater storage is graphically depicted in Figure 6.6. Marginal pumping costs rise dramatically as groundwater is removed from storage when the aquifer is confined and then increase at a much slower rate once the quantity in storage is less than 915,000 acre feet and the system becomes unconfined.

This unusual shape is primarily due to changes in drawdown experienced when the aquifer is confined, unconfined or in the transition zone between the two systems. When an aquifer is confined, the system remains saturated and water is literally squeezed out of storage as pumping lowers the hydrostatic pressure partially supporting the overlying confining layer. By contrast, in an unconfined aquifer pumping actually causes pore spaces to be dewatered and a much larger quantity of water is released from storage for the same unit of effort (as

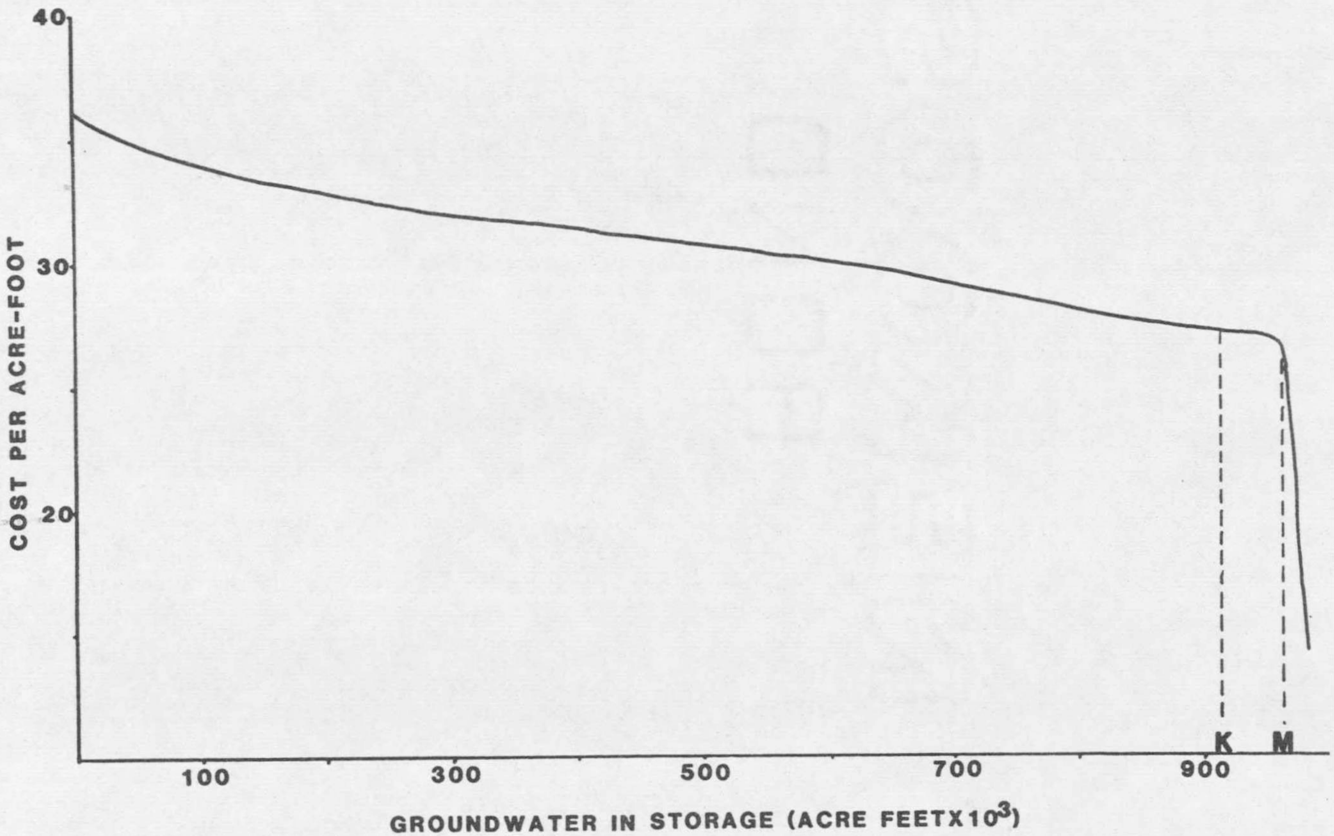

Figure 6.6. Groundwater Pumping Costs as a Function of Storage.

measured by change in head). Thus, as described above, the storage coefficient for an unconfined aquifer is much larger. The difference in effort required to produce a given quantity of water from a well in a confined versus an unconfined aquifer are reflected by the levels of drawdown in each system. Drawdown per unit discharge is much greater when the aquifer is confined, resulting in steeper increases in marginal pumping costs as additional quantities are withdrawn from storage. This cost function is further complicated by the lumpiness of capital costs associated with pumping equipment particularly when pumping depths are large.

The severe curvature of this relationship made estimation of a functional form extremely difficult. The technique of grafted polynomials was employed in an effort to smooth the function and make it continuous. (For an explanation of this technique and how it is used, see Fuller, 1969.) Three polynomials -- cubic, quadratic and linear -- were "grafted" together to approximate the entire function. A cubic was used for the initial segment for estimating pumping costs when total storage is between zero and 914,432 acre feet. At the "join" point K (941,432 acre feet), a quadratic segment was blended into the cubic with the additional restriction that the polynomials be continuous in the first derivative. At the second join point M (966,500 acre feet), a linear segment was grafted to the quadratic to estimate the remainder of the function. The continuous first derivative restriction was dropped, however, to permit greater flexibility. On the basis of the grafting, the following model was used:

$$Y = c_o + c_1X_1 + c_2X_2 + c_3X_3 + c_4X_4 + c_5X_5,$$

where Y = marginal cost of groundwater use;

X = quantity of groundwater in storage

for $X < K$ (first join point): $X_1 = X$; $X_2 = X^2$; $X_3 = X^3$; $X_4 = 0$; $X_5 = 0$,

for $K \leq X < M$ (second join point): $X_1 = X$; $X_2 = X^2$; $X_3 = (-2\ K^3 + 3\ K^2\ X)$; $X_4 = (X-K)^2$; $X_5 = 0$,

for $M \leq X$: $X_1 = M$; $X_2 = M^2$; $X_3 = (-2\ K^3 + 3\ K^2\ M)$; $X_4 = (M-K)^2$; $X_5 = (X-M)$.

Least squares estimates of the parameters c_0, c_1, c_2, c_3, c_4, and c_5 are presented in Table 6.10 along with several summary statistics. However, it should be recognized that these estimates represent simple curve fitting rather than statistical data.

To derive an estimate of the expected immediate net returns from groundwater use, pumping costs are multiplied by the level of groundwater use and subtracted from the gross returns function estimated from the LP model. Algebraically the expected net returns function is described by the following expression:

$$NR = a_o + a_1U + a_2U^2 - [c_0 + c_1X_1 + c_2X_2 + c_3X_3 + c_4X_4 + c_5X_5]\ U,$$

where U = level of groundwater use (acre feet)

and X = quantity of groundwater in storage (acre feet).

Table 6.10. Statistical Summary[1] of Cost Equations.

1. Base Model: $\bar{R}^2 = .9969$ s = .30907 df = 26

$$\hat{Y} = .36037E{+}02 - .17929E{-}04X_1 + .20462E{-}10X_2 - .12732E{-}16X_3 - .69283E{-}10X_4 - .71291E{-}03X_5$$

(.30600) (.28204E-05) (.75540E-11) (.54543E-17) (.15348E-09) (.11781E-04)

2. Smaller Basin Size: $\bar{R}^2 = .99476$ s = .40772 df = 26

$$\hat{Y} = .36015E{+}02 - .20893E{-}04X_1 + .24957E{-}10X_2 - .17255E{-}16X_3 - .68241E{-}09X_4 - .95416E{-}03X_5$$

(.40364) (.46377E-05) (.15487E-10) (.13944E-16) (.29904E-9) (.21592E-04)

3. Largin Basin Size: $\bar{R}^2 = .98112$ s = .7739 df = 26

$$\hat{Y} = .35948E{+}02 - .10955E{-}04X_1 + .19487E{-}11X_2 + .14949E{-}17X_3 - .82429E{-}09X_4 - .71644E{-}03X_5$$

(.76601) (.58310E-05) (.12905E-10) (.77025E-17) (.222780E-09) (.34363E-04)

4. 100% Electric Rate Increase: $\bar{R}^2 = .99668$ s = .49696 df = 26

$$\hat{Y} = .56319E{+}02 - .31587E{-}04X_1 + .42003E{-}10X_2 - .26296{-}16X_3 + .58675E{-}10X_4 - .11250E{-}02X_5$$

(.49202) (.45349E-05) (.12146E-10) (.87700E-17) (.24679E-09) (.18943E-04)

5. 300% Electric Rate Increase: $\bar{R}^2 = .99607$ s = .91669 df = 26

$$\hat{Y} = .96882E{+}02 - .58881E{-}04X_1 + .85137E{-}10X_2 - .53498E{-}16X_3 + .31768E{-}09X_4 - .19499E{-}02X_5$$

(.90758) (.83651E-05) (.22405E-10) (.16177E-16) (.45523E-09) (.34942E-04)

[1] Estimates represent simple curve fitting and not statistical data. Standard errors in parentheses below coefficients.

Despite efforts to smooth the cost function through the use of grafted polynomials, the irregular shape of the function resulted in some estimation problems, particularly in the transition zone between the confined and unconfined systems. These irregularities were transmitted into the expected net returns function. As a result, the expected returns functions was not perfectly concave but contained several inflection points and convex regions. This, in turn, caused some irregularities in the decision rule and the marginal value of groundwater stocks at various states of groundwater storage. These irregularities were not given much weight in the final interpretation of the optimization results, however, since pumping costs in the study area might diverge from the estimated relationship by a considerable amount when the piezometric surface falls below the confining layer. The irregularities emanate from lumpiness in the cost estimates along certain intervals and the compounding effect of function smoothing on these estimates. Actual costs would tend to be smoother because of the random way in which wells would be constructed and deepened.

DP Model Description

The single state variable model used in solving the dynamic optimization problem can be summarized by the following recursive relationship:

$$F_n(X) = \underset{U}{\text{Max}}\ [NR(X,U) + \beta F_{n-1}\ (X + W - U)],$$

where:

n = the stage or interval into which the decision process is divided -- in this case one year;

$F_n(X)$ = the total present value of returns to the basin of an n-stage process where an optimal policy is followed and the initial level of groundwater stocks is X;

Max = maximum operator;

U = The quantity of groundwater used per period (decision variable);

X = the quantity of groundwater in stock (state variable);

NR(X,U) = the expected immediate net returns given the X^{th} state, U^{th} decision and n^{th} stage of the process; this corresponds to the expression on p. 160;

β = the discount factor used to convert the stream of benefits to a present value; $\beta = 1/(1 + 4)$ where r is the periodic rate of interest in real terms;

$F_{n-1}(X + W - U)$ = the total value of returns to the basin of an n-1 stage process;

W = net natural recharge to the basin, assumed to be constant.

Since net natural recharge is assumed to be constant (estimated at 30,000 acre feet per year), transformation of the state variable can be expressed by the highly simplified function:

$$X_t = X_{t-1} + W - U_{t-1}$$

This very intuitive result simply says that the level of groundwater stocks at the beginning of time t is equal to the level of stocks at the beginning of the previous period plus recharge less the amount of groundwater used during t-1. If recharge is not assumed to be constant, the function is considerably more complex, involving a probability density function for recharge. For a discussion of the functional form of the recurrence equation when additions to stock are stochastic, see Burt (1964a, b).

Burt (1964b) notes that under an infinite planning horizon (relevant for deriving an optimal allocation rule), as $n \to \infty$, $F_{n+1}(X) \to F_n(X)$ and the recurrence equation reduces to:

$$F(X) = \underset{U}{\text{Max}}\ [NR(X,U) + \beta F(X+W-U)]$$

This convergence property is valid only if NR(X,U) is constant and not a function of n.

A FORTRAN program modified from one used by Burt (1981) in his study of the economics of soil conservation in the Palouse Area was used to derive a numeric solution to the dynamic programming problem and the associated decision rule. A total of 209 different levels of the state variable (groundwater in storage) were examined in the analysis, ranging from that reflecting conditions at the time of the study (estimated at 978,000 acre feet) to an arbitrary lower limit of 50,000 acre feet. Because of the convexity problems mentioned earlier with the net returns function, a continuous variable refinement was not used for the decision variable (U). Instead discrete intervals of 1,000 acre feet up to a maximum of 50,000 acre feet were used for the values the decision variable could take on. Thus, 50 different levels of use were examined to determine which would maximize the present value of net returns to the basin at each specified state.

A linear interpolation scheme was used to approximate these returns in the recursion equation when the values fell between discrete intervals on the present value returns function.

Computations were carried out for a sufficiently large number of iterations or stages (n = 75) until the decision policy converged to some constant rule for all larger n. This optimal policy corresponds to that under an infinite planning horizon since it is invariant with stage. The fact that policy convergence did not occur quickly but involved a rather protracted period of time is instructive. It indicates that with this particular optimization problem the length of the planning period even beyond the myopic one year horizon is critical to the structure of the decision rule.

Results of the Analysis - Baseline Model

The analysis was initially carried out using a baseline set of data designed to reflect various economic and physical conditions as they currently exist. For example, Wyatt's (1981) estimate of basin size (60,160 acres) was used in estimating storage and pumping costs. Current electric rates (1980 dollars) were used in deriving pumping cost and gross revenue function parameters. A six percent real rate of interest was used to calculate the present value of returns to the basin. Slight curvature was introduced to the gross returns function generated from the LP analysis to account for differences in land productivity. Specifically, a decay rate of 0.000015 was used, corresponding to a "kick-off" elasticity (η) of .01.

Figure 6.7 summarizes the computed decision rules as functions of the state variable for a one year (open access) and an infinite planning horizon (optimal). A decision rule describes the amount of annual groundwater use for every possible quantity of water in storage in the aquifer. When use exceeds recharge (30,000 acre feet per year), water is mined from the basin. However, when use is less than recharge, groundwater stocks (the quantity in storage) increase. Within the context of this study the general structure (shape) of the decision rules is of interest rather than the absolute level of groundwater use implied by the rules. The one year rule simulates the open access scenario in which future returns are discounted at an infinite rate. The marginal value of groundwater in current use is still equated with the marginal value of stocks, but under this setting stocks have zero value. Thus, for each state groundwater is extracted until the marginal value of water in use is zero.

By contrast under an infinite planning horizon stocks have a positive marginal value (Figure 6.8) and less groundwater is extracted. Two equilibria (X_1^* and X_2^*) are established under the decision rule. In this context an equilibrium is defined as the quantity of groundwater stocks in which the associated annual use is exactly equal to recharge. When this occurs the groundwater system is in equilibrium

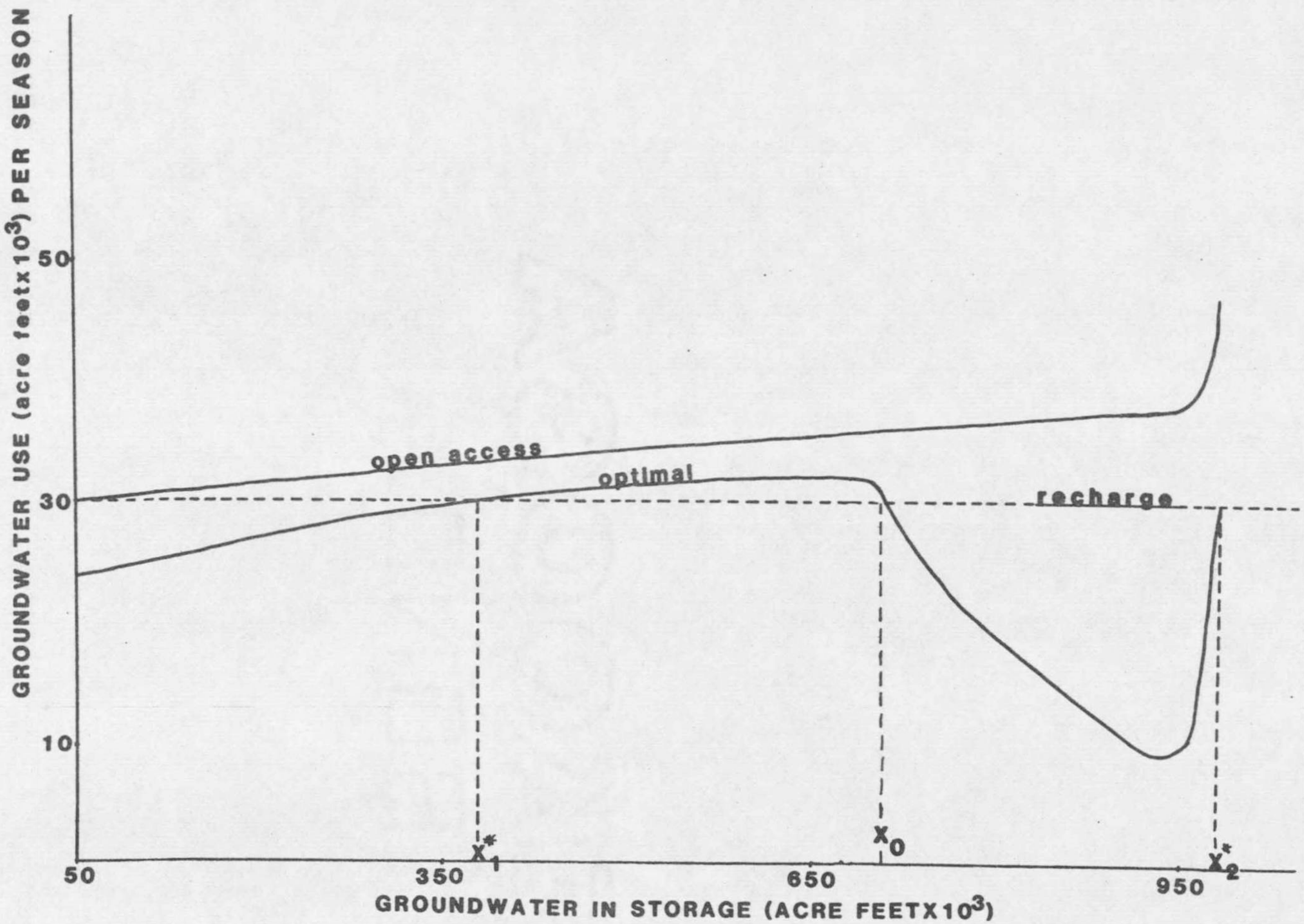

Figure 6.7. Derived Decision Rules Under an Optimal and Open Access Policy -- Baseline model.

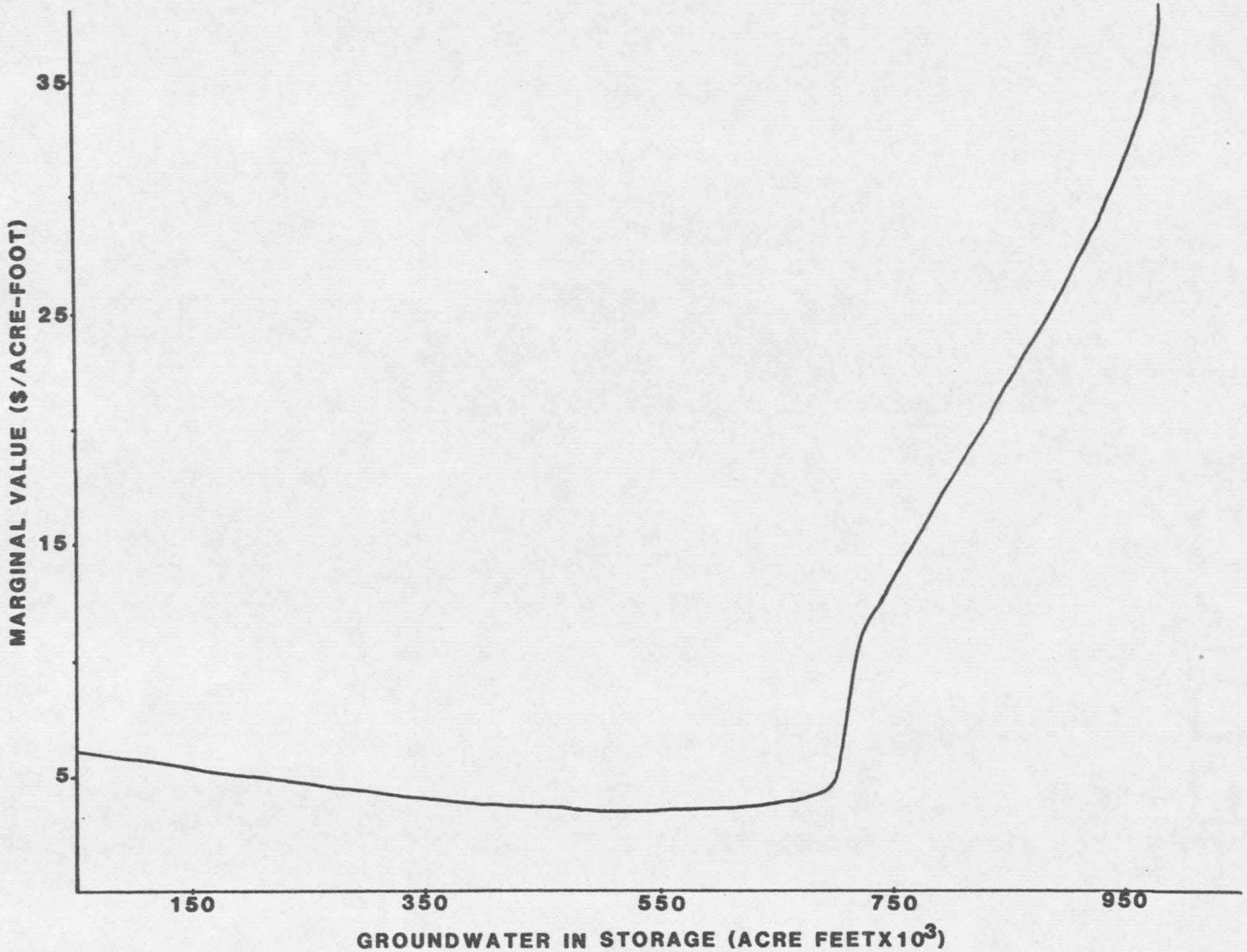

Figure 6.8. Derived Marginal Values of Groundwater Stocks as a Function of Storage Under an Optimal Policy.

and there is no tendency for change either with respect to the quantity in storage or the amount of use. When stocks are less than X_1^* (approximately 380,000 acre feet), use is less than recharge and the system moves toward X_1^*. When stocks are less than X_0 but greater than X_1^*, the optimal level of use is more than recharge and stocks decline, moving the system back toward X_1^*. Beyond the critical switching point X_0 (approximately 707,000 acre feet), the optimal level of use moves the system to a new equilibrium X_2^*, the maximum amount of storage given current pumping activities. Movement to this second equilibrium or steady state involves a large build up of stocks initially and then a nearly linear decline in the rate of stock growth until X_2^* is reached. Some smoothing of the decision rule has been incorporated here to minimize the influence of irregularities in the net returns function.

The presence of two stable equilibria is due to the fact that once stocks are greater than a certain level (estimated at 914,432 acre feet), the aquifer is confined and pumping costs are substantially lower. Thus, if groundwater stocks are greater than X_0, it is advantageous to build up stocks and forego current returns in favor of reduced pumping costs in the future. However, when the system has less than X_0 in storage, current groundwater use must be curtailed by such a large amount and over such an extended period of time to return the system to an artesian setting that it is no longer economic to do so. Instead the stocks are used for <u>current</u> production, driving the system to the lower equilibrium (X_1^*). Once below X_1^*, pumping costs relative to current returns become too great and the use of stocks is substantially reduced, moving the system back to X_1^*. As expected, sensitivity analysis indicates that the position of these key turning points is greatly influenced by the level of the discount rate -- the rate at which future returns are reduced to present value terms. Under a one year planning horizon, future returns and pumping costs are of no consequence and the system is slowly driven to a single equilibrium at virtually the bottom of the aquifer ($X \leq 90{,}000$ acre feet).

Figure 6.9 traces the time path of groundwater stocks following an optimal policy and one for a one-year planning horizon over 75 years, arbitrarily assuming an initial stock of 930,000 acre feet at $t = 0$. Eventually a steady state would be reached under the one-year horizon when stocks are less than 90,000 acre feet. However, the time path to this point is too protracted to conveniently fit on a graph and, thus, the figure is truncated at $t = 75$. Even truncated, it graphically depicts the broad differences which result from following the two decision rules. These differences can be translated into efficiency losses or gains by contrasting the present value of expected returns under each policy. Table 6.11 summarizes the differences for seven different states of the aquifer system. In essence these

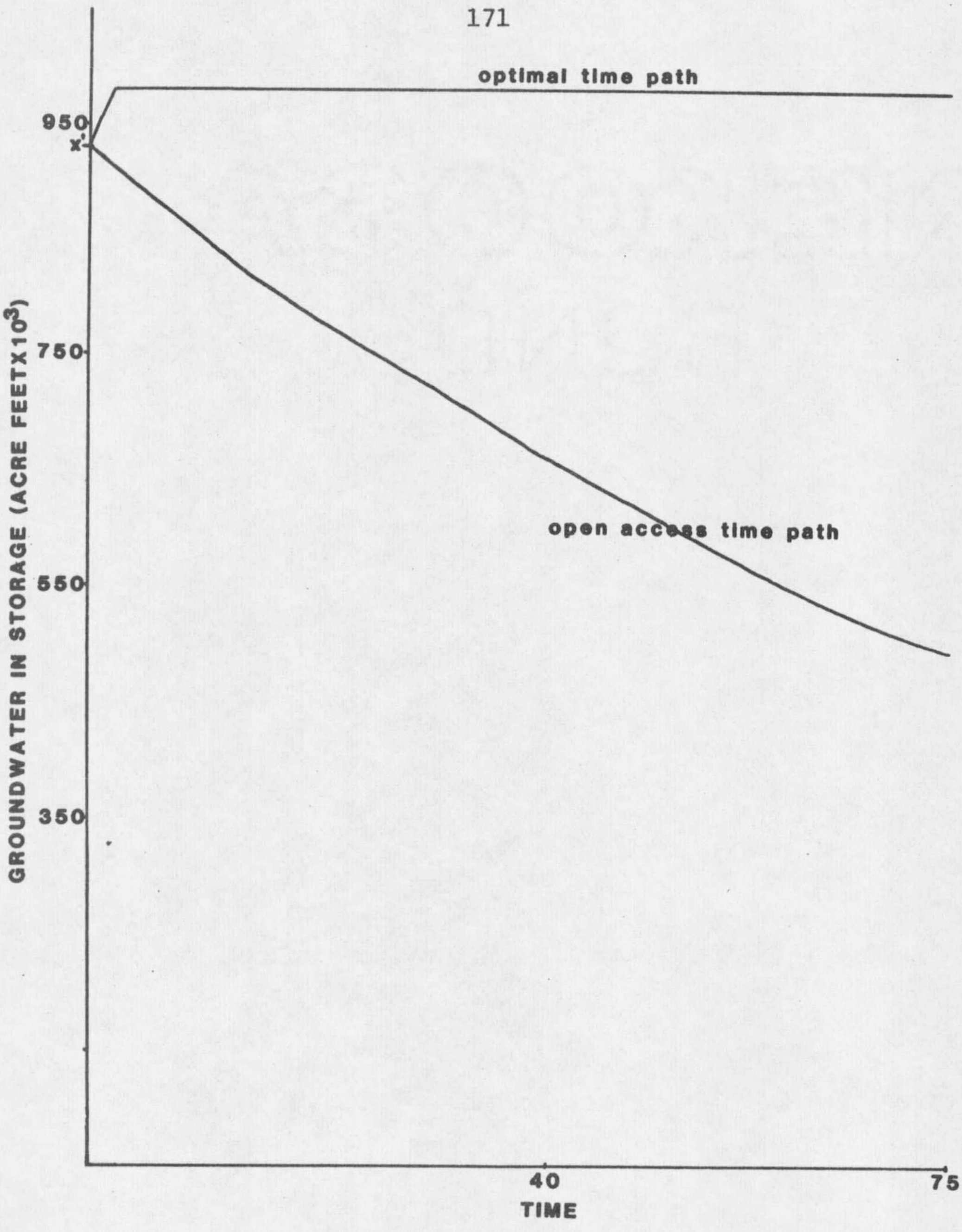

Figure 6.9. Time Paths to a Steady State Under Optimal and Open Access Policies. An Initial Level of Storage (X'= 930,000 acre feet) is Assumed. A Steady State is Eventually Reached Under an Open Access Policy When X≤90,000, However the Graph is Truncated at t=75.

Table 6.11. Welfare Gains from Following an Optimal Groundwater Use Policy Versus an Open Access Policy -- Base Model.

State[1]	Present Value ($) of Net Returns[2]		Actual ($) Difference[3]	% Change
	Optimal Allocation	Open Access		
100,000	10,174,809	9,938,739	+ 236,070	+ 2.38
300,000	11,194,269	11,031,209	+ 163,060	+ 1.48
600,000	12,387,669	12,281,419	+ 106,250	+ 0.87
800,000	14,104,729	13,116,379	+ 988,350	+ 7.54
900,000	16,302,309	13,626,529	+ 2,675,780	+ 19.64
950,000	17,678,589	13,925,189	+ 3,753,400	+ 26.95
978,000	18,571,839	14,399,609	+ 4,172,230	+ 28.98

[1]In acre feet of groundwater.

[2]Net of returns to currently irrigated acreage and dryland crops.

[3]Actual difference = net returns (optimal allocation) - net returns (open access). Does not consider costs of optimal basin management.

differences measure the cost of the externality; that is, the welfare loss to the basin when the value of groundwater stocks is ignored in the decision process. Optimal basin management, however, is not a costless process and the actual magnitude of the externality is partially offset by these costs. While no effort has been made to net out management costs in the returns calculations in Table 6.11, their existence should not be ignored.

As the results from the table indicate, welfare losses are greater as the level of stocks increase and the system moves closer to the second equilibrium. When stocks are small there is little difference in the present value of returns under an optimal allocation versus the open access situation since the decision rule always keeps the system unconfined. As stocks get large, however, the gap widens substantially since under an optimal policy the decision rule takes advantage of lower pumping costs by moving to and maintaining the artesian pressure. This is not the case under an open access policy where the decision rule moves the system to an ever increasing pumping cost.

The trend toward larger efficiency losses when there are greater quantities in storage also is visible from the derived marginal values of groundwater stocks (Figure 6.8). For example, when X = 600,000 acre feet, the marginal value of groundwater stocks is only $3.87. However, when storage is at a level of 950,000 acre feet this value climbs to $36.10, dramatically increasing the cost to the basin of ignoring stock values in the decision making process. This result presents an interesting contrast to a study of the Pecos River Basin by Gisser and Sanchez (1980). In their empirical analysis of groundwater management, the researchers conclude that there is little difference in the temporal allocation of groundwater under optimal control versus open access when the storage capacity of an aquifer is relatively large.

Welfare losses gross of management costs actually may be larger than those reported in Table 6.11 since these measures do not consider the concomitant effects of groundwater extraction such as land subsidence that may be experienced under an open access rule. As groundwater is extracted, the hydraulic head surrounding the well declines and the effective stress or intergranular pressure on particles in the aquifer increases. Compression of these materials results in aquifer compaction. The extent of this compaction depends on a number of factors, including the structure of materials present in the aquifer. However, when compaction is severe it can result in land subsidence.

Incidences of land subsidence have been well documented in the U.S. and throughout the world (Bouwer, 1978). Subsidence is particularly severe when pumping exceeds net natural recharge and groundwater levels are not allowed to recover. Once long-term subsidence has occurred, rebound of the land surface (by a reduction in pumping or even injection of water into the system) is only slight and the storage capability of the aquifer may be permanently impaired. In time the structure of the aquifer may become so distorted that the artesian character may be permanently lost. Under these conditions the size of the welfare losses and the differences yielded by the two allocation schemes hardly seem trivial.

It must be emphasized, however, that the results of this analysis cannot be uniformly applied to all groundwater settings. The fact that the aquifer is confined sharply influences the nature of the decision rule. Had this not been the case, a totally different decision policy would have resulted. The shape of it, in turn, would have depended on myriad other factors. To suggest a single, hard and fast decision rule for all groundwater basins ignores the fact that every basin is different, either in terms of its physical or economic setting. An optimal decision policy, as such, must be tailored to the setting in which it operates.

Once an optimal decision policy has been established, considerable information is available for managing a particular basin. The most obvious is that the rule establishes the optimal quantity of groundwater that should be extracted from the basin given an initial state. This quantity is the basis for quota systems or use limits which may be imposed. The marginal values of groundwater stocks obtained in deriving the decision rule (Figure 6.8) reflect the divergence between marginal social and private costs in pumping a unit of groundwater. As such, they represent optimal levels of use taxes given a particular state which can be applied to restore the equality between private and social costs. This equality, as previously discussed, is a necessary condition for economic efficiency. The decision rule also indirectly indicates the optimal number of acres to bring under irrigation. Assuming as we have throughout the analysis that 1.8 acre feet of water are typically required for each acre of irrigated cropland, the optimal number of irrigated acres (in addition to those currently under irrigation) can be calculated by dividing the level of groundwater use (U) by 1.8. For example, under the baseline model when the level of groundwater in storage is 960,000 (X) acre feet, the optimal policy is to use 12,000 (U) acre feet of groundwater (see Figure 6.7). This translates into an additional 6,666.67 acres of irrigated cropland.

SENSITIVITY ANALYSIS

Once a decision rule was derived from the baseline model, various arguments of the model were modified to determine the sensitivity of program results to changes in these parameters. Obviously there are countless combinations of variables that can be examined in such an analysis. However, to limit the scope of this segment of the study to a manageable size only four basic "areas" were explored through sensitivity analysis. These include: the discount rate; the electric power rate for irrigation; the area of the basin; and, the productivity of the potentially irrigable acreage.

Changes in the Discount Rate

The discount rate determines how much a dollar received in the future is worth today. As such, it can be expected to have an important influence on decisions as to when and how much groundwater should be used.

Figures 6.10 and 6.11 summarize the decision rules for one-year and infinite planning horizons under a 3 and 12 percent discount rate, respectively. These two rates have the effect of halving and doubling the six percent rate used in the baseline model.

As can be seen from the figures, the choice of the discount factor does have a very decided impact on the optimal decision rule. When a smaller discount factor is used, only one equilibrium occurs at the current state (X_1^*. As long as the level of groundwater in storage is less than X_1^*, stocks are being built up. Even when storage is small, use is less than recharge (positive growth in stocks). The actual pattern of this growth is similar to the baseline model. Because future returns now are being discounted at a smaller rate it is more profitable throughout to forego current returns at higher pumping costs in favor of letting stocks build up and obtaining future returns at lower pumping costs.

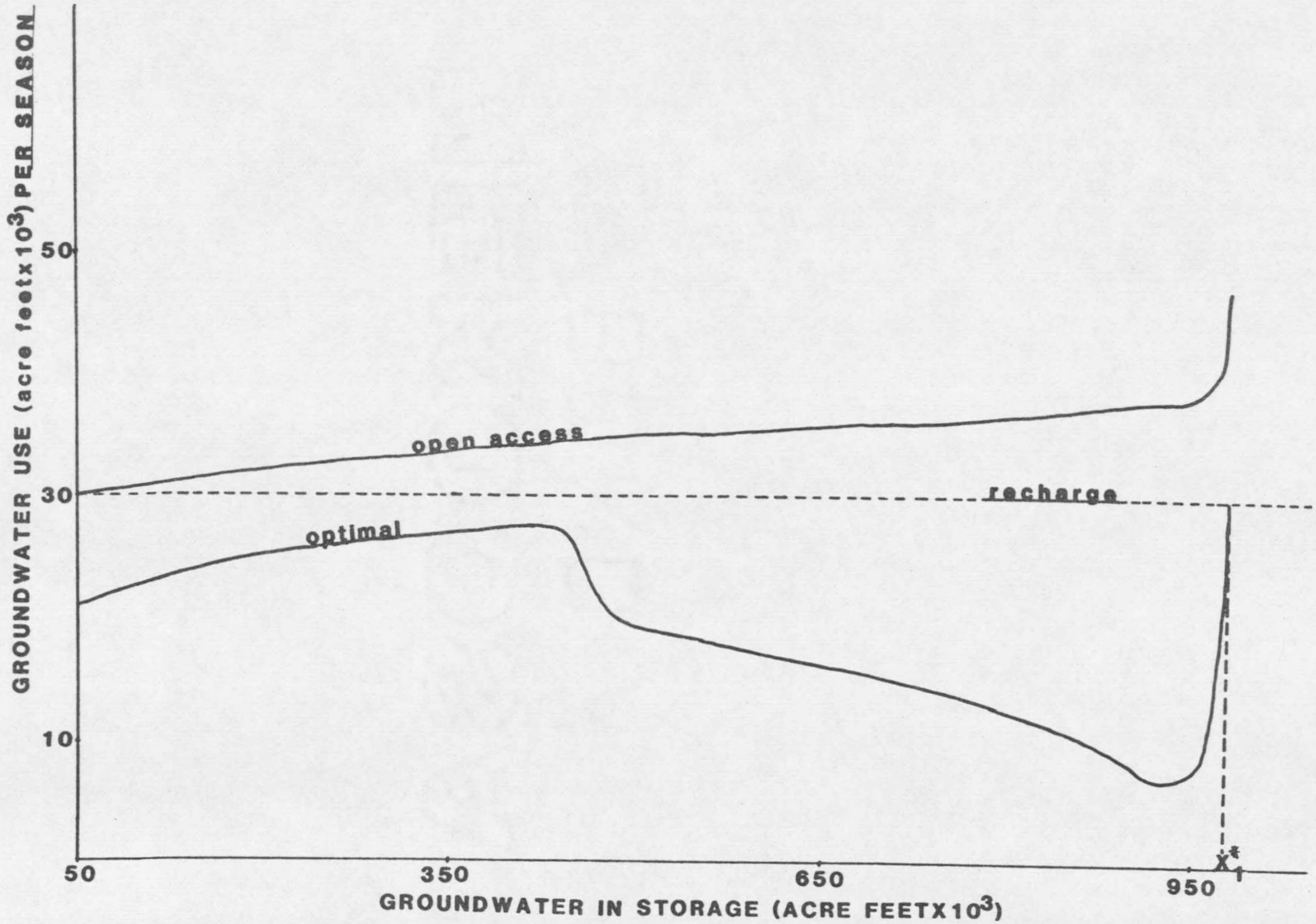

Figure 6.10. Derived Decision Rules Under an Optimal and Open Access Policy -- 3 Percent Discount Rate.

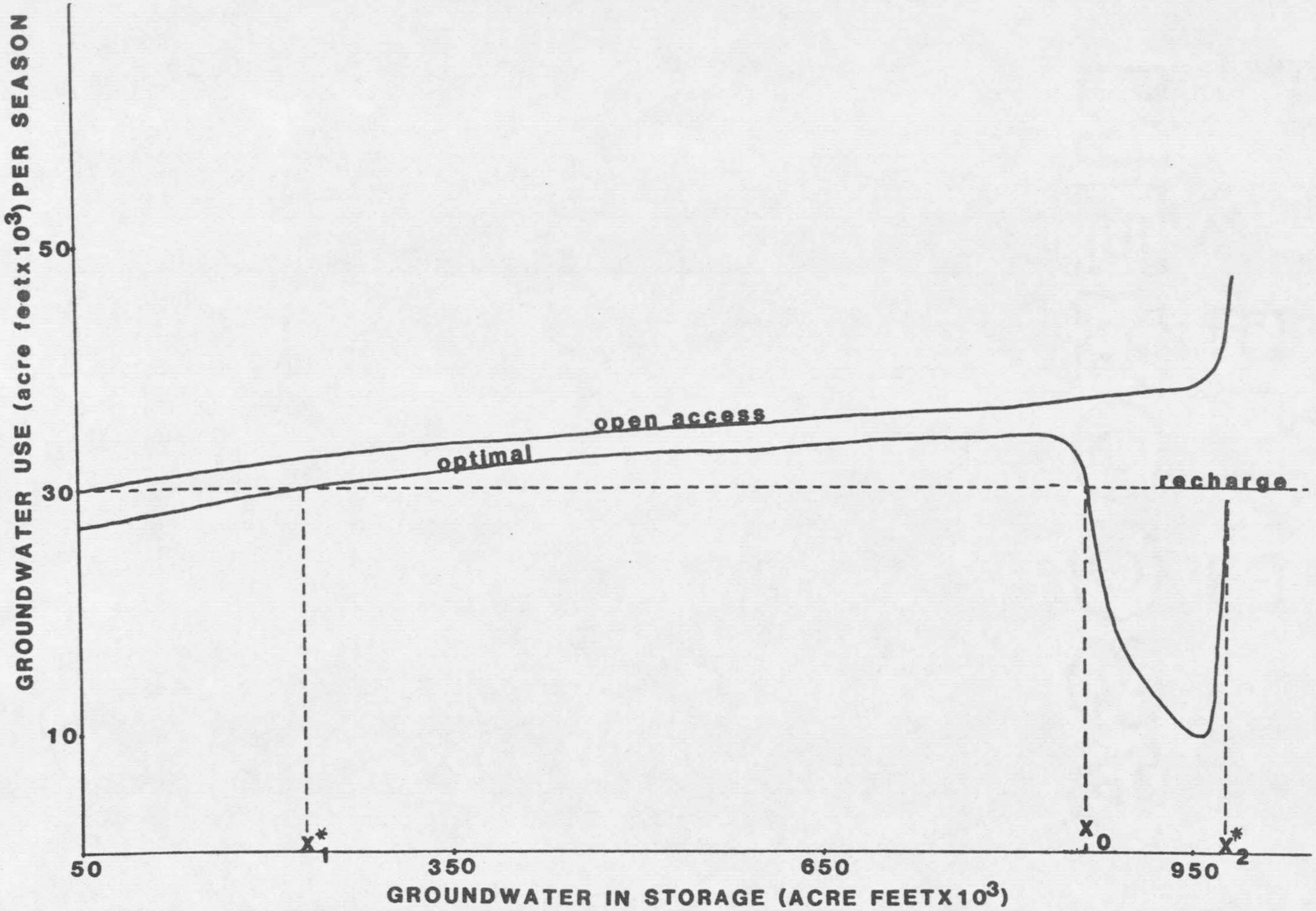

Figure 6.11. Derived Decision Rules Under an Optimal and Open Access Policy -- 12 Percent Discount Rate.

When a larger discount rate is applied, just the opposite happens. As in the baseline model, there are two equilibria. The first equilibrium (X_1^*) occurs at a lower level of storage than in the baseline model. The switching point (X_0) for moving to the second equilibrium occurs at a much greater level of storage than in the baseline model. In essence, the opportunity cost of building up groundwater stocks in this region is much higher. A dollar in the future now is worth less today. Thus it is more economic to use the groundwater today at higher pumping costs (driving the system toward the lower equilibrium, X_1^*) than at some future point. Beyond X_0, however, the system behaves much as it did in the baseline model.

Tables 6.12 and 6.13 summarize the efficiency gains of following the optimal decision policy versus a one-year planning horizon under the two discount rates. As expected the size of the gains are larger with a lower discount rate when the future or stock value of the resource has relatively more weight, and smaller with a larger discount rate when these values have less significance.

Irrigation Power Rates

Power represents a significant portion of the variable cost incurred in obtaining and using groundwater. As a result, electric rates for irrigation are likely to have tremendous impact on the level of groundwater use which maximizes net returns to a basin. Proposals are

Table 6.12. Welfare Gains from Following an Optimal Groundwater Use Policy Versus an Open Access Policy -- r = .03.

State[1]	Present Value ($) of Net Returns[2]: Optimal Allocation	Open Access	Actual ($) Difference[3]	% Change
100,000	18,218,839	17,415,539	+ 803,300	+ 4.61
300,000	19,764,039	19,160,339	+ 603,700	+ 3.15
600,000	23,159,039	21,271,839	+ 1,887,200	+ 8.87
800,000	27,515,839	22,628,339	+ 4,887,500	+ 21.60
900,000	30,216,939	23,415,039	+ 6,801,900	+ 29.05
950,000	31,691,039	23,862,939	+ 7,828,100	+ 32.80
978,000	32,584,839	24,396,439	+ 8,188,400	+ 33.56

[1]In acre feet of groundwater.

[2]Net of returns to currently irrigated acreage and dryland crops.

[3]Actual difference = net returns (optimal allocation) - net returns (open access). Does not consider costs of optimal basin management.

Table 6.13. Welfare Gains from Following an Optimal Groundwater Use Policy Versus an Open Access Policy -- r = .12.

State[1]	Present Value of Net Returns[2] Optimal Allocation	Open Access	Actual ($) Difference[3]	% Change
100,000	5,372,172	5,323,862	+ 48,310	+ 0.91
300,000	5,982,522	5,953,562	+ 28,960	+ 0.49
600,000	6,662,642	6,644,672	+ 17,970	+ 0.27
800,000	7,152,222	7,126,782	+ 25,440	+ 0.37
900,000	7,869,612	7,436,152	+ 433,460	+ 5.83
950,000	9,046,482	7,622,552	+ 1,423,930	+ 18.68
978,000	9,934,272	8,051,582	+ 1,882,690	+ 23.38

[1]In acre feet of groundwater.

[2]Net of returns to currently irrigated acreage and dryland crops.

[3]Actual difference = net returns (optimal allocation) - net returns (open access). Does not consider costs of optimal basin management.

currently before the state's Public Service Commission to substantially increase these rates. If accepted, these new rates will have a dramatic influence on groundwater use decisions both under an infinite planning period and a one year horizon. To see how the derived decision policies change under different energy pricing schemes, power costs were increased by 100 and 300 percent in the optimization model. Figures 6.12 and 6.13 summarize the resulting decision rules under 100 percent and 300 percent energy cost increases, respectively.

Under the 100 percent increase scenario, the two decision rules closely follow each other. Both have a single equilibrium and both are extremely sensitive to pumping costs. Under the open access policy, the higher energy (and associated pumping) costs result in stocks being built up until an equilibrium is reached at X^*_{cp} (approximately 975,000 acre feet). Prior to this pumping costs are too great relative to returns to justify the use of stocks. Once storage is greater than X^*_{cp}, however, pumping costs are small enough that stocks can be profitably used and the system is driven back to its equilibrium. When the planning period is infinite, profit is maximized by building stocks throughout until the system moves into an equilibrium (X^*_o) corresponding to the current level of storage. When energy costs are increased to 300 percent, pumping costs become the dominate variable in the decision rule and no groundwater is used under either the infinite or one year planning horizons.

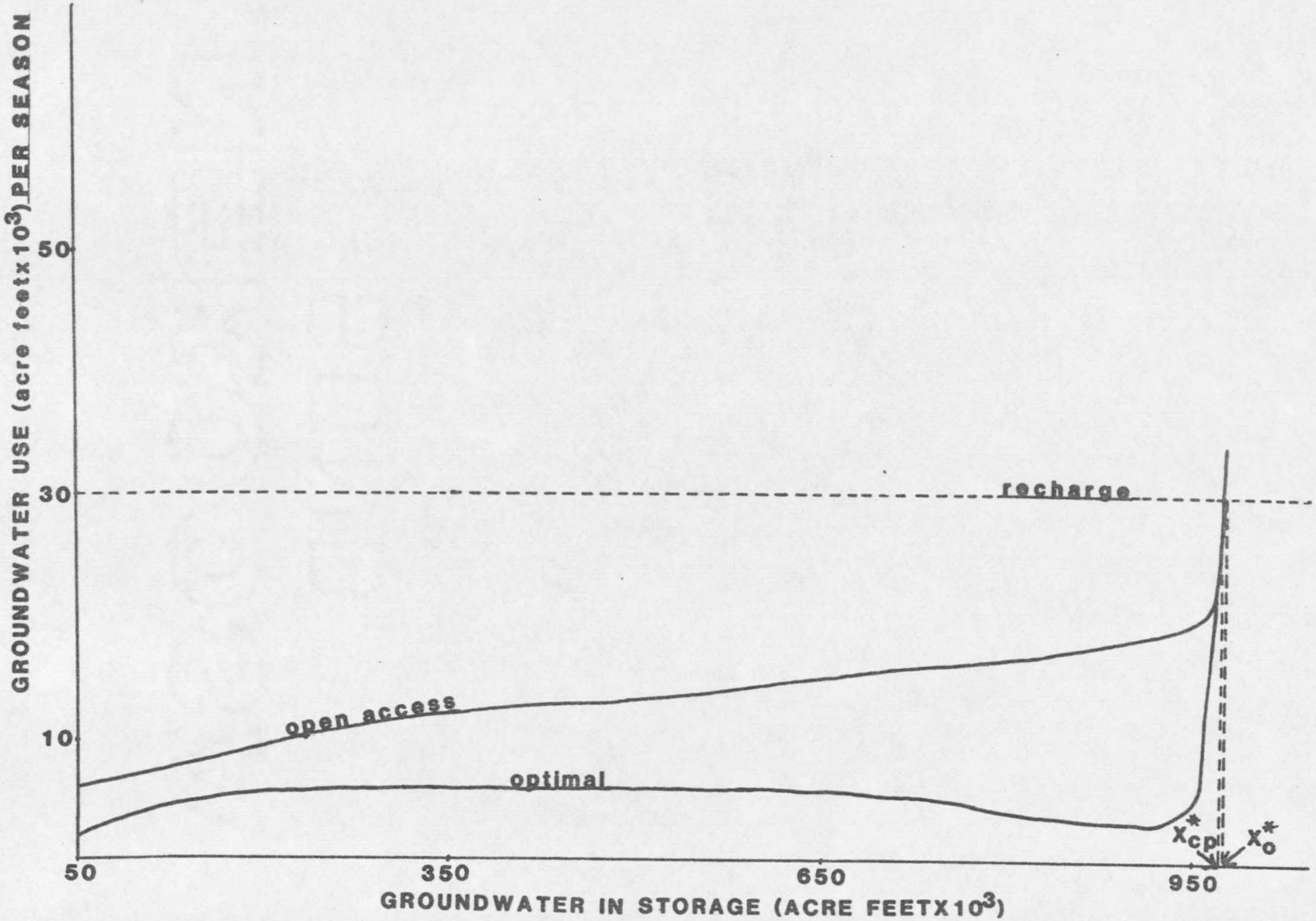

Figure 6.12. Derived Decision Rules Under an Optimal and Open Access Policy -- 100 Percent Electric Rate Increase.

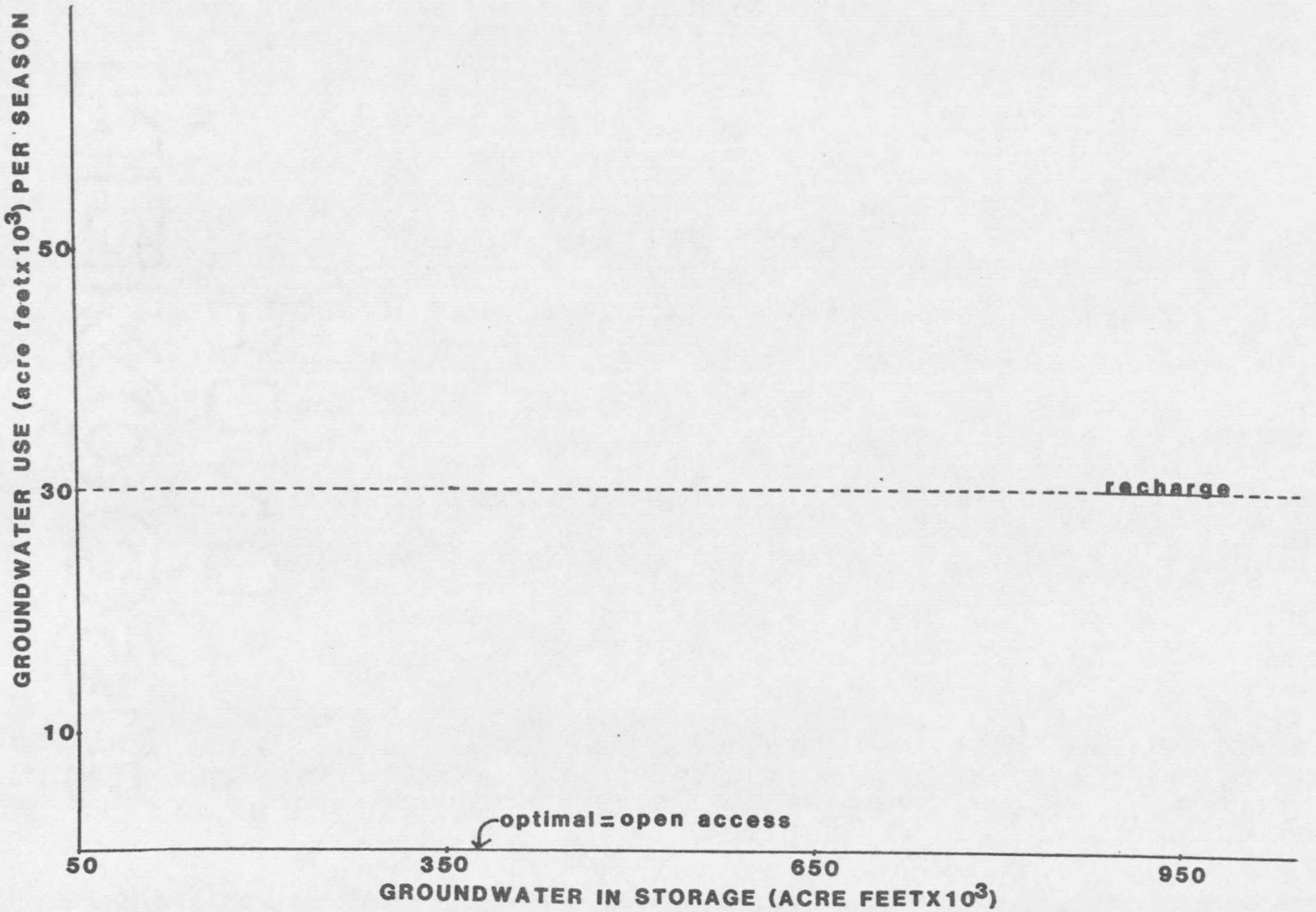

Figure 6.13. Derived Decision Rules Under an Optimal and Open Access Policy -- 300 Percent Electric Rate Increase.

Aquifer Size

The actual areal extent of an aquifer is never precisely known. Rather, educated estimates are made on the basis of limited hydrologic and geologic data. Further refinement of these estimates is both time consuming and costly. In this part of the analysis an attempt is made to determine how critical estimates of aquifer size are to the structure of the final decision rule. To do this the assumed aquifer size was increased and decreased by 20 percent and the resulting policies under each model compared.

Figures 6.14 and 6.15 depict the derived decision rules assuming a basin size of 72,192 and 48,128 acres, respectively. In both the shape of the optimal decision rules are virtually identical to the baseline model. Two equilibria are present, the second (X_2^*) occurring at a state value corresponding to the maximum storage level possible given current pumping conditions. While the location of the first equilibria (X_1^*) and associated switching points (X_0) vary among the models, given comparable state variable values they are not terribly different. That is, the locations of the first equilibrium point and switching point in the model assuming a 20 percent smaller basin size closely correspond to state values 20 percent smaller than those in the baseline model. A similar relationship holds for the larger basin size where the points occur at values approximately 20 percent larger. These relationships are not exact but are felt to be close enough to

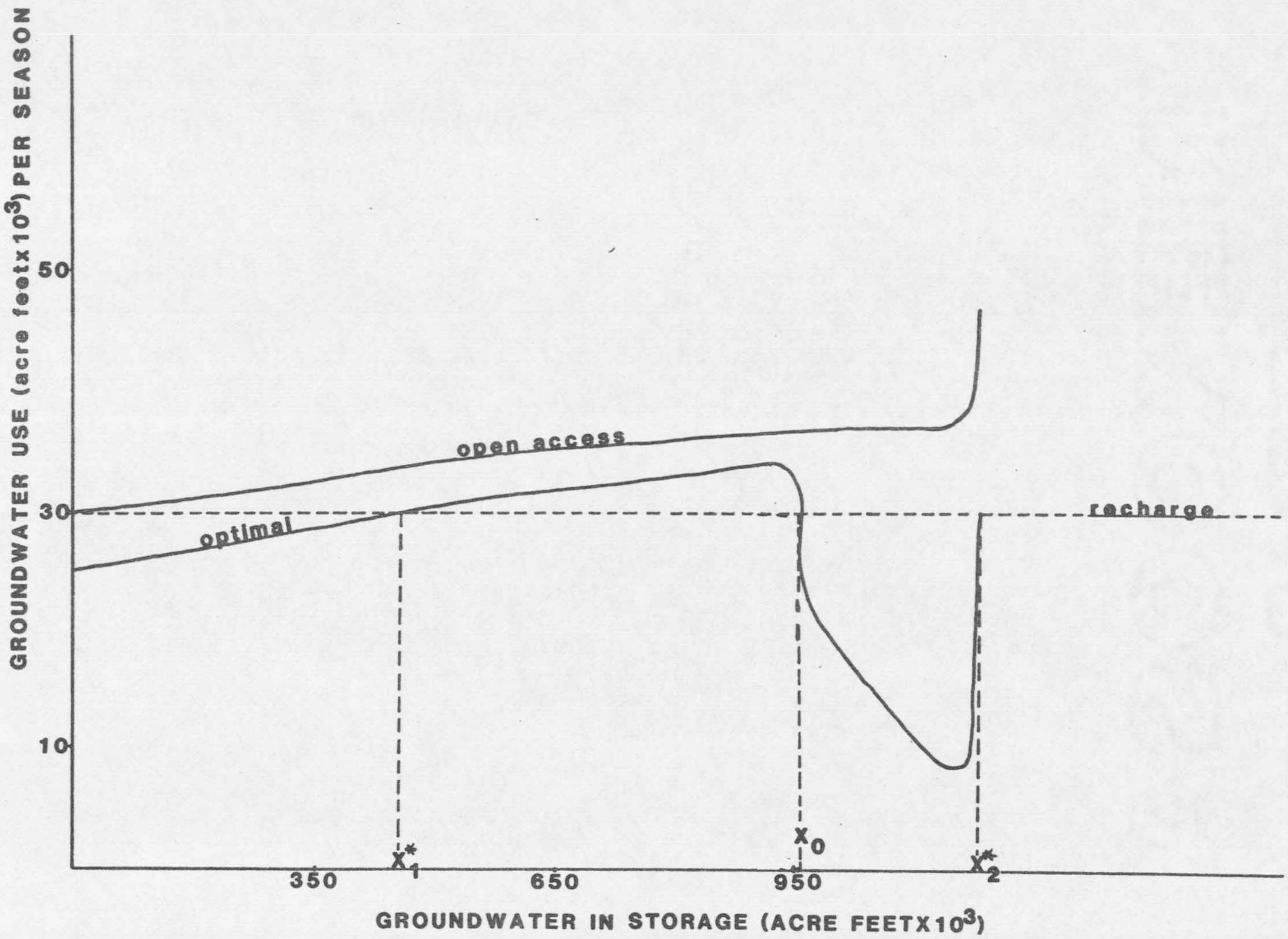

Figure 6.14. Derived Decision Rules Under an Optimal and Open Access Policy -- Larger Basin Size.

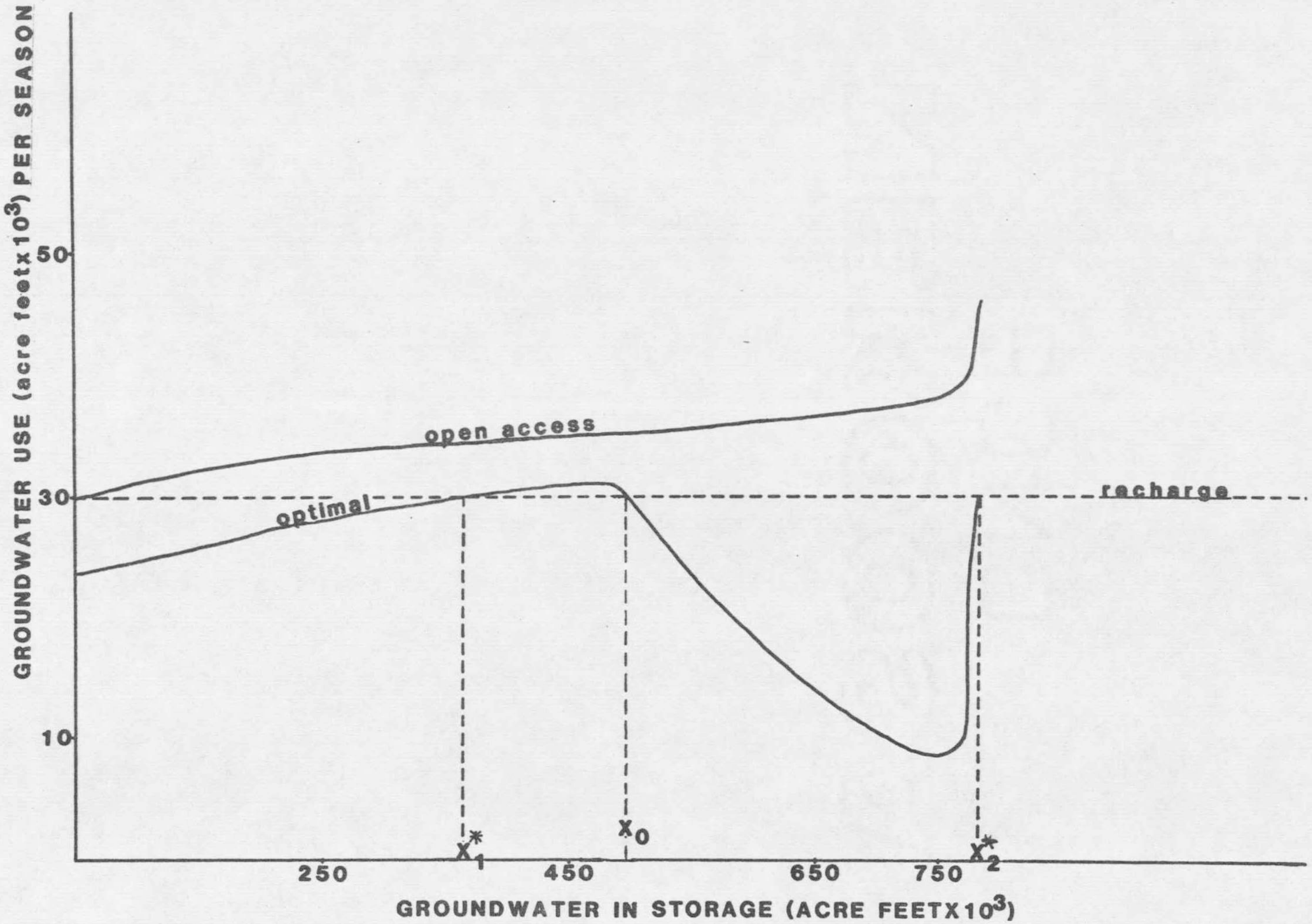

Figure 6.15. Derived Decision Rules Under an Optimal and Open Access Policy -- Smaller Basin Size.

provide a plausible explanation.

Tables 6.14 and 6.15 summarize data on welfare gains from following an optimal policy. As in the baseline model, the trend toward substantial gains as the level of stocks rise is clearly visible.

Land Productivity

One of the more dramatic results in the sensitivity analysis involves the impact of changes in the curvature of the gross returns function on the decision rule. As detailed in the LP section of this chapter (see pp. 119-121), curvature in the gross returns function is introduced as a w-y of accounting for differences in land productivity among various land classes. In the baseline model a small amount of curvature was assumed. To contrast with this, two additional optimization models were calculated -- one assuming equal land productivity ($\eta = 0$) and another with twice as much curvature as the base model ($\eta = .02$). The resulting decision rules are depicted in Figures 6.16 and 6.17.

When greater curvature is introduced, corresponding to greater diminishing marginal productivity of additional land brought under irrigation, only one equilibrium appears in the decision rule. Under an infinite planning horizon no stocks are used and the system is driven to a steady state at X_0^*. Even under a one year horizon, stocks are not used until levels of storage are greater than 970,000 acre feet, pushing the system back to an equilibrium at X_{cp}^*. The added

Table 6.14. Welfare Gains from Following an Optimal Groundwater Use Policy Versus an Open Access Policy -- Larger Aquifer Size.

State[1]	($) Present Value of Net Returns[2] Optimal Allocation	Open Access	Actual ($) Difference[3]	% Change
100,000	9,905,739	9,760,009	+ 145,730	+ 1.49
300,000	10,837,899	10,687,179	+ 150,720	+ 1.41
600,000	12,113,569	12,000,569	+ 113,000	+ 0.94
800,000	12,811,339	12,725,289	+ 86,050	+ 0.68
1,000,000	14,147,549	13,287,249	+ 860,300	+ 6.48
1,100,000	16,424,469	13,463,669	+ 2,960,800	+ 21.99
1,174,000	18,619,479	14,236,869	+ 4,382,610	+ 30.78

[1]In acre feet of groundwater.

[2]Net of returns to currently irrigated acreage and dryland crops.

[3]Actual difference = net returns (optimal allocation) - net returns (open access). Does not consider costs of optimal basin management.

Table 6.15. Welfare Gains from Following an Optimal Groundwater Use Policy Versus an Open Access Policy -- Smaller Aquifer Size.

State[1]	Present Value ($) of Net Returns[2] Optimal Allocation	Open Access	Actual ($) Difference[3]	% Change
100,000	10,356,999	10,032,269	+ 327,730	+ 3.27
200,000	10,974,329	10,720,119	+ 254,210	+ 2.37
400,000	12,025,749	11,850,249	+ 175,500	+ 1.48
600,000	13,872,139	12,824,759	+ 1,047,380	+ 8.17
700,000	16,016,169	13,347,519	+ 2,668,650	+ 19.99
750,000	17,369,029	13,641,809	+ 3,727,220	+ 27.32
782,000	18,359,609	14,173,759	+ 4,185,850	+ 29.53

[1]In acre feet of groundwater.

[2]Net of returns to currently irrigated acreage and dryland crops.

[3]Actual difference = net returns (optimal allocation) - net returns (open access). Does not consider costs of optimal basin management.

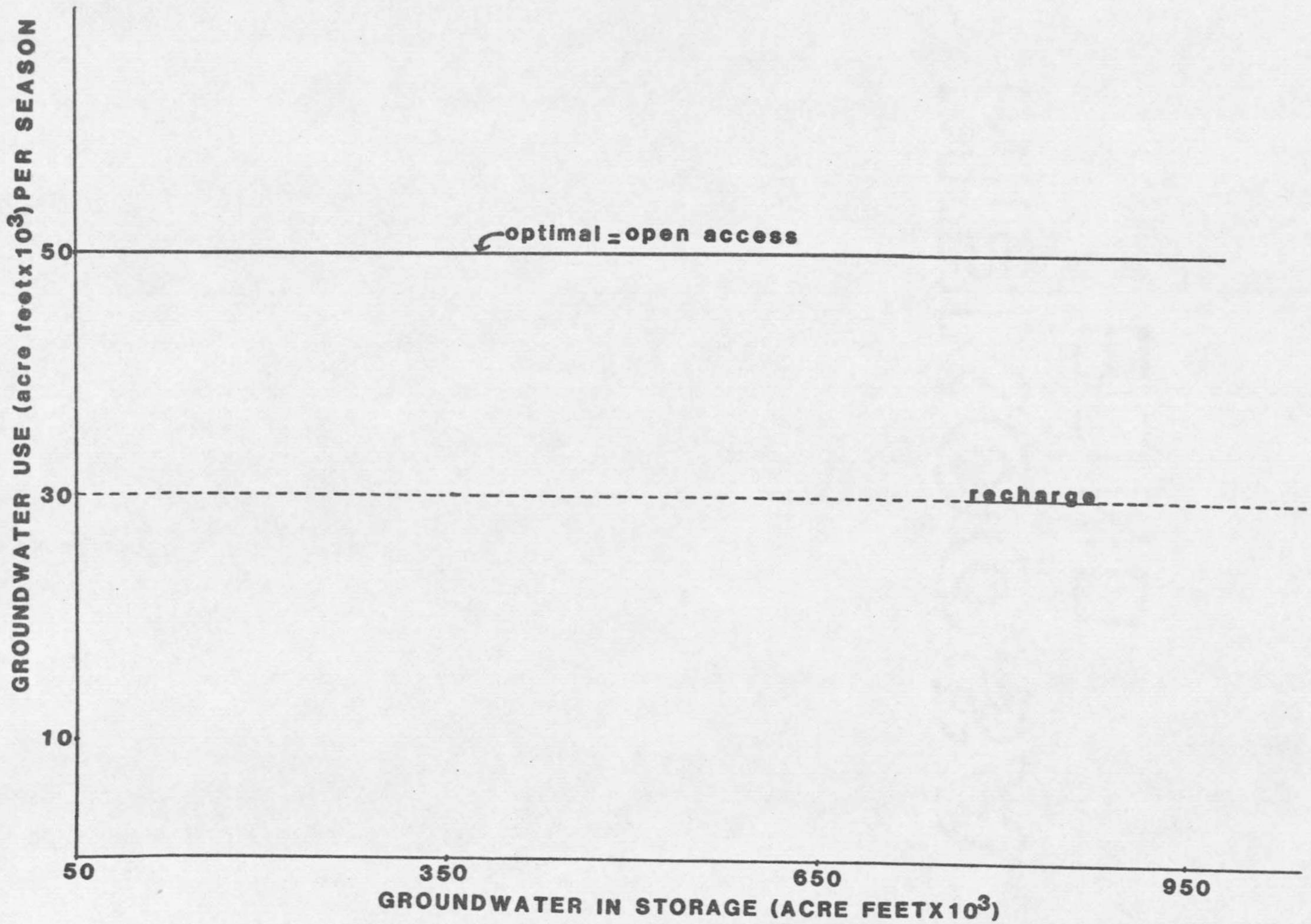

Figure 6.16. Derived Decision Rules Under an Optimal and Open Access Policy -- Constant Marginal Land Productivity.

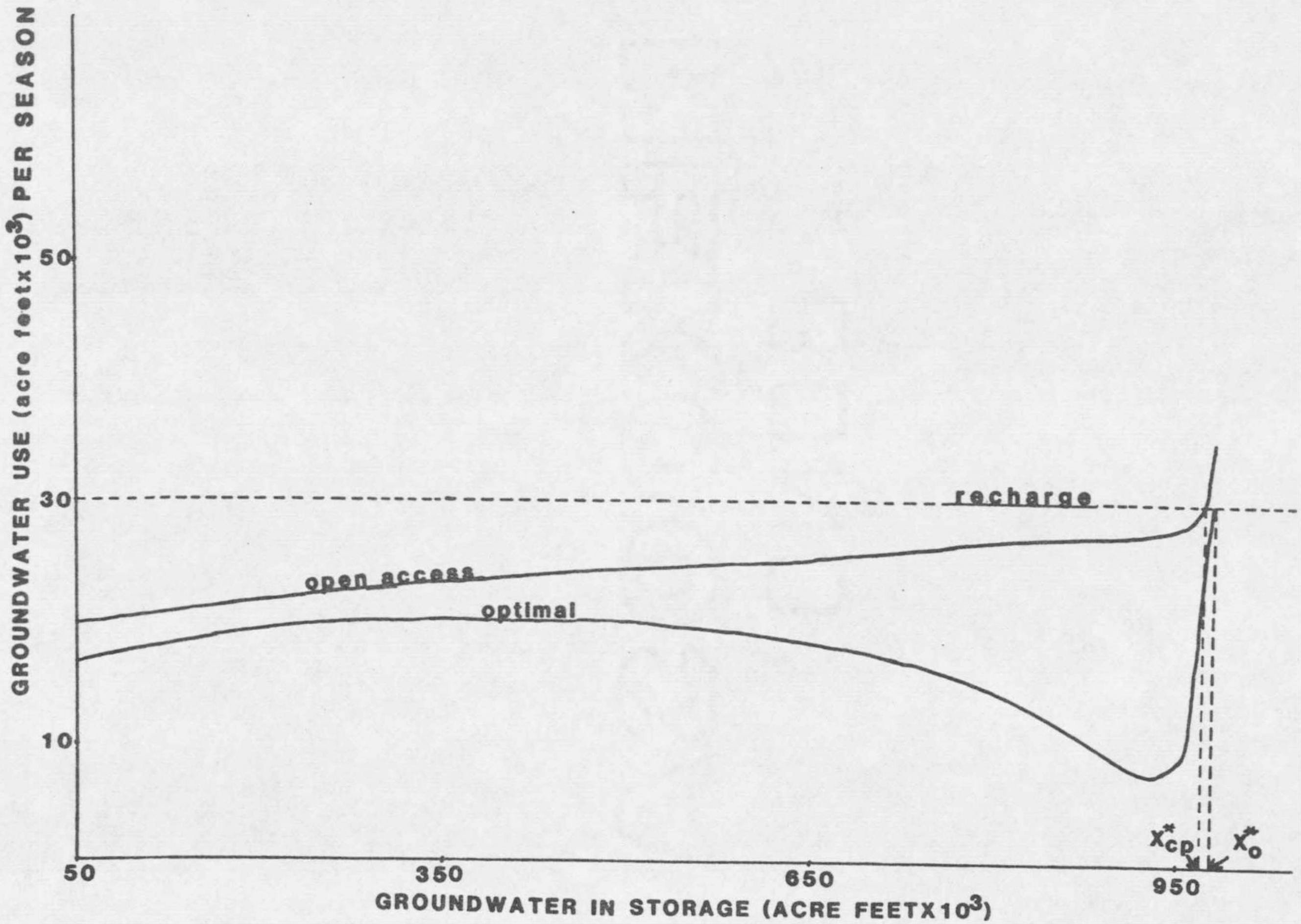

Figure 6.17. Derived Decision Rules Under an Optimal and Open Access Policy -- Greater Diminishing Marginal Land Productivity.

curvature in the gross returns function lowers both the marginal returns of groundwater in current use and its marginal value in stock. Thus it is less and less profitable to use larger quantities of groundwater regardless of the time dimension. Table 6.16 summarizes the differences in returns under an optimal versus an open access policy when greater diminishing marginal land productivity is assumed.

By contrast when no curvature is introduced, the returns function is nearly linear and an endpoint or boundary solution is optimal at every state. The maximum amount of groundwater (50,000 acre feet) is used regardless of state or stage. Both the optimal and open access decision rules are identical and, thus, there is no difference in the present value of net returns under the two policies.

This model was further modified to see if the nearly linear returns function when coupled with a smaller discount rate or larger electric rate still results in an endpoint solution. A three percent discount rate leaves the open access decision rule unchanged (Figure 6.18), but dramatically shifts the optimal decision rule away from the maximum level of use when storage levels are greater than 925,000 acre feet. At this point, use is substantially reduced and stocks build rapidly. When storage levels reach 945,000 acre feet, use increases almost monotonically and the system reaches an equilibrium (X_1^*) at a state corresponding to current storage conditions.

When electric rates are increased by 300 percent, the decision

Table 6.16. Welfare Gains from Following an Optimal Groundwater Use Policy Versus an Open Access Policy -- Greater Diminishing Marginal Land Productivity.

State[1]	Present Value ($) of Net Returns[2] Optimal Allocation	Open Access	Actual ($) Difference[3]	% Change
100,000	7,184,469	7,119,559	+ 64,910	+ 0.91
300,000	7,860,639	7,784,179	+ 76,460	+ 0.98
600,000	9,234,809	8,644,749	+ 590,060	+ 6.83
800,000	11,191,969	9,392,079	+ 1,799,890	+ 19.16
900,000	12,761,669	9,995,649	+ 2,766,020	+ 27.67
950,000	13,704,989	10,560,659	+ 3,144,330	+ 29.77
978,000	14,331,589	11,615,199	+ 2,716,390	+ 23.39

[1] In acre feet of groundwater.

[2] Net of returns to currently irrigated acreage and dryland crops.

[3] Actual difference = net returns (optimal allocation) - net returns (open access). Does not consider costs of optimal basin management.

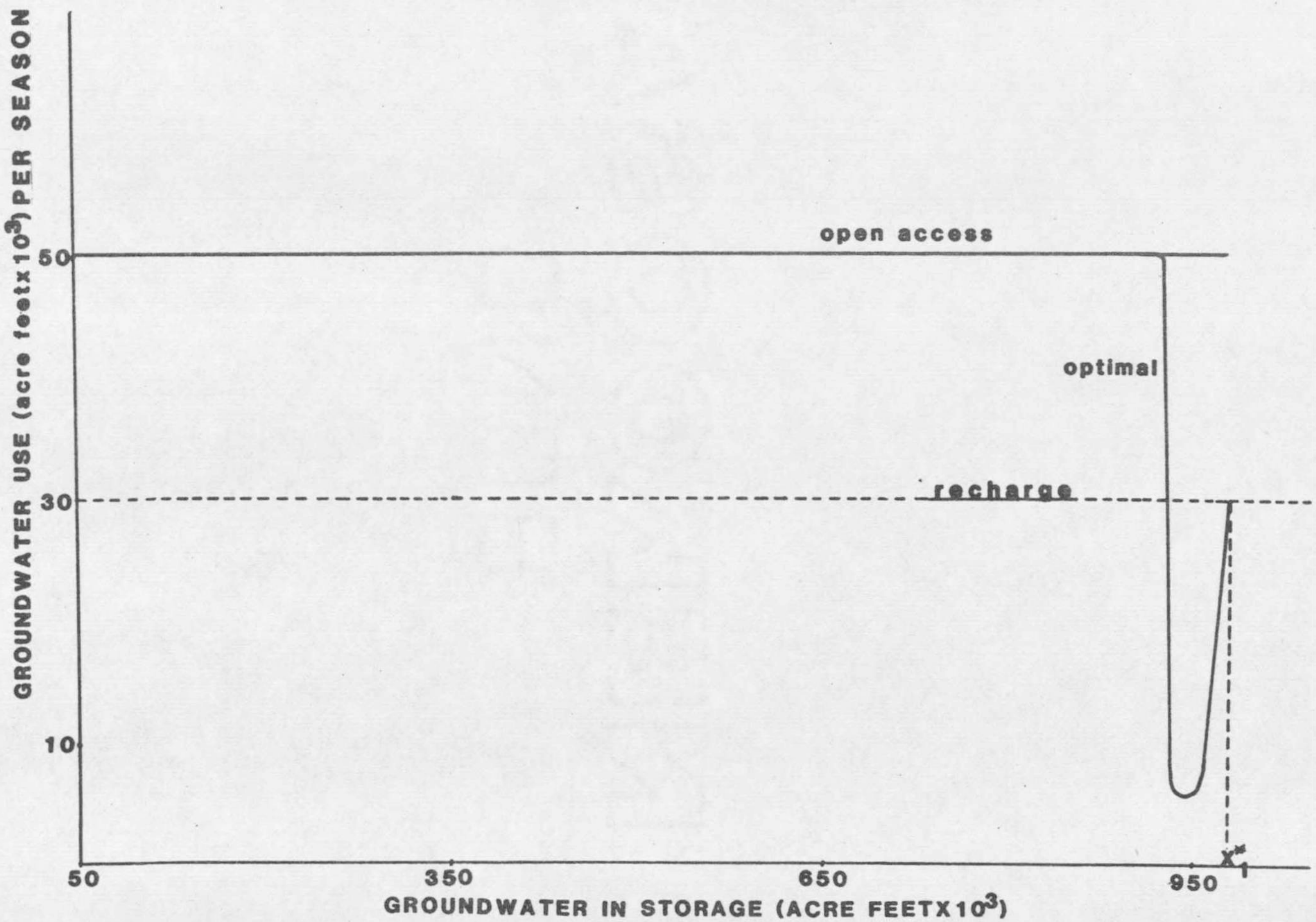

Figure 6.18. Derived Decision Rules Under an Optimal and Open Access Policy -- Constant Marginal Land Productivity and a 3 Percent Discount Rate.

rule moves to the opposite endpoint and no groundwater is used except at the maximum storage level possible (Figure 6.19). The decision policies are identical regardless of the length of the planning horizon. This result indicates that the decision rule is perhaps the most sensitive to power costs.

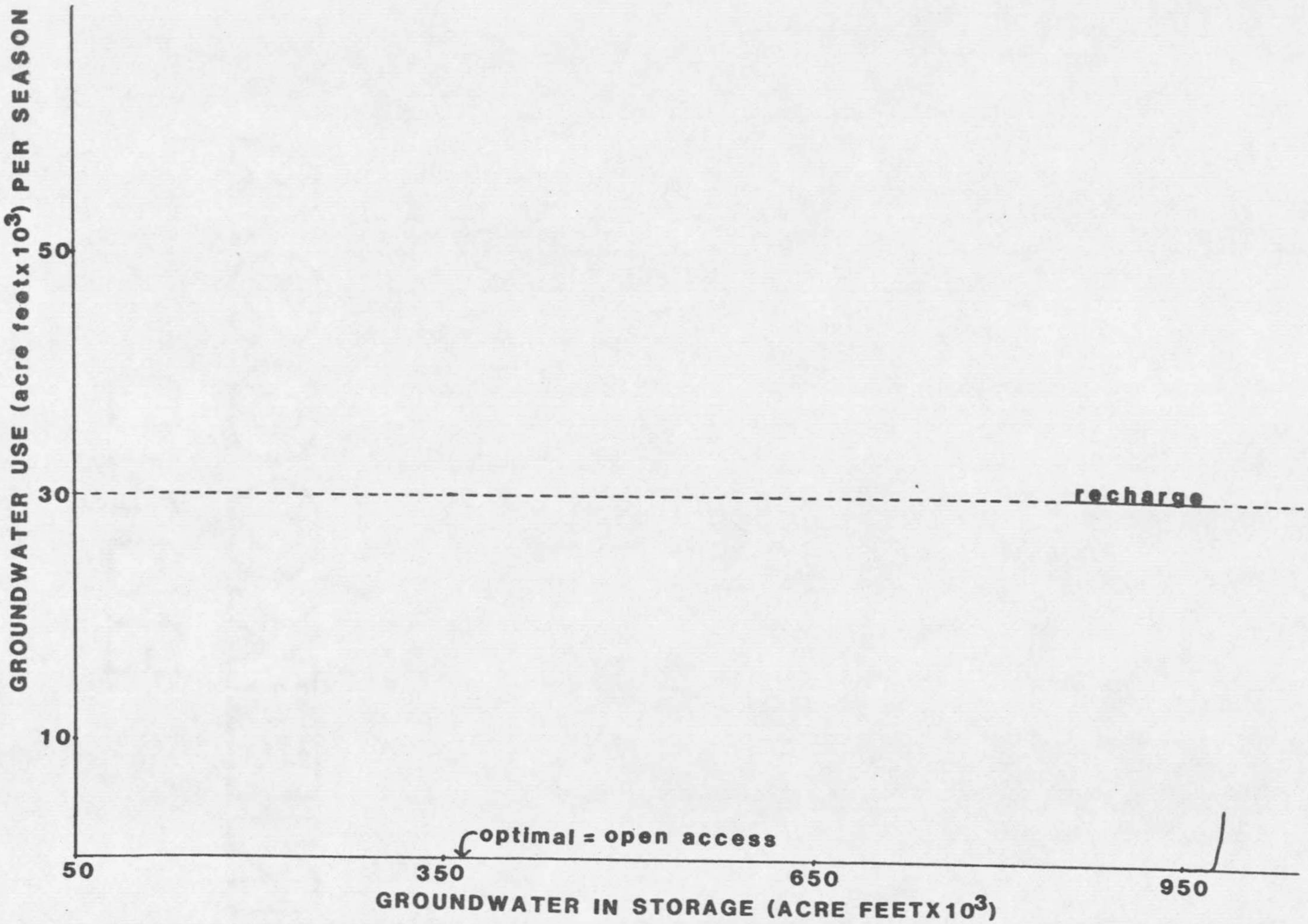

Figure 6.19. Derived Decision Rules Under an Optimal and Open Access Policy -- Constant Marginal Land Productivity and a 300 Percent Electric Rate Increase.

CHAPTER 7

SUMMARY AND CONCLUSIONS

In the previous chapter it was demonstrated that efficiency losses associated with commonality problems in groundwater use are not trivial. Under the assumptions of the baseline model, net returns to the study basin are reduced by nearly 30 percent when groundwater is allocated under an open access regime. This study attempts to describe the economic conditions which result in such inefficiencies; and, given the presence of these conditions, what institutional alternatives are available for dealing with them from both a theoretical and practical point of view.

At the heart of much of the commonality problem lies the voluminous body of law governing the allocation and use of groundwater. Ironically it is the failure of this body to establish explicit property rights to groundwater that has perpetuated inefficiencies in the resource's use. Specific aspects of groundwater law -- in Montana and elsewhere -- are examined in the study to identify problem areas.

While resource policy can take on myriad objectives, the primary concern of this study is the promotion of economic efficiency. Equity and distributional impacts are equally valid concerns. However, as a science, economics seems to provide the most unambiguous and least value-laden tools for evaluating efficiency objectives. It is within this context that various centralized and decentralized approaches to groundwater management are evaluated.

A case study is made of the Crow Creek Valley in Southwestern Montana to demonstrate how an optimization model can be used to determine the most efficient temporal allocation of groundwater from a basin. In general terms an optimal temporal allocation is one which maximizes net returns to the basin over an infinite planning horizon. Implicit in this definition of efficiency are several critical marginal conditions. While rational producers always equate the marginal value of groundwater in current use with its marginal value as stock (or user cost) in the pumping decision, under an open access policy this stock component is given zero value. The resulting allocation is suboptimal from society's perspective and the resource is wasted.

The dynamic programming model used in this analysis is based on methodologies established by Burt (1964 a, b, 1966, 1967, 1970) in his series of studies on groundwater management. Although the actual model used here is quite simplistic -- for example recharge to the basin is treated as a constant -- its numeric solution provides information on a host of problems associated with the optimization. In addition to establishing conditionally optimal extraction rates, the derived decision rule can be used to evaluate the marginal value of groundwater stocks, the magnitude of efficiency losses under an open access rule, the optimal number of acres to bring under irrigation, and time paths to a steady state level of stocks (use equal to net natural recharge). The structure of the model assumes the basin is under the control of some central decision agent. This does not necessarily imply that centralized management is a superior control strategy. Rather the model is used for expository purposes to demonstrate conditions necessary for efficient allocation; conditions necessary under any optimization strategy.

Conclusions

The decision rule derived in the above analysis has a variety of implications for allocation of groundwater resources from basins similar to the one underlying Crow Creek Valley. Where systems are confined there is a decided economic advantage in maintaining the piezometric surface above the confining layer, thereby preserving the artesian pressure. When stocks are mined from a confined aquifer (use greater than recharge) the piezometric surface drops and marginal pumping costs increase; rapidly at first and then more slowly as the system becomes unconfined. Whether the economic advantage of maintaining this artesian pressure (and the lower pumping costs associated with it) holds for all quantities of groundwater storage in an aquifer depends on several factors: 1) the rate at which future returns from the basin are reduced to present value terms (the size of the discount rate); 2) the shape of the gross returns function from groundwater use; and 3) relative pumping costs, primarily determined by power costs.

In the baseline model the decision rule establishes two equilibria -- states in which the optimal level of groundwater use is equal to recharge, leaving the system unchanged. The first equilibrium forces the system to a level of stocks corresponding to current conditions (the maximum storage possible given current pumping activities). However, once stocks go below a certain quantity, too much must be sacrificed to restore the artesian pressure, and the system is directed toward a lower equilibrium in which the aquifer is unconfined.

At higher power costs or lower discount rates, the level of sacrifice is no longer constraining and only the first equilibrium is relevant. Thus the optimal pattern of use moves the system to a confined setting, regardless of the initial quantity in storage. A similar result holds when substantial curvature is present in the gross returns function.

Expected net returns calculated in the solution are used to analyze differences in returns to the basin under an optimal allocation and an open access setting. While these differences do not consider the management costs incurred in achieving this optimal allocation, in a gross sense they represent the welfare loss to society of ignoring the positive value of groundwater stocks. Marginal values of stocks drop rapidly as the system becomes unconfined. As a result, welfare gains are greatest when an optimal policy is followed and storage levels are large.

The structure of the optimal decision policy derived in this analysis is largely dependent upon the physical and economic character of the study basin. The presence of two equilibria is entirely related to the confined nature of the aquifer. In addition, the marginal value product of groundwater in the Crow Creek Basin is relatively low as compared with other basins in which crops such as fruits and vegetables (rather than cereal grains and hay) are grown. As a result, groundwater irrigation use decisions in the study area are likely to be more sensitive to pumping costs than in basins where groundwater has a greater marginal value product.

This observation is partially borne out by the dramatic impact increases in energy costs have on the decision rule. Of the four variables examined in the sensitivity analysis section of this study, energy costs are the most critical in shaping groundwater use decisions. A 100 percent increase in energy costs results in stocks being build up for most states, even under an open access rule. When energy costs increase 300 percent, optimal and open access decision rules are identical and no groundwater is used for irrigation. The only exception to this occurs when the gross returns function is nearly linear and storage is at the maximum level possible. Even under this scenario only 5,000 acre feet are pumped. These results are consistent with observations reported by Frederick (1981) in a study on the future role of Western irrigation: "The most immediate threats to groundwater irrigation are the higher costs resulting from rising energy prices . . . Further expansion likely will be limited to areas with relatively low pumping depths or access to energy supplies under relatively favorable terms" (p. 21). He notes that corn prices would have to rise by roughly 25 percent to offset cost increases stemming from a doubling of electricity prices (p. 22). Thus ironically, increases in energy costs could eliminate actual conflicts over groundwater use even though in theory the commonality problem still remains.

As a matter of convenience differences in land productivity among individual land classes are often assumed away. Results of this analysis indicate that land productivity, vis-a-vis its impact on the shape of the gross returns function, has a very significant influence on the optimal allocation of groundwater resources. In this study curvature is artificially introduced in the returns function to simulate diminishing land productivity. When no curvature is introduced, the nearly linear returns function results in a boundary solution and the optimal allocation policy is identical to that under an open access setting. As greater curvature is applied, however, the difference between optimal and open access decision rules becomes more pronounced.

Basin size appears to have little impact on the general structure of the optimal decision rule. When basin size is increased and decreased by 20 percent in the optimization model, there is little change in the relative position of critical switching and equilibria points.

The primary objective of the empirical analysis of Crow Creek Valley was to demonstrate in a general sense the use of an economic optimization model for allocating groundwater resources. However, the results of this study also raise some important implications for public policy toward further development of this basin. Maintenance of the artesian pressure in the aquifer is a critical management objective if the basin is to be utilized in an economically efficient manner. Even relatively minor overdraft may destroy this pressure, eliminating a vital dimension of the groundwater resource underlying Crow Creek Valley. However, the actual point at which overdraft becomes critical is not clearly enough defined in this study to permit establishment of specific basin regulatory guidelines. More complete data is needed to replace some of the assumptions made in the model used here. Ironically the primary mechanism for generating this additional information -- further basin development -- may threaten the very artesian character an optimal allocation scheme would seek to protect. Thus new pumping permits should be carefully evaluated before issuance and pressure levels carefully monitored as more information becomes available. At some point only temporary permits might be issued in the basin. The permits would be valid for a sufficient period of time to enable users to recover their investment costs (15 years) but after this period could be revoked if new information indicates a loss of the artesian pressure.

In addition to the rather specific results of the optimization model, there are more general conclusions which can be drawn from the study. Perhaps the most unambiguous is the need for a greater data base on the physical character and distribution of groundwater resources in Montana. Active groundwater management -- whether by a central agency or individual pumpers -- requires a certain "base" of information on the physical properties of the basin. For example in the optimization model used above the following information was needed to complete the analysis: size of basin; depth of aquifer; depth to the overlying confining layer; depth of piezometric surface; storage coefficients; transmissivity; drawdown and pumping lift estimates; well efficiencies and locations; recharge and discharge estimates;

general consistency of aquifer characteristics across the basin (distribution of these characteristics).

Unfortunately such information is rarely available unless a basin has been extensively developed or specific hydrologic studies have been pursued. Even then the appropriate information may not be directly available. (In the Crow Creek model many assumptions were employed because of information gaps.) Groundwater exploration is an expensive proposition. However efforts can be made to minimize these costs by utilizing existing wells and encouraging greater cooperation between private well owners and researchers, perhaps through the use of special development permits or temporary permits as mentioned above. Sensitivity analysis, such as that performed in this study, using a simplified hydrologic-economic model of an aquifer basin also can be used to identify parameters critical to the overall structure of the decision policy and thereby direct basic data collection efforts.

Well logs are another area where improvements can be made in data collection. Often logs are the only source of hydrologic information in a basin. As such they have the potential to provide key information vital to management efforts. Unfortunately many logs are inconsistent and incomplete, and, as a result, useless as information sources. Thus greater emphasis should be placed on well log accuracy and consistency.

Even under decentralized management strategies where the burden of risk in decision making is borne by individual users, physical information on basin characteristics is essential. For example, the deeds approach suggested by Smith (1977) and others requires knowledge of recharge levels, basin storage capacity and estimates of recoverable stocks. Thus, regardless of the institution, groundwater management will necessitate a greater commitment to baseline groundwater surveys.

Like its neighboring appropriation states, Montana has laws which limit the certainty and transferability of property rights to groundwater. Such limits aggravate commonality problems. Some of the specific problem areas identified in this study include: beneficial and reasonable use clauses, judicially and legislatively imposed use preferences; forfeiture clauses; the usufructuary nature of rights; transferability and third party protection; and water quality aspects. The provision for creating special management basins or controlled groundwater zones is seen as a double-edged sword. While such designation creates uncertainty as to the long-term security of a groundwater right, it also introduces an element of flexibility. A cursory review of other states' laws as they relate to groundwater management in areas where use conflicts have arisen indicates that current Montana statutes provide far greater flexibility than most. Once an area is designated as a controlled zone in Montana, virtually any management strategy can be pursued. Given the variability of economic and hydrologic conditions, this flexibility is seen as a decided advantage in promoting efficient resource use.

Recommendations for Future Study

As is often the case, this study poses as many questions for future research as it does answers. Any water management program must consider the conjunctive aspects of ground and surface waters. In this study attention was focused only on groundwater use problems. Yet the principles of hydrology establish that on a broad scale the two are inseparable. Thus a comprehensive water management program must treat ground and surface waters as an integrated system. While models have been developed for conjunctive management in other regions (Burt, 1964a; Noel et al., 1980; Young and Bredehoeft, 1972), this work should be extended to Montana. An expanded study of the Crow Creek Valley, for example, could contrast decision rules under integrated management and when groundwater is treated separately (as in this analysis).

A growing segment of the economics literature on common pool resources urges greater reliance on the market and individual decision makers in bringing about efficient resource allocation. Several such decentralized approaches to groundwater management are described in this study. However none of these strategies have actually been implemented. Additional research is needed in this area. Test basins could be established in which decentralized management schemes are used and their effectiveness monitored. Montana's controlled groundwater zone provisions appear to be flexible enough to permit such experimentation.

Further refinements of the model used in this analysis also would generate valuable information. A model in which net natural recharge is treated as a random variable rather than a constant would do much to improve the "realism" of the optimization results. However, far more physical data on recharge estimates are needed before the model can be treated in a stochastic framework. Better estimates of hydrologic parameters also would add to the realism of the results. This is particularly true for areas where no information was available and educated assumptions were used instead. Drawdown estimates, particularly when the system becomes unconfined, were arbitrarily selected at a level far less than that calculated for the confined setting. Additional analysis using different rates of drawdown would indicate the overall sensitivity of the decision rule structure to this variable. The impact of different transmissivity measures and differences in other physical characteristics <u>within</u> the basin also would be extremely instructive. While such differences greatly complicate the optimization model, lack of uniformity within a basin is probably more the rule than the exception. Finally, risk and uncertainty could be incorporated into the objective function used in generating a gross returns function for groundwater use to examine their impact on the optimal decision rule.

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APPENDICES

Appendix A. Linear Programming Matrix for Deriving Marginal Value Function For Groundwater Use.

RESOURCE CONSTRAINT: / ACTIVITY:		Currently Irrigated Land				Potentially Irrigable Land				Dryland		
		Alfalfa Hay	Spring Wheat	Barley	Seed Potato	Alfalfa Hay	Spring Wheat	Barley	Seed Potato	Winter Wheat	Barley	Summer Fallow
Objective Function	0	180.60	142.03	78.99	401.26	138.97	100.40	37.36	359.63	60.88	47.46	-7.45
Labor Balance Equation[1]	0	-2.0	2.18	-2.18	-6.87	-2.00	-2.18	-2.18	-6.87	-.41	-.47	-.29
Groundwater Balance Equation	0[2]					2.14	1.29	1.29	1.85			
Currently Irrigated Land Base[3]	17,090.00	1.0	1.0	1.0	1.0							
Class I land	921.85				1.0							
Potentially Irrigable Land Base	31,961.00					1.0	1.0	1.0	1.0	1.0	1.0	1.0
Class I Potentially Irrigable Land	361.00								1.0			
Alfalfa Hay Balance Equation	0	.50	-.50	-.50	-.50	.50	-.50	-.50	-.50			
Irrigated Grain Balance Equation	0	-.75	.25	.25	-.75	-.75	.25	.25	-.75			
Irrigated Barley Balance Equation	0	.12	.12	-.88	.12	.12	.12	-.88	.12			
Summer Fallow Balance Equation	0									1.0	1.0	-1.0

[1] Not a constraint but entered to account for the units of labor used.

[2] Varied parametrically in increments of 2,500 acre feet up to a maximum of 50,000 acre feet.

[3] Water is assumed not to be a constraint.

Appendix B. Variable Cost Calculations for Alfalfa Hay[1] (1980 dollars).

Variable Cost Description	Quantity	Cost
Nitrogen	22 lbs	5.58
Phosphate	110 lbs	19.52
Potash	30 lbs	3.80
Fertilizer Spreading	1 acre	1.90
Insecticide	1 acre	5.39
Stand Establishment	1 acre	2.26
Plow-up Alfalfa	1 acre	1.53
Misc. Expenses	1 acre	6.48
Pickup Costs	20 miles	3.04
Machinery	1 acre	9.99
Tractors	1 acre	4.04
Labor (Tractor & Machinery)[2]	1.30 hrs	6.50
Interest on Operating Capital	12.14 dollars	1.38
Twine	120 bales	4.56
Irrigation Labor[2]	.7 hrs	3.50
Irrigation Equipment Maintenance[3]	1 acre	3.67
Irrigation Equipment Insurance[4]	1 acre	.88
Power (Irrigation)[5]	1 acre	8.26
Total Variable Cost, Currently Irrigated Land		92.28
Irrigation Well[6] and Distribution Equipment Investment Cost		40.68
Well Maintenance Cost		.55
Well Insurance Cost		.40
Total Variable Cost, Potentially Irrigable Land		133.91

[1] Updated from Enterprise Costs of Irrigated Crops in Broadwater County, Bulletin 1187, Montana Cooperative Extension Service, April 1978.

[2] Assumes fifty percent supplied by management. Irrigation labor requirements are different from that reported in the enterprise cost study. Labor costs are computed at $5/hr.

[3] Based on information supplied by irrigation equipment dealers.

[4] New Cost/2 x .006/acres.

[5] Assumes zero lift.

[6] Well cost excludes pump, motor, panel and wiring.

Appendix C. Variable Cost Calculations for Irrigated Spring Wheat[1] (1980 dollars).

Variable Cost Description	Quantity	Cost
Nitrogen	100 lbs	25.35
Phosphate	45 lbs	7.98
Fertilizer Spreading	1 acre	1.90
Seed	1.17 bu	7.41
Roundup	1 acre	1.27
2,4-D	1 acre	3.36
Hail Insurance	1 acre	7.60
Misc. Expenses	1 acre	8.22
Pickup Costs	20 miles	3.04
Machinery	1 acre	7.41
Tractors	1 acre	11.33
Labor (Tractor & Machinery)[2]	1.48 hrs	7.40
Interest on Operating Capital	19.45 dollars	2.22
Custom Combine	1 acre	15.21
Irrigation Labor[2]	.7 hrs	3.50
Irrigation Equipment Maintenance[3]	1 acre	3.67
Irrigation Equipment Insurance[4]	1 acre	.88
Power (irrigation)[5]	1 acre	6.06
Total Variable Cost, Currently Irrigated Land		123.77
Irrigation Well[6] and Distribution Equipment Investment Cost		40.68
Well Maintenance Cost		.55
Well Insurance Cost		.40
Total Variable Cost, Potentially Irrigable Land		165.40

[1] Updated from Enterprise Costs of Irrigated Crops in Broadwater County, Bulletin 1187, Montana Cooperative Extension Service, April 1978.

[2] Assumes fifty percent supplied by management. Irrigation labor requirements are different from that reported in the enterprise cost study. Labor costs are computed at $5/hr.

[3] Based on information supplied by irrigation equipment dealers.

[4] New Cost/2 x .006/acres.

[5] Assumes zero lift.

[6] Well cost excludes pump, motor, panel and wiring.

Appendix D. Variable Cost Calculations for Irrigated Barley[1] (1980 dollars).

Variable Cost Description	Quantity	Cost
Nitrogen	70 lbs	17.74
Phosphate	45 lbs	7.98
Potash	25 lbs	3.17
Fertilizer Spreading	1 acre	1.90
Seed	75 lbs	7.60
Roundup	1 acre	1.27
2,4-D	1 acre	3.36
Hail Insurance	1 acre	7.60
Misc. Expenses	1 acre	7.82
Pickup Cost	20 miles	3.04
Machinery	1 acre	7.41
Tractors	1 acre	11.37
Labor (Machinery & Tractor)[2]	1.48 hrs	7.40
Interest on Operating Capital	18.34 dollars	7.09
Custom Combine	1 acre	15.21
Irrigation Labor[2]	.7 hrs	3.50
Irrigation Equipment Maintenance[3]	1 acre	3.67
Irrigation Equipment Insurance[4]	1 acre	.88
Power (Irrigation)[5]	1 acre	6.06
Total Variable Cost, Currently Irrigated Land		119.01
Irrigation Well[6] and Distribution Equipment Investment Cost		40.63
Well Maintenance Cost		.55
Well Insurance Cost		.40
Total Variable Cost, Potentially Irrigable Land		160.64

[1]Updated from Enterprise Costs of Irrigated Crops in Broadwater County, Bulletin 1187, Montana Cooperative Extension Service, April 1978.

[2]Assumes fifty percent supplied by management. Irrigation labor requirements are different from that reported in the enterprise cost study. Labor costs are computed at $5/hr.

[3]Based on information supplied by irrigation equipment dealers.

[4]New Cost/2 x .006/acres.

[5]Assumes zero lift.

[6]Well cost excludes pump, motor, panel and wiring.

Appendix E. Variable Cost Calculations for Seed Potatoes[1] (1980 dollars).

Variable Cost Description	Quantity	Cost
Potato Seed	19 sacks	114.00
Nitrogen	112 lbs	25.76
Phosphate	112 lbs	24.64
Potash	112 lbs	13.44
Disyston	20 lbs	15.00
Monitor	1 acre	17.00
Des-i-cate	1 acre	6.00
Sort Potatoes	250 sacks	150.00
Automobile Cost	15 miles	2.25
Misc. Expenses	1 acre	36.65
Machinery	1 acre	85.84
Tractors	1 acre	41.20
Labor (Machinery & Tractors)[2]	6.17 hrs	30.85
Interest on Operating Capital	75.94 dollars	10.63
Irrigation Labor[2]	.7 hrs	3.50
Irrigation Equipment Maintenance[3]	1 acre	3.67
Irrigation Equipment Insurance[4]	1 acre	.88
Power (Irrigation)[5]	1 acre	7.59
Total Variable Cost, Currently Irrigated Land		588.90
Irrigation Well[6] and Distribution Equipment Investment Cost		40.68
Well Maintenance Cost		.55
Well Insurance Cost		.40
Total Variable Cost, Potentially Irrigable Land		630.53

[1]From Enterprise Costs of Irrigated Seed Potatoes in Lake County, Bulletin 1245, Montana Cooperative Extension Service, November 1980.

[2]Assumes fifty percent supplied by management. Irrigation labor requirements are different from that reported in the enterprise cost study. Labor costs are computed at $5/hr.

[3]Based on information supplied by irrigation equipment dealers.

[4]New Cost/2 x .006/acres.

[5]Assumes zero lift.

[6]Well cost excludes pump, motor, panel and wiring.

Appendix F. Variable Cost Calculations for Dryland Winter Wheat After Fallow[1] (1980 dollars).

Variable Cost Description		Quantity	Cost
Seed		65 lbs	4.79
Fertilizer:	Nitrogen	70 lbs	23.06
	Phosphorus	30 lbs	
Crop Chemicals (2,4-D & Fargo)		1 acre	4.75
Fertilizer Spreading		1 acre	1.58
Machinery		1 acre	5.36
Pickup Cost		2.75 miles	.42
Misc. Expenses		1 acre	3.36
Interest on Operating Capital		7.49 dollars	.85
Labor[2]		.41 hrs	2.05
Total Variable Cost			46.22

[1]Updated from Costs of Dryland Crop Production in Gallatin County, Bulletin 1139 (Revised), Montana Cooperative Extension Service, April 1978.

[2]Assumes fifty percent supplied by management. Labor costs are computed at $5/hr.

Appendix G. Variable Cost Calculations for Dryland Barley After Fallow[1] (1980 dollars).

Variable Cost Description	Quantity	Cost
Seed	65 lbs	4.28
Fertilizer: Nitrogen	21 lbs	7.10
Phosphorus	10 lbs	
Crop Chemicals (2,4-D & Fargo)	1 acre	4.75
Fertilizer Spreading	1 acre	1.58
Machinery	1 acre	6.25
Pickup Cost	2.75 miles	.42
Misc. Expenses	1 acre	2.66
Interest on Operating Capital	6.71 dollars	.79
Labor[2]	.47 hrs	2.33
Total Variable Cost		30.16

[1] Updated from Costs of Dryland Crop Production in Gallatin County, Bulletin 1139 (Revised), Montana Cooperative Extension Service, April 1978.

[2] Assumes fifty percent supplied by management. Labor costs are computed at $5/hr.

Appendix H. Variable Cost Calculations for Summer Fallow[1] (1980 dollars).

Variable Cost Description	Quantity	Cost
Machinery	1 acre	4.54
Pickup Cost	2.75 miles	.42
Misc. Expenses	1 acre	.82
Interest on Operating Capital	1.65 dollars	.24
Labor[2]	.29 hrs	1.43
Total Variable Cost		7.45

[1]Updated from Costs of Dryland Crop Production in Gallatin County, Bulletin 1139 (Revised), Montana Cooperative Extension Service, April 1978.

[2]Assumes fifty percent supplied by management. Labor costs are computed at $5/hr.

Appendix I. Irrigation electricity rate schedules for Montana Power Company and Vigilante Rural Power Cooperative.

1. Montana Power Company

KWH per horsepower billed	Charge
1 to 500 kwh	$12.511795 per hp billed
501 to 750 kwh	$0.025024 per kwh
751 to 1000 kwh	$0.020701 per kwh
1001 to 1250 kwh	$0.019302 per kwh
1251 to 1500 kwh	$0.017777 per kwh
1501 to 2000 kwh	$0.016377 per kwh
2001 to 2500 kwh	$0.014978 per kwh
over 2500 kwh	$0.014089 per kwh

Minimal seasonal bill: $12.511795 per horsepower billed

2. Vigilante Power Cooperative

$10/horsepower + $0.012/kwh