SPATIAL WATER ALLOCATION UNDER CONJUNCTIVE USE

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To U. C. and J. R.

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ABSTRACT

This dissertation studies the optimal allocation for conjunctive use of surface and groundwater. The optimal model defines economic principles which determine the spatial allocation of surface and groundwater, the level of conveyance expenditure, the level of on-farm investment in water conservation, and shadow prices of surface and groundwater. The static spatial model identifies the economic principles which govern water allocation for conjunctive use of surface and groundwater. Two models, seepage in the canal and seepage in the canal and on the field are considered. The optimal water allocation is examined with fixed on-farm investment in water conservation and with different canal loss rates. The static base model is extended to incorporate endogenous on-farm investment in water conservation and to consider the effect of the seepage rate on choice of technology, conveyance expenditure, water allocation and land rents. Analytical results are obtained for endogenous crop choice when land quality is homogeneous and shadow price of water is spatially increasing. The study compares the effects of heterogeneous land quality, changes in output price, pumping cost, uniform price for groundwater, and uniform prices for water such as the marginal cost of water generation at the source. The spatial dynamic model of conjunctive water use defines conditions which govern the intertemporal and spatial optimal allocation of water. Five important results are as follows: (i) When seepage is small, the conjunctive use model does not make a significant difference, and the surface water model is a good approximation of the conjunctive use model. (ii) Additional seepage from the field generates a positive

externality to water consumers and the resulting optimal shadow price of water is less than the shadow price of the utility. (iii) An output price increase, heterogeneous land quality, and a fixed price for water generate huge aggregate land rents. (iv) Spatial inequity of land rents is worsened by heterogeneous land quality. (v) Temporal allocation of water resources is governed by the Hotelling rule variant similar to the optimal allocation rule for exhaustible resources.

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LIST OF SYMBOLS

Latin Letters

a	fraction of water lost in conveyance per unit length of canal
a_0	base loss rate
subscript A	crop A
subscript B	crop B
e	effective water
F	fixed cost of irrigation farming
f	production function per unit land area
superscript f	uniform water pricing
g	cost of generating water at source
subscript g	groundwater
h	proportion of water delivered to the plant (water efficiency)
H	Hamiltonian function
I	on-farm investment
J_t	total net benefit at period t
k	conveyance expenditure per unit surface area of the canal
L	Lagrangian function
m	reduction in the conveyance loss rate
MNB	marginal net benefit of the water project
NB	net benefit of the water project
p	output price
q_g	quantity of groundwater used per unit land area
q_s	quantity of surface water used per unit land area
r	interest rate
R_L	land rents
R_W	water rents
S	total amount of water in storage
S_t	water stock remaining in storage at period t
subscript s	surface water
subscript t	time period
w	pumping cost per unit of water extracted
x	distance from the source of canal
X	length of project area
Xs	switching point from surface water to groundwater
y	crop yield per unit land area
z_g	residual quantity of surface water in the canal
z_s	residual quantity of groundwater available for pumping

Greek Letters

α	width of the project area
β	fraction of water lost in the canal which recharges the aquifer
Γ	distribution parameter for S
γ	shift parameter
Δ	distribution parameter for S
δ_t	shadow price of surface water at period t
λ_{Ac}	critical shadow price for which land rents of crop A are zero
λ_{Bc}	critical shadow price for which land rents of crop B are zero
λ_g	shadow price of groundwater
λ_s	shadow price of surface water
$\lambda(X^c)$	critical shadow price for which net revenue of crop A and crop B are equal

LIST OF ABBREVIATIONS

FTSC	seepage in the canal with fixed technology
FTSCF	seepage in the canal and on the field with fixed technology
ETSC	seepage in the canal with endogenous technology
ETSCF	seepage in the canal and on the field with endogenous technology
HPETSC	seepage in the canal with heterogeneous land quality
HPETSCF	seepage in the canal and on the field with heterogeneous land quality
MC	marginal cost
VMP	value of marginal product

CHAPTER 1

INTRODUCTION

1.1 The Problem

The agricultural sector consumes by far the largest portion of water resources compared to any other production sector in the world. The contribution of irrigation systems to agricultural growth is significant. As a result, about 33 percent of the world's total agricultural production today comes from irrigated land, which accounts for 18 percent of total cultivated area. In order to increase agricultural production, governments and international aid agencies have allocated substantial funds to construct irrigation systems. In this century alone, over $350 billion will be spent for Third World irrigation projects (Reppeto, 1986). In spite of such massive efforts by both donor and host countries to expand new capacity, the performance of large-scale irrigation projects in the Third World is rather disappointing. Even in the United States, public irrigation projects suffer from severe operation and maintenance problems, and have led to environmental problems as well (Reisner, 1993).

Inefficiency can largely be attributed to the following causes. First, governments in developing countries often invest in new irrigation projects but fail to invest in completion, rehabilitation and modernization of existing systems. As a result, regular maintenance is neglected. Second, cost recovery of public irrigation systems is very low and is usually less than the costs of operation and management. In other words, the price of water is too low and barely covers the marginal cost of ope···tion and maintenance of irrigation systems. Therefore, farmers tend to substitute water for other inputs, causing a rise in the sub-surface water levels.

A third cause of inefficiency is rent-seeking. In both developed and developing countries, heavily subsidized cheap water generates huge economic rents for land owners. Thus, large farmers form political coalitions to influence public irrigation investment decisions as well as the design of irrigation systems. As a result, investment decisions are made with overly optimistic assumptions and are not always economically viable. Large new projects are favored at the expense of improving existing projects, with costs exceeding available public funding (Repetto, 1986).

In addition, the environmental effects of water logging and salinization are serious and can affect large agricultural areas. The process of salinization can be outlined as follows. First, poor maintenance of public irrigation systems causes seepage of water, resulting in rising sub-surface water levels. This has an initial positive effect of recharging underground aquifers where groundwater is used for irrigation. However, where drainage is insufficient, seepage also causes water logging and salinization. Second, waterlogged areas improve as tubewells pump groundwater and lower the sub-surface water levels. Third, irrigation from canals and private tubewells increases as soil fertility improves. Fourth, as a result of the overuse of water and poor management of irrigation systems, the sub-surface water level rises and waterlogging intensifies causing soil deterioration (O'Mara, 1988). Salinization of groundwater affects not only the irrigation area but also downstream areas via river flow[1] (Repetto, 1986). San Joaquin Valley in California is famous for its layer of Corcoran Clay which lies under the world's most profitable land and allows very little water to seep through to the underground. This clay layer has caused a couple of thousand acres to stop agricultural production due to waterlogging and salinization (Reisner, 1993).

It is now widely accepted that public irrigation projects in developing countries should not focus on further increases in total capacity of irrigation systems, but rather should provide for efficient allocation of water resources by seeking to improve the existing systems and management (Repetto, 1986; O'mara, 1988; Howe and Dixon, 1993). Also, the importance of integrating both engineering and economic analysis is being recognized. At the design stage, economic optimization including technological and design relationships of the project should be explicitly considered rather than simply adopting engineering criteria such as physical efficiency, which does not take into account economic opportunity costs (Chakravorty and Roumasset, 1994).

In many areas, water from canal irrigation is supplemented with groundwater. In the United States, groundwater provided about 40 percent of irrigation water in 1985 (Boggess et al., 1993). Where groundwater is available, farmers construct private tubewells and use them to increase their total water supply and mitigate fluctuations in the supply of irrigation water (Tsur, 1990). Private extraction of groundwater follows quite different management and control schemes than centralized irrigation systems do.

[1] For example, agricultural return flows transport three million tons of salt from the agricultural field to the Colorado River annually (Lee, 1989).

Appropriate control mechanisms for groundwater usage is required to avoid depletion of an aquifer. When surface water is used in conjunction with groundwater in the project area, lost water from seepage in canals is likely to go underground and replenish the aquifer. Therefore, the optimal allocation of water resources should take into account management schemes for both surface water and groundwater which is subject to common property problems. The problem of policy makers, i.e., government, is to satisfy some constraints which are not formally recognized by policy receivers such as firms (O'Mara and Duloy, 1988).

1.2 Literature Review

Water is generally considered as renewable (flow) resources and groundwater as non-renewable (stock) resources (Young and Haveman, 1985). There are a variety of water sources; and each has different quantity, quality, and spatial and temporal supply dimensions that jointly determine the availability and cost of water (Boggess et al., 1993). In general, three water use systems, the groundwater system, the surface water system, and the conjunctive use system can be considered. The first section explains institutional aspects of water allocation. The second section concentrates on groundwater models and externality issues. The third section describes models for conjunctive use of surface and groundwater particularly with reference to their spatial and dynamic dimensions.

1.2.1 Institutional aspects of water allocation

Institutions are, in a broad sense, the rules which govern human behavior in society consisting of markets, laws, and customs. Historically, these rules such as water laws and regulations have affected the efficiency of water allocation (Boggess et al., 1993). Young and Haveman (1985) mention two important factors that affect water laws and regulations. These are the relative scarcity of water and the transactions costs that are necessary to establish and enforce a water rights regime.

In the United States, water laws are set by the state. Water rights doctrines are categorized into (i) watercourse, (ii) groundwater, and (iii) diffused water (Young and Haveman, 1985).

(i) Watercourse doctrines

The Prior Appropriation Doctrine provides water rights to users based on the date of the initial beneficial use of water. Under this doctrine, senior rights is superior to junior rights. This system was established when water was relatively abundant. In the western United States, these water rights are transferable.

(ii) Groundwater doctrines

Absolute Ownership Doctrine (English Law) assigns a landowner the right to withdraw an unlimited amount of water from the sub-surface water resources -- without regard to the effects on neighboring landowners -- to use on site or to transport to another area for use. Reasonable Use Doctrine (American Law), on the other hand, gives a landowner the right to use groundwater, but the transporting of water to another location is restricted if it disturbs the water supply of adjacent landowners. The Doctrine of

Correlative Rights (California Rule) provide landowners with equal rights to reasonable use of groundwater from a common source; and water use that impairs other users is prohibited. The Prior Appropriation Doctrine for groundwater protects senior rights and restricts junior rights for tne defined lifetime of the aquifer.

(iii) Diffused surface water doctrine

The Common Enemy Doctrine permits upper watershed landowners to protect property from damages caused by diffused water with no liability. Civil Law Doctrine gives liability to landowners for damages imposed by others. Under the Reasonable Use Doctrine, liability for a damage is based upon whether reasonable use is violated.

Transferable water permits allow those water rights regimes to move from second-best towards Pareto optimal allocation (Gisser, 1983). In order to improve economic efficiency and water conservation, a transition from water rights doctrines to a water market has been discussed by numerous authors (Howe, et al., 1986; Dinar and Letey, 1991; Shah et al., 1993; Zilberman et al., 1994). However, in a case with spatial externalities, i.e., underinvestments in canal conveyance by firms occur because the benefits from investments are not appropriable by each individual firm, so the water market may result in suboptimal water allocation (Chakravorty et al., 1995).

A water pricing rule is another important institutional arrangement. Here, four principles identified by Young and Haveman (1985) are introduced. The "marginal cost pricing" principle is purposed to achieve allocative efficiency. Water price is set according to the marginal cost of supplying water. However, in practice, applying marginal cost pricing is difficult due to various transaction costs associated with monitoring and administrating a system for charging. The "ability to pay" principle, on the other hand, is based on consideration of equity. Under this regime, cost recovery is only for operating costs and a small portion of the fixed costs of investment. The "net benefit" principle tries to capture most of the economic rents that accrue to the water user. This system tends to ignore the incentive effects of a system of charging. The "average cost" principle aims to recover all costs by charging the average cost per unit of water used. Although pricing is simple and equitable, price does not usually reflect the opportunity costs.

Although institutional aspects are not a primary concern of this dissertation, the legal and institutional regimes mentioned above which already prevail are important because first best solutions are generally constrained by existing institutions[2] (Negri and Brooks, 1990). However, alternative institutional choices such as a transition to water markets and its benefits and costs should be evaluated along with the solutions of the first best models in mind.

1.2.2 Models for groundwater use

When there is no replenishment, an aquifer is a non-renewable resource stock similar to a mine. The optimal extraction rate is determined when the net marginal benefit of extraction from the resource is equal to the marginal cost of extraction, which

[2] Negri and Brooks (1990) assert that the prices of water firms pay is irrelevant to the firms' decision for water use and production at the margin because: (i) institutions of water rights control surface water allocation, (ii) legal water rights doctrines and institutions restrict market transactions of water rights. Therefore, the amount of water that firms receive is sometimes already predetermined by the institutions.

is the present value of the net marginal benefit. However, when replenishment is available, a groundwater stock shares some characteristics with a renewable resource (Brown, 1974). For instance, lowering the level of groundwater will increase the rate of natural recharge, which can be considered as a stock effect of groundwater similar to the natural growth of a fishery stock[3]. In reality, it is quite difficult to define the growth function of a groundwater stock due to complex geohydrological variables involved. Some studies try to formulate growth of groundwater storage as a function of stock (Wilson et al., 1989).

Vaux (1985) analyzes groundwater use in his dynamic optimization model. In a monopoly case when there is only one farmer, this farmer will pump water up to the point where the marginal benefit from water is equal to the extraction cost plus the user cost. In the steady-state, the extraction rate is equal to the recharge rate. When there are many farmers, each farmer will not recognize the effect of individual extraction on the overall aquifer, or competitive forces will drive user cost to zero, resulting in overextraction of the resource. In this case, the depth of the aquifer from the surface is greater than the optimal case at the steady-state (Vaux, 1985). This is a typical common property resource problem.

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[3] In groundwater hydrology, a storage coefficient or storativity is defined as the volume of water that an aquifer releases from or takes into storage per unit surface area of aquifer when the groundwater table is lowered. In most confined aquifers, values range between 0.00005 and 0.005. For example, if the storativity is 0.005, lowering the water table by 1 foot with an area of 1 acre of an aquifer will release 0.005 acre-feet of water into storage (Todd, 1980).

Traditionally, extraction of groundwater is treated as a common property resource problem in which externalities[4] of pumping are transmitted to other users via the aquifer level. The pumping cost externality is a public good externality which affects everyone's welfare without exclusion. In general, common property resources are used interchangeably with free access resources. However, in the case of groundwater use, various legal and institutional constraints as mentioned in the previous section limit free access to the resource in the short run. Therefore, the groundwater resource can be better characterized as a common property resource which is an impure public good whose benefits are partially rival and/or partially excludable (Cornes and Sandler, 1986).

The earlier groundwater models paid much attention to the case of pumping cost externalities[5] which arise due to the public good characteristic of groundwater resources. The pumping cost externality is also expressed as a "stock externality" (Smith, 1969). More recently, other authors identify different types of externalities. Provencher and Burt (1993) distinguish the stock externality from the pumping cost externality. The stock externality is generated because the total stock of groundwater, being finite, constrains each firm's pumping decisions. Provencher and Burt (1993) also identify a "risk

[4] Scitovsky (1954) distinguishes the two classical concepts of externalities, namely pecuniary externalities and technological externalities. However, Scitovsky's distinction of two external economies is not appropriate in dealing with externalities related to environmental quality. Nijkamp (1977) defines *environmental external effects* as follows: "Environmental external effects are non-market effects (positive or negative), which results as a side-effect of economic activities of producers and consumers (including governmental activities) and which affect the welfare or profit conditions of other households through spill-overs via man's surroundings."

[5] Kim et al. (1989) analyze a pumping cost externality and its effect on the depletion path of groundwater and an endogenous intertemporal cropping pattern.

externality" which is produced by the income risk of each firm due to the availability of the total stock of groundwater for pumping. Negri (1989) defines a "strategic externality". This externality arises because each firm tries to pump more water knowing that leaving water underground will stimulate pumping by other firms.

Boggess et al. (1993) suggest three alternative methods for intervention in the case of sub-optimal groundwater resource allocation. The first scheme is to levy a tax on water which is equal to the user cost. The second method is to issue tradable groundwater permits while limiting the total amount of permits to coincide with the optimal level of groundwater extraction. This method is discussed in detail by Gisser (1983), comparing various groundwater management schemes in the United States. The third method is to approximate a tax by observing crop or irrigation technologies. This method can be used when monitoring individual pumping is not possible.

1.2.3 Models for conjunctive use of surface and groundwater

There are three cases which characterize the conjunctive use of surface and groundwater (Gisser, 1983; Boggess et al., 1993). The first case is the situation where the supply of surface water and groundwater are totally independent. Since there is no recharge from surface water, groundwater can be considered a non-renewable resource. The second case is just the opposite. Surface flow is directly linked with groundwater and the extraction of one will decrease the other source as well. In the third case, surface water recharges the groundwater, which is now renewable. The use of surface water produces a positive externality by adding to the groundwater stock. It is also often the case that groundwater is used to supplement variability in the supply of surface water (Boggess et al., 1993).

O'Mara (1984) defines the spatial efficiency of water use[6]. "Efficient spatial operation of a pure surface water irrigation system requires that the social opportunity cost of water, i.e., the value of its marginal product at efficiency prices, at a common source be equalized across farms and regions at each point in time." O'Mara further generalizes this proposition to conjunctive use. "Efficient operation of a joint surface-groundwater irrigation system requires that the discounted social opportunity cost of surface water equal the discounted social opportunity cost of groundwater across farms and regions at each point in time." However, O'Mara's proposition for conjunctive use does not provide general results for spatial dynamic conjunctive water use.

As an example of an operational conjunctive use model, O'Mara and Duloy (1988) develop a large-scale model for Indus Basin to provide answers to some policy-relevant questions such as mechanization, technical change, agricultural policy, irrigation system management and evaluation of irrigation projects. This model is a comparative statical model with about 8,000 constraints and simulates long-run (5-10 years) producer response such as cropping patterns, cropping intensities, and livestock holdings to policy intervention for environmental change (O'Mara and Duloy, 1988). They conclude that more efficient conjunctive use of surface and groundwater increases agricultural

[6] For further development of the spatial efficiency of water allocation, see Roumasset (1987) and Chakravorty and Roumasset (1991).

production by 20% and employment by 16% in the Indus Basin. However, it is less clear that O'Mara's aforementioned efficiency condition for spatial conjunctive use is incorporated in this empirical model.

The studies which deal with conjunctive use of surface and groundwater are primarily dynamic (Burt, 1964; Young and Bredehoeft, 1972; Tsur, 1990; Tsur & Graham-Tomasi, 1991), or static approximations of the dynamic problem (Gisser, 1983). Often emphasis is placed mainly on the optimal control of water resources, such as canal irrigation, reservoirs, and groundwater, or on the role of groundwater as a buffer due to the randomness of surface water supply. However, spatial aspects of water resource allocation have not been addressed often in the literature. Chakravorty and Roumasset (1991) and Chakravorty et al. (1995) analyze the spatial allocation of irrigation water, conveyance expenditure and its effects on distribution of rents in a water project. However, their analysis is limited to the case of surface water allocation.

In the surface water model, seepage from the canal has been treated as a negative effect on a water project. However, in reality, water goes down and replenishes the aquifer, generating positive effects on the groundwater stock (O'Mara, 1988). Therefore, to consider the conjunctive use of water resources is more realistic than to consider surface water only, and thus provides a stage for more concrete policy analysis. Also, in water management literature, discussions of spatial dynamic models of conjunctive use are sparse. Thus this study will extend the Chakravorty et al. (1995) analysis by incorporating the availability of groundwater supply in conjunction with irrigation water and its dynamic dimensions of resource allocation.

1.3 Objectives of the Study

The objectives of the study are:

1) to determine rules for efficient spatial allocation of surface and groundwater while accounting for positive and/or negative externalities of using both resources. This involves determination of the optimal project area (length), water allocation at each point, output, land rents, water rents, shadow prices for surface and groundwater, and the optimal initial stock of surface water.

2) to compare the optimal allocation rule under different scenarios such as: a) endogenous technological choice, b) endogenous crop choice, c) heterogeneous land quality, d) output price change, e) change in pumping cost, e) uniform price for groundwater, and f) uniform price of water such as marginal cost of water generation at the source.

3) to construct a simple three-period model to analyze the optimal water allocation over time for the case of conjunctive use of surface and groundwater.

4) to apply these analytical results to secondary data from California and provide some policy implications to remedy sub-optimal allocation of water resources.

Issues not covered in this study are as follows. First, negative environmental problems such as water logging, salinization and contamination of groundwater are not treated here. Second, this study does not assume uncertainty. Third, models used are first best models, and which have been abstracted from the second best, i.e., transaction cost and the third best considerations such as rent-seeking and strategic externalities.

1.4 Organization of the Study

In order to accomplish aforementioned objectives, this dissertation consists of four main chapters as follows:

Chapter 2 defines two optimal models for conjunctive use of surface and groundwater. One is a model with seepage in the canal and the other is a model with seepage in the canal *and* on the field. The first section presents specifications of the problem which generally apply to all models. The next section defines the optimization problem in an optimal control framework and the necessary conditions for optimality. From the necessary conditions, some observations on the characterization of each control variable and key parameters are presented. This is followed by the explanation of actual functional forms and data for fixed parameters and the method of simulation. These two optimal models define the optimal initial stock of water, length of canal, conveyance expenditure, surface and groundwater use for production, and shadow prices of both surface and groundwater at each location of the canal to maximize total net benefit of the project area. Two cases are considered: (i) a model with fixed technology, and (ii) a model with high and low conveyance costs.

Chapter 3 considers two types of endogenous choice by firms. One is the case when on-farm investment in water conservation is endogenous. The other case is when crop choice is endogenous. As in the case of fixed technology in Chapter 2, first specification of the problem is defined followed by formal presentation of the optimal model and necessary conditions. Results of the simulation are compared with results of the surface water model without groundwater availability. The second part of Chapter 3 illustrates endogenous crop choice when firms select one of two crops according to the optimal production schedule. The conditions for optimal choice of crop type are discussed with the implications to exogenous parameter changes such as output price change and heterogeneous land quality.

Chapter 4 is concerned with the effect of heterogeneous land quality, changes in exogenous parameters, and suboptimal water pricing on the optimal allocation of water and endogenous technology. Five scenarios are considered for the two base models of Chapter 3. The first scenario is the case in which land quality is heterogeneous and fertile land is concentrated at the head of the project area. The next two scenarios for exogenous parameter changes include changes in output price and in pumping cost. The last two scenarios deal with suboptimal water pricing. One is the case when the utility fails to charge firms the optimal shadow price of groundwater and charges a fixed price for groundwater. The other case deals with the utility charging firms a uniform price for water such as the marginal cost of generating water at the source. The results of the simulation for each case are provided with some policy implications.

Chapter 5 develops a spatial dynamic optimal water allocation model for conjunctive use of surface and groundwater. This chapter extends the static spatial allocation model discussed in Chapter 2 to a dynamic framework. The first section illustrates the specification of the problem and defines the optimization problem of spatial dynamic allocation of water followed by the necessary conditions for optimality. The rules governing spatial dynamics are identified. The next sections explain the data, the method of simulation and results from the simulation. The last section concludes with some policy implications and alternative specifications of the spatial dynamic model.

Chapter 6 concludes this dissertation by summarizing major results of each chapter, discussing some policy implications based on the results, and finally by providing limitations and possible future extensions of the study.

CHAPTER 2

THE OPTIMAL CONJUNCTIVE USE OF IRRIGATION WATER

2.1 Introduction

In water management literature, spatial allocation models are sparse. O'Mara (1984), for example, defines conditions for the spatial efficiency of water use for surface water irrigation. However, it is not clear how this spatial efficiency is operationalized. Chakravorty and Roumasset (1991) and Chakravorty et al. (1995) develop the spatial allocation of irrigation water, conveyance expenditure and analyze its effects on the distribution of rents in a water project. However, their analysis is limited to the case of surface water allocation. Given that in reality seepage from a canal replenishes the aquifer and the groundwater resource supplements surface water in many cases, it is more realistic to consider conjunctive use of surface and groundwater. Thus this chapter extends the study of Chakravorty et al. (1995) by incorporating the availability of groundwater supply in conjunction with irrigation water in the project area.

Section 2 develops the optimal model with seepage in the canal. Section 3 presents the optimal model with seepage in the canal *and* on the field. Section 4 explains various functions and data for parameters used followed by the method of simulation. Section 5 and 6 show the simulation results with fixed levels of on-farm investment for modern and traditional irrigation technologies, and high conveyance costs, respectively. Section 7 concludes the chapter.

2.2 The Optimal Model with Seepage in the Canal

The first model considered here is a static optimal model[7] for conjunctive use of surface and groundwater. In this model, seepage is allowed only from the canal. The first section explains the common specification of the problem which generally applies to all models discussed in this study. The second part defines the optimization problem in an optimal control framework. This is followed by the characterization of the optimal path for each variable. In the subsequent sections, some assumptions given in this section are relaxed to extend models in alternate settings.

2.2.1 Specification of the problem

A central planner or a utility is assumed to invest optimally in a canal irrigation project and charges each farmer the shadow price of water in the project area. There is an aquifer underlying the project area and individual farmers have a choice of using groundwater in conjunction with surface water distributed by the irrigation canal. There is seepage from the canal which goes through the ground and recharges the aquifer. The optimal solution determines the optimal project area (length), surface water use,

[7] Tsur (1990) suggests that a single period model is a legitimate approximation of a dynamic problem if one of the following conditions holds: (i) the level of the water table eventually arrives at steady state in which the rate of water recharge to the aquifer is at least as large as that of water extraction, or (ii) the aquifer is large compared to the project area of concern and any water extraction has only negligible effects on the level of water table and thus on the marginal cost of pumping. In this model, steady-state of groundwater level is implied by limiting the amount of pumping to only recharge from seepage.

groundwater use, conveyance expenditure, investment in on-farm technology, land and water rents at each location and the optimal initial stocks of surface water.

A case under consideration is a water project for a simple one cropping season. Monocropping is assumed for the entire project area. Water is distributed by the utility from the head point of the project area through the canal. Firms are located on both sides of the canal and the project area is rectangular with the same width α at any location x where x is the distance measured from the canal source (see Figure 2.1). Firms receive water distributed by the utility from the canal to their individual farms. Homogeneous land quality and no uncertainty are assumed.

The utility endogenously chooses the amount of the initial stock of surface water $z_s(0)$ ($z_s(x=0)$) at the source flowing into the canal. Throughout this section, except as otherwise noted, subscripts s and g denote surface water and groundwater, respectively. Let $g(z_s(0))$ be the cost of generating water at the source, including capital expenditure and the cost of operation and maintenance per cropping period. The function $g(z_s(0))$ is assumed to be an increasing, twice differentiable and convex function such that $g'(z_s(0))>0$ and $g''(z_s(0))<0$. The initial stock of surface water is assumed to be a variable, so the marginal cost of generating water also increases with the initial stock level. The quantity of surface water and groundwater used at location x per unit land area are $q_s(x)$ and $q_g(x)$, respectively with $q_s(x) \geq 0$ and $q_g(x) \geq 0$. The fraction of water lost in conveyance per unit length of the canal is represented by $a(x)$ with $a(x) \geq 0$. Then the residual quantity of water flowing in the canal per unit length at location x is $z_s(x)$ where $z_s(x) \geq 0$ with the initial stock of water at $x=0$ being $z_s(0)$. The change in the residual

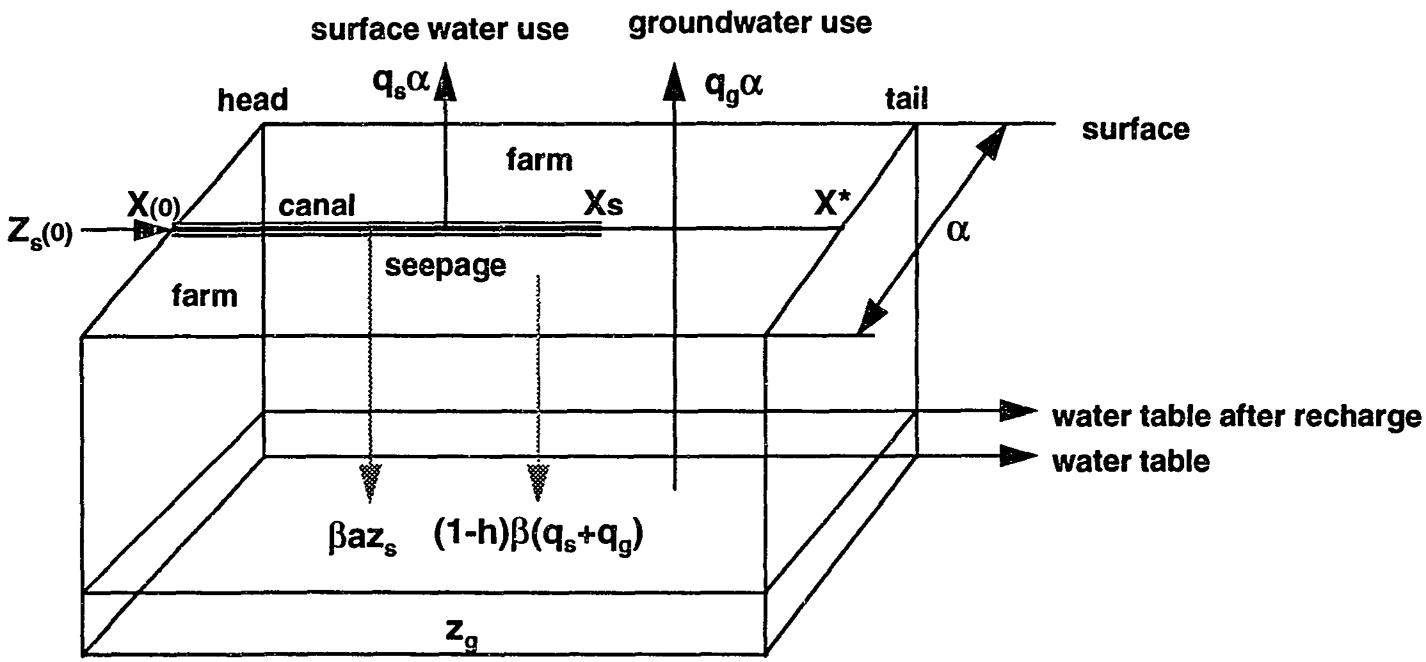

Figure 2.1. Water Project Area and an Aquifer

stock of water $z_s(x)$ at each location x is given by the total water withdrawn from the canal, $q_s(x)\alpha$, and the total water lost, $a(x)z_s(x)$, as follows:

$$z_s'(x) = - q_s(x)\alpha - a(x)z_s(x) \quad (1)$$

where $z_s'(x) = dz_s/dx$. The fraction of water loss a(x) depends on k(x), conveyance expenditure per unit surface area of the canal which varies with location of the canal, x.

$$a(x) = a_0 - m(k(x)) \quad a_0 \in [0,1], \ m \in [0,a_0), \ a(x) \in (0,1] \quad (2)$$

where a_0 is the constant base loss rate and m(k(x)) denotes the reduction in the conveyance loss rate given by the conveyance expenditure k(x) for the canal. Investment in conveyance will decrease water loss, thus reducing a(x). If no investment in conveyance expenditures is made, i.e., k(x)=0, then the fraction of water loss is the same as the base loss rate a_0 throughout the canal. The reduction function m(k(x)) is assumed to be an increasing, twice differentiable function and decreasing in returns to scale with respect to k so that $m(k)\in [0,a_0)$, $m'(k)>0$, $m''(k)<0$, $\lim_{k\to\infty}m(k)=a_0$, $\lim_{k\to 0}m'(k)=\infty$.

Let β be the fraction of water lost in the canal that goes underground and recharges the aquifer, with $0 < \beta < 1$. The remaining fraction $(1-\beta)$ of lost water in the canal will be lost by evaporation or exit from the project area. Further, assume for simplification that the total amount of groundwater available for pumping is exactly equal to the total amount of water recharging the aquifer. No natural recharge is considered in this static model. Because there is no time dimension in this model, seepage is assumed to recharge the aquifer instantaneously. Let $z_g'(x)$ denote the change of groundwater stock available for pumping at x with $z_g(0)=0$. Thus, $z_g'(x)$ is written as the amount of recharge from the canal to the aquifer, $\beta a(x)z_g(x)$, and the amount of extraction of groundwater, $q_g(x)\alpha$, at x.

$$z_g'(x) = \beta a(x)z_s(x) - q_g(x)\alpha \tag{3}$$

The production function for crop yields per unit land area is specified by $y(x) = f[(q_s(x)+q_g(x))h]$ with $y(x)$ as output, $(q_s(x)+q_g(x))$ as applied water, and $(q_s(x)+q_g(x))h$ as effective water denoted by $e(x)$, i.e., water which is actually consumed for evapotranspiration by the crop. The production function is assumed to be increasing, twice differentiable and decreasing in returns to scale with respect to a single input, effective water, so that $f(e)>0$, $\partial f/\partial e>0$, and $\partial^2 f/\partial e^2<0$. The proportion of water delivered to the plant h(i) is a function of on-farm investment. For simplicity, h is assumed to be constant in this model. Since this fraction is fixed, the level of on-farm investment, I, is also fixed. The assumption of fixed on-farm technology is relaxed later to consider endogenous technology. This parameter represents the level of on-farm technology for water conservation. In reality, this irrigation effectiveness varies from 0.6 under traditional furrow irrigation to 0.85 and 0.95 under modern sprinkler and drip irrigation (Caswell & Zilberman, 1986).

2.2.2 The optimization problem

The utility is assumed to choose $q_s(x)$, $q_g(x)$, $k(x)$ and X, the end point of the project area, so as to maximize net benefit from the water project.

$$\underset{q_s,\, q_g,\, k,\, X^*}{\text{maximize}}\ NB(z_s(0)) = \int_0^{X^*} \{[pf[(q_s+q_g)h] - I - F - wq_g]\alpha - k\}dx \qquad (4)$$

subject to two state constraints (1) and (3) where p is the constant output price, assuming price-taking producers; X* is the optimal length of the project area; I is the expenditure of on-farm investment; and F is the fixed costs for irrigated farming[8]. A pumping cost, w, is assumed to be constant over the project area and the unit cost of conveyance is considered to be unity. Let $\lambda_s(x)$ and $\lambda_g(x)$ be co-state variables for surface and groundwater resources. The Hamiltonian of this problem is defined as follows, with $z_s(x)$ and $z_g(x)$ as state variables and $q_s(x)$, $q_g(x)$ and $k(x)$ as control variables.

$$H\ (q_s, q_g, k, \lambda_s, \lambda_g) = [pf[(q_s+q_g)h] - I - F - wq_g]\alpha - k$$
$$- \lambda_s\ [q_s\alpha + az_s] + \lambda_g\ [\beta az_s - q_g\alpha] \qquad (5)$$

Let q_s*, q_g*, k*, z_s*, z_g*, and X* denote the corresponding optimal values for this

[8] Fixed cost for irrigated farming includes the nonirrigation costs of production, equipment and set up cost of irrigation system, and may vary depending on the technology adopted, and land quality (Caswell et al., 1990; Zilberman et al., 1994). For simplicity, it is assumed that the fixed cost of irrigated farming does not depend on those factors for modern technology.

optimization problem. In this case we cannot avoid the possibility of a corner solution. Assume that Hamiltonian is concave in q_s, q_g, k, z_s, z_g and the sufficiency conditions are met. Then the necessary conditions for optimality are given by the Pontryagin Maximum Principle[9] as follows:

$$\partial H/\partial q_s = (pf'h - \lambda_s)\alpha \leq 0 \tag{6}$$

$$\partial H/\partial q_g = (pf'h - w - \lambda_g)\alpha \leq 0 \tag{7}$$

$$\lambda_s' = -\,\partial H/\partial z_s = a\lambda_s - a\beta\lambda_g = a(\lambda_s - \beta\lambda_g) \tag{8}$$

$$\lambda_g' = -\,\partial H/\partial z_g = 0 \tag{9}$$

$$\partial H/\partial k = -\,1 + \lambda_s z_s m'(k) - \lambda_g \beta z_s m'(k) \leq 0 \tag{10}$$

where $f' = \partial f/\partial q_s$, and $\lambda_s' = d\lambda_s/dx$. Also, since this is a free terminal point problem, the transversality condition states that the Hamiltonian at the terminal point X* is zero and there is no restriction on the terminal shadow price of resources, $\lambda_s(X^*)$ and $\lambda_g(X^*)$ (Chiang, 1992). Thus, in summary,

$$pf'h \leq \lambda_s \tag{11}$$

$$pf'h \leq w + \lambda_g \tag{12}$$

$$\lambda_s' = a(\lambda_s - \beta\lambda_g) \tag{13}$$

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[9] In optimal control theory, the first-order necessary condition is called the Pontryagin Maximum Principle and is defined by L. S. Pontryagin, V. G. Boltyanskii, R. V. Gamkrelidze, and E. F. Mishchenko, in their book in 1962, *The Mathematical Theory of Optimal Processes*, Interscience, New York.

$$\lambda_g' = 0 \tag{14}$$

$$(\lambda_s - \beta\lambda_g)z_s m'(k) \leq 1 \tag{15}$$

$$[H\ (q_s,\ q_g,\ k,\ \lambda_s,\ \lambda_g)]_{x=X^*} = 0 \tag{16}$$

Equations (11) through (15) constitute necessary conditions for optimality. The condition (11) states that the marginal value product of surface water is equal to or smaller than the shadow price of surface water. Similarly, the condition (12) states that the marginal value product of groundwater is equal to or smaller than the supply price of groundwater, i.e., the marginal pumping cost plus the shadow price of groundwater. The change in shadow price of surface water in condition (13) is equal to the loss rate from the canal times the net shadow price of surface water, $(\lambda_s - \beta\lambda_g)$, taking into account the availability of the groundwater supply. In other words, the shadow value of surface water in the canal is actually $(\lambda_s - \beta\lambda_g)$ because of seepage. The next condition (14) suggests that the change in shadow price of groundwater is zero which means λ_g is constant. This result is to be expected since pumping cost is uniform among firms throughout the project area. The right hand side of condition (15) shows the marginal cost of increasing one unit of conveyance which is unity, and the left hand side is the marginal benefit of increasing one unit of conveyance. The marginal benefit of conveyance is expressed by the increase in residual flow at the location x by increasing one more unit of conveyance, $z_s m'(k)$, times the net shadow price of surface water, $(\lambda_s - \beta\lambda_g)$. Condition (16) shows that at the tail of the project area when x=X*, the net benefits from the project (i.e., total revenue less investment on conveyance) are exactly offset by the shadow value of water at the tail.

If we compare these necessary conditions with those for the earlier surface water model by Chakravorty et al. (1995), there are some similarities and differences between the two models. The marginal condition for surface water production is the same for both cases. Also in the surface water model, the rate of change for shadow price of surface water increases at the rate of water loss so that $\lambda_s' = a\lambda_s$ or $\lambda_s'/\lambda_s = a$. In the conjunctive use model, λ_s is replaced by $(\lambda_s - \beta\lambda_g)$, the net shadow price of surface water when seepage recharges groundwater stock. The equation (13) can be rewritten as follows:

$$\lambda_s'/\lambda_s = a - \beta(\lambda_g/\lambda_s) \tag{13'}$$

which shows that the rate of change of shadow price is reduced by $\beta(\lambda_g/\lambda_s)$ because of conjunctive use. The shadow price of surface water, λ_s, is also replaced by $(\lambda_s - \beta\lambda_g)$ in the marginal condition for conveyance expenditure. Because of groundwater availability, two additional necessary conditions include one for groundwater production (12), and the other for groundwater stock, (14).

Let us define the optimal net benefit function given the initial stock of surface water $z_s(0)$ as $NB^*(z_s(0))$. The optimal initial stock of water, $z_s(0)^*$, is estimated from the following optimization problem (Chakravorty et al., 1995):

$$\underset{z_s(0)}{\text{maximize}}\ NB^*(z_s(0)) - g(z_s(0)) \tag{17}$$

which defines the optimal initial stock of surface water $z_s(0)$ from the first order necessary condition, $NB^{*\prime}(z_s(0)) = g'(z_s(0))$. Partial differentiation of NB* with respect to the given optimal initial stock of surface water $z_s(0)$ gives:

$$\partial NB^*/\partial z_s(0) = \lambda_s^*(0) \tag{18}$$

In condition (18), the optimally defined co-state variable, $\lambda_s^*(0)$, indicates the marginal change of the optimal net benefit, NB*, with respect to the marginal change in the initial stock of surface water, $z_s(0)$ (Chiang, 1992). The initial shadow price of the stock of surface water at source, $\lambda_s^*(0)$ can be equated with the marginal cost of generating water at source using the first order condition given above. Thus, from the equation (18), we obtain a salvage value condition as follows:

$$\lambda_s^*(0) = g'(z_s(0)) \tag{19}$$

This condition (19) states that the shadow price of surface water at the source, which means the value of water to the utility at the source, is equal to the marginal cost of generating water.

2.2.3 Characterization of the optimal path for each variable

In condition (15), if we assume $k > 0$ at the beginning, then $m'(k) > 0$. And since $z_s > 0$, $(\lambda_s - \beta\lambda_g) > 0$ because $\lambda_s \geq \lambda_g$. This result shows that in condition (13), $\lambda_s' > 0$

so that the shadow price of surface water increases away from the source. The optimal allocation provides a corner solution for this problem. Figure 2.2 shows the spatial distribution of the optimal shadow price of surface and groundwater, $\lambda_s^*(x)$, $\lambda_g^*(x)$, surface and groundwater use, $q_s^*(x)$, $q_g^*(x)$, and land rents at each location x. The shadow price of surface water increases until it reaches the efficiency price of groundwater which is the shadow price of groundwater plus pumping cost at the switching point Xs. After this switching point, Xs, farmers start using groundwater instead of withdrawing surface water (see Figure 2.2). This optimal allocation of water is guaranteed as long as the utility charges farmers the user cost of surface water $\lambda_s^*(x)$ as well as that of groundwater $\lambda_g^*(x)$ per unit of water used and invest in the optimal conveyance expenditures k*(x) at each location x (Brown, 1974). If the utility does not charge farmers the user cost of groundwater, farmers will equate the marginal benefit of groundwater with the private cost of pumping, w, and over-extraction of groundwater will result in diversion away from the optimal water allocation.

The surface water used by each firm $q_s(x)$ decreases away from the source until Xs and becomes zero after Xs, because of the increase in shadow price of surface water $\lambda_s^*(x)$. The level of groundwater use flattens after Xs since the efficiency price of groundwater is the same for all farmers. Therefore, the surface water use at Xs, $q_s(Xs)$, is equal to groundwater use, $q_g(x)$, from Xs to the end of the project area X*.

The spatial change of conveyance expenditure k(x) is not given directly from the necessary conditions. There are two factors which affect the distribution of k(x). First, increasing scarcity of the resource indicated by the change of $\lambda_s^*(x)$ increases the level

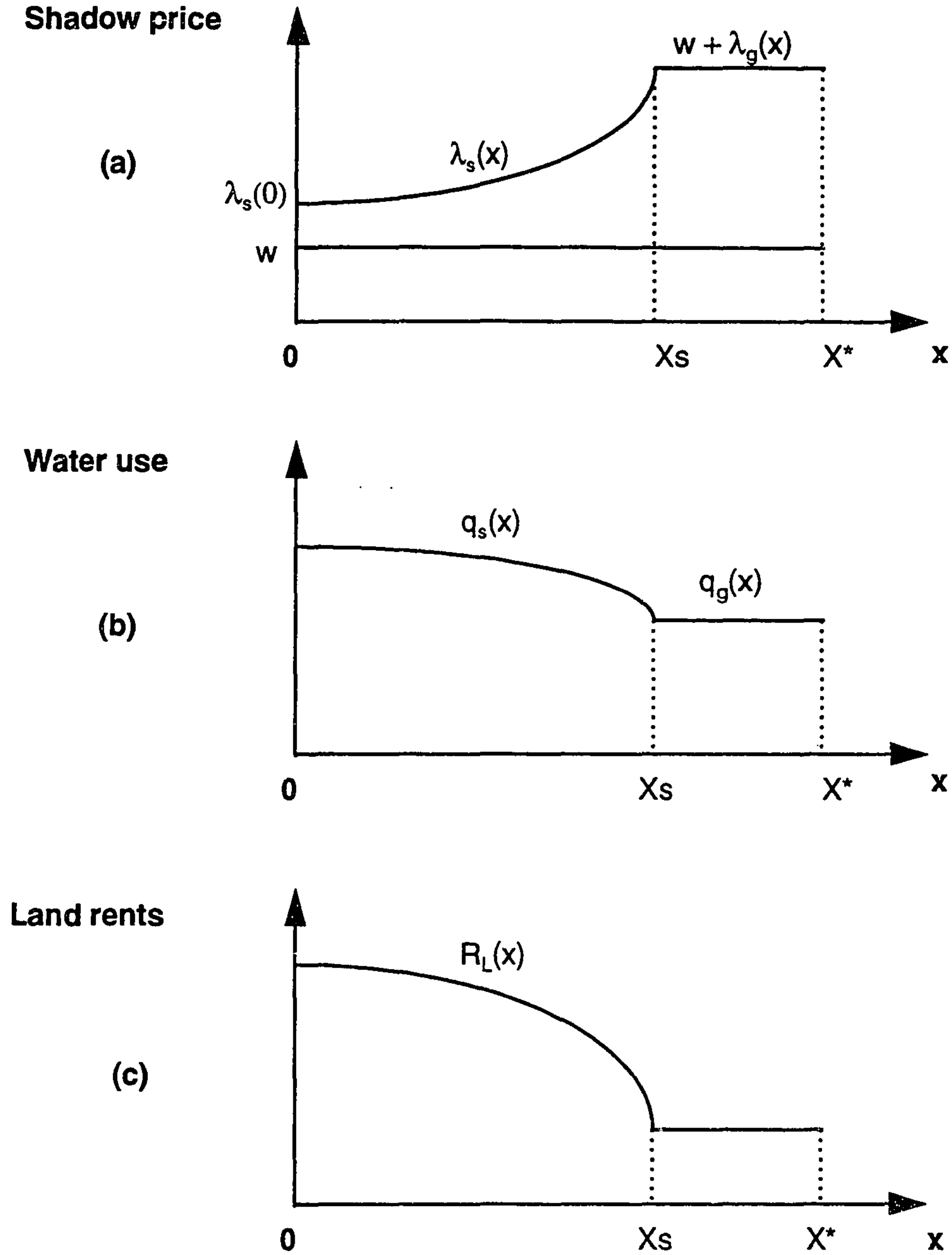


Figure 2.2
Spatial Distribution of Shadow Price, Water Use and Land Rents

of optimal conveyance expenditure. On the other hand, the decreasing residual stock of surface water $z_s(x)$ away from the source tends to decrease the conveyance expenditure due to a "volume" effect. From equation (2) and (13), $z_s'/z_s = -(q_s a/z_s) - a$, and $\lambda_s'/\lambda_s = a - (a\beta\lambda_g/\lambda_s)$. Since $z_s'/z_s - \lambda_s'/\lambda_s = -(q_s a/z_s) - (a\beta\lambda_g/\lambda_s) < 0$, the rate of decrease in the residual volume of water in the canal at given x is larger than the rate of increase in the shadow price of surface water. Therefore, the value of the residual stock of water flowing in the canal at x, $\lambda_s(x)z_s(x)$, falls towards the end of the canal and the optimal conveyance expenditure decreases away from the source, eventually becoming zero when no surface water is used by firms.

A similar result is obtained for land rents. Let us denote land rents, R_L, which accrue to farmers and water rents, R_W, which accrue to the utility at location x as follows:

$$R_L(x) = \{pf[(q_s(x)+q_g(x))h]-\lambda_s(x)q_s(x)-(w+\lambda_g(x))q_g(x)-I-F\}\alpha \quad (20)$$

$$R_W(x) = [\lambda_s(x)q_s(x)+\lambda_g(x)q_g(x)]\alpha - k(x) \quad (21)$$

Since the shadow price of surface water $\lambda_s(x)$ increases away from the source and surface water use $q_s(x)$ decreases at a rate less than a(x); the rate of change of $\lambda_s(x)$, water charges to firms $\lambda_s(x)q_s(x)\alpha$ increases with distance. Hence, land rents decrease and water rents increase until Xs. Equal land rents and water rents accrue to all groundwater users after Xs. Water rents for groundwater use after Xs are $R_W(x) = \lambda_g(x)q_g(x)\alpha$ because no conveyance expenditure is necessary after Xs. Even though water rights are given to firms together with land entitlement, water rents accrue to a utility if $\lambda_g(x)$ is charged to groundwater users. This result indicates that the distribution of land rent is skewed to the head farmers. An increase in conveyance expenditure reduces water loss from the canal and has the effect of decreasing land rents and increasing water rents[10].

2.3 The Optimal Model with Seepage in the Canal *and* on the Field

In the first model, seepage occurred only from the canal. This assumption is rather restrictive if we consider the fact that a large part of the return flow to groundwater comes from seepage from the field. The second model considered in this section allows not only seepage in the canal but also seepage on the field.

2.3.1 Specification of the problem

When seepage from the field is allowed, additional water lost from the production site is added to the groundwater stock. As defined in the first model, the effective water $(q_s(x)+q_g(x))h$ is used for actual production thus remaining water $(1-h)(q_s(x)+q_g(x))$ will be lost on the field. If we assume that the fraction β of total water lost on the field recharges the aquifer, the amount of seepage $\beta(1-h)(q_s(x)+q_g(x))$ builds up the groundwater stock in addition to the seepage from the canal at each location x. Thus the state constraint for the groundwater resource in this case is defined as follows:

$$z_g'(x) = \beta a(x)z_s(x) - q_g(x)\alpha + \beta(1-h)(q_s(x)+q_g(x))\alpha \qquad (22)$$

[10] See Chakravorty et al. (1995) for a proof of this result.

Other specifications of the problem are the same as those for the first model mentioned in Section 2.2.1.

2.3.2 The optimization problem

Similar to the first optimization problem in Section 2.2.2, the utility maximizes the net benefit of the water project, i.e., the objective function (4) subject to state constraints (1) and (22). The Hamiltonian of this problem is given as follows:

$$H\ (q_s, q_g, k, \lambda_s, \lambda_g) = [pf[(q_s+q_g)h] - I - F - wq_g]\alpha - k$$
$$- \lambda_s[q_s\alpha + az_s] + \lambda_g[\beta az_s - q_g\alpha + \beta(1-h)(q_s+q_g)\alpha] \qquad (23)$$

Assuming the sufficiency conditions are met, the necessary conditions for optimality are given as follows:

$$\partial H/\partial q_s \leq 0 \qquad (24)$$

$$\partial H/\partial q_s \leq 0 \qquad (25)$$

$$\lambda_s' = -\ \partial H/\partial z_s \qquad (26)$$

$$\lambda_s' = -\ \partial H/\partial z_g \qquad (27)$$

$$\partial H/\partial k \leq 0 \qquad (28)$$

Due to additional seepage of water from the field, the necessary conditions (24) and (25) include an additional term. Other conditions (26) through (28) are the same as the first model. Thus, summarizing with transversality condition:

$$pf'h \leq \lambda_s - \lambda_g\beta(1-h) \tag{29}$$

$$pf'h \leq w + \lambda_g[1-\beta(1-h)] \tag{30}$$

$$\lambda_s' = a(\lambda_s - \beta\lambda_g) \tag{31}$$

$$\lambda_g' = 0 \tag{32}$$

$$(\lambda_s - \beta\lambda_g)z_s m'(k) \leq 1 \tag{33}$$

$$[H\,(q_s, q_g, k, \lambda_s, \lambda_g)]_{x=X*} = 0 \tag{34}$$

The condition (29) involves an additional term, $-\lambda_g\beta(1-h)$, which indicates that firms that use surface water will maximize their benefits when their value of marginal product from the surface water is equal to or less than the shadow price of surface water, λ_s, minus the shadow price of groundwater times the fraction of water which recharges the aquifer, $\lambda_g\beta(1-h)$. This condition suggests that in order to maximize the net benefit from the project, the marginal cost of production using surface water is actually less than the shadow price of surface water because by using the surface water for production, firms are incidentally adding extra water to the groundwater stock.

This is a positive externality[11] generated by firms, i.e., water consumers, with benefits that are transmitted back to firms through the aquifer without exclusion due to the public good characteristic of groundwater resources. Thus, because of this externality,

[11] Seepage externality is a public good externality which affects everybody's welfare without exclusion. This positive externality can be considered a technological externality in a broad sense since it is a non-market effect.

firms receive a benefit of less net marginal cost of production for using surface water. This may be analogous to the situation where government imposes a Pigovian tax on negative externalities associated with a public 'bad' such as air pollution. While economic agents who discharge a public 'bad' could be taxed, those who add a public 'good' could be rewarded through non-market channels of resource allocation[12].

The condition (29) shows that this positive externality is already internalized by the utility through charging shadow prices for water resources. The net shadow price $\lambda_s(x) - \lambda_g(x)\beta(1-h)$ is actually the marginal social cost of water at location x. The condition (29) can be restated as follows:

$pf'h$	+	$\lambda_g\beta(1-h)$	$\leq$	λ_s
marginal benefit to surface water consumers		positive externality to surface water consumers		marginal benefit to surface water owner

For the same reason, an additional term $-\lambda_g\beta(1-h)$ enters in the marginal condition for groundwater production (30) to give credit to groundwater users. One interesting result is that the resource owner, i.e., the utility and the resource consumers, i.e., firms, face different shadow prices. The utility faces shadow prices λ_s and λ_g in this case. On the other hand, the utility is required to charge firms the net shadow price $\lambda_s(x)$ –

[12] Arrow (1969) states that the situation of competitive equilibrium not existing is a sufficient condition for resorting to non-market resource allocation. In this model, existence of a seepage externality as well as a spatial externality, i.e., benefits from investing in conveyance expenditure that are not appropriable by individual firms, makes non-market resource allocation necessary to restore efficiency.

$\lambda_g(x)\beta(1-h)$ for surface water and $\lambda_g[1-\beta(1-h)]$ for groundwater at each location x to obtain optimal allocation of water resources. If the utility charges λ_s and λ_g, the shadow price is higher than the optimal and the resulting levels of water use q_s and q_g are less than optimal. The change in shadow price of surface and groundwater in condition (31) and (32) are exactly the same as condition (13) and (14) in the first model. The same salvage value condition (19) applies to this case.

2.3.3 Characterization of the optimal path for each variable

The basic characterization of variables for the model with seepage in the canal *and* on the field is the same as the first model. Some aspects different from the first model are identified below.

The net shadow prices of surface and groundwater which firms should face are of particular concern. As mentioned in the previous section, the marginal cost of both surface and ground water production involves an extra constant term, $-\lambda_g\beta(1-h)$. Because the change in shadow price of groundwater is zero, the change in net shadow price of surface and groundwater are the same as shadow prices shown in conditions (31) and (32). Therefore, the extra term shifts the net shadow prices down as illustrated in Figure 2.3. While the seepage on the field directly affects the shadow price of water and the optimal schedule on the production site, seepage in the canal affects the rate of change of shadow price through the loss function. In both cases, a higher total amount of groundwater resource that is available for production contributes to a lower shadow price of groundwater.

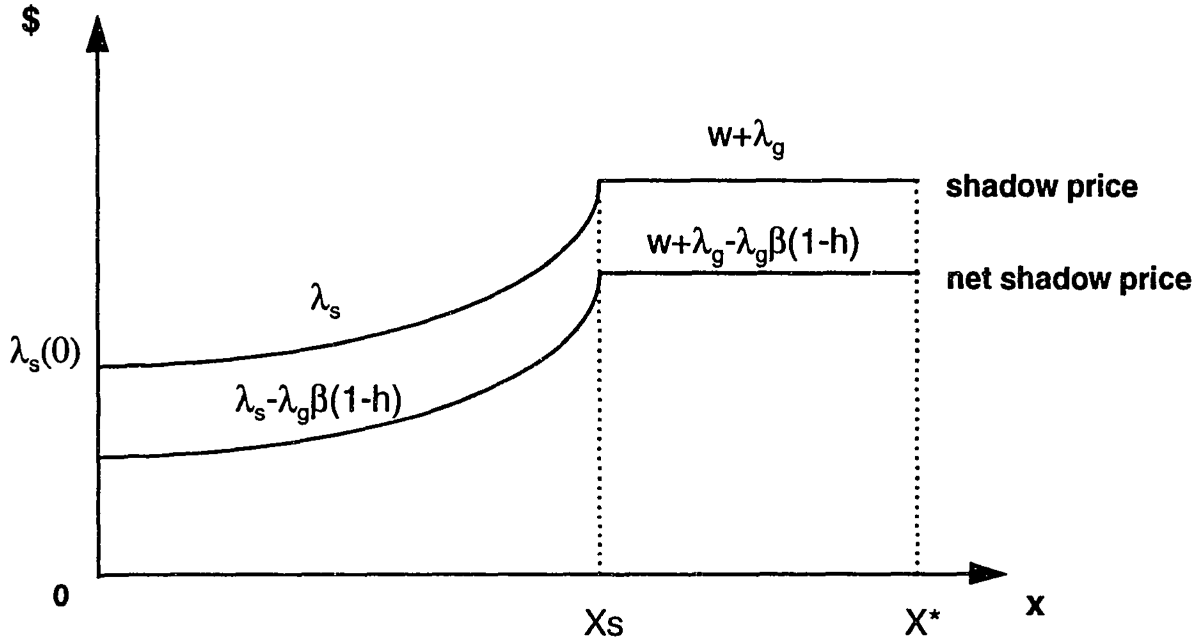


Figure 2.3. Shadow Price and Net Shadow Price with Fixed Technology

Compared to the first model with seepage only from the canal, the lower shadow price causes higher water use in the whole project area and the switching point to groundwater Xs is shorter if the initial stock of water is fixed. Also, a lower shadow price of water makes conveyance expenditure less attractive and as a result, water loss from the canal is greater than in the first model.

Land rents and water rents defined in (35) and (36) also include an additional term for a water charge. As in the first model, land rents decrease and water rents increase until Xs.

$$R_L(x) = \{pf[(q_s(x)+q_g(x))h] - [\lambda_s(x)-\lambda_g\beta(1-h)]q_s(x) - (w+\lambda_g(x)[1-\beta(1-h)])q_g(x) - I - F\}\alpha \tag{35}$$

$$R_W(x) = \{[\lambda_s(x)-\lambda_g\beta(1-h)]q_s(x)+\lambda_g(x)[1-\beta(1-h)]q_g(x)\}\alpha - k(x) \tag{36}$$

2.4 Data and Method of Simulation

2.4.1 Data

The production function, water loss function, loss reduction function and marginal cost function for water supply are those adopted by Chakravorty et al. (1995) in analyzing optimal water conveyance for California cotton[13] production. A production function for

[13] Cotton can be irrigated from one to four times per cropping season depending on the irrigation regimes. (Yaron and Bresler, 1983)

California cotton production is defined as a quadratic function of effective water. This production function yields a maximum of 1,500 lbs. with 3.0 acre-feet of effective water and yields 1,200 lbs. with 2.0 acre-feet of effective water. The revenue function in US$ is given by the following function:

$$Pf(e) = -0.2224 + 1.0944*e - 0.5984*e^2 \quad (37)$$

where output price of cotton is US$0.75 per lb. (Zilberman et al., 1994) and the effective water, e, is in m^3. Partial differentiation of equation (37) with respect to e provides the value of marginal product function:

$$Pf'(e) = 1.0944 - 1.1968*e \quad (38)$$

The on-farm water conservation is a function of on-farm investment. The conservation function is estimated from expenditures in irrigation technologies in California (University of California, 1988). It is constructed so that in the case of traditional furrow irrigation when no investment is made, i.e., $I = 0$, the proportion of water delivered to the field and actually used for production is $h = 0.6$. Increasing the level of on-farm investment increases the efficiency so that $0.6 < h < 1$. The function is defined as follows:

$$h(I) = 0.6 + 21.67*I - 333.3*I^2 \quad (39)$$

where $\partial h/\partial I>0$ and $\partial^2 h/\partial I^2<0$ and I is in US\$/m². In this chapter, both I and h are fixed to be US\$0.02/m² and 0.9, respectively. In the subsequent chapter, this assumption will be relaxed and on-farm technology is considered endogenous. Irrigated farming requires fixed costs of US\$0.107/m² (US\$433/acre), assumed to be constant regardless of the level of on-farm technology (University of California, 1988), except for traditional furrow irrigation fixed costs which are assumed to be US\$0.0535/m² (US\$217/acre). In reality, fixed costs may vary according to the type of technology adopted[14].

The water loss function is a quadratic function of conveyance expenditure which was constructed from data of average lining and piping costs in 17 states in Western United States. For example, piped canal with a conveyance expenditure of US\$200/m attains a maximum reduction equivalent to base loss and resulting in zero conveyance loss. An investment in concrete lining costs US\$100/m and gives a total loss rate of 10^{-5}/m with a conveyance loss rate of 0.1 for a 10km length of the canal or a conveyance efficiency of 0.9/10km. Further, if there is no conveyance expenditure, no reduction in loss is achieved. Therefore, the loss rate is the same as the base loss rate, $4*10^{-5}$/m, with a conveyance loss rate of 0.4/10km or a conveyance efficiency of 0.6/10km. The water loss function at each location of the canal x is defined as:

$$a(x) = 4*10^{-5} - (4*10^{-7}k(x) - 10^{-9}k(x)^2) \tag{40}$$

[14] Zilberman et al. (1994) showed varying fixed costs of irrigation technology for California cotton production. According to their estimates, fixed costs increase from US\$500/acre for furrow irrigation with irrigation efficiency of 0.6 to US\$633/acre for drip irrigation with efficiency of 0.95.

where base loss $a_0 = 4*10^{-5}$, and the loss reduction function is defined as:

$$m(k) = 4*10^{-7}k - 10^{-9}k^2, \quad 0 \leq k \leq 200 \tag{41}$$

which is increasing at a decreasing rate with respect to conveyance expenditure, k, so that $\partial m/\partial k \geq 0$, and $\partial^2 m/\partial k^2 \leq 0$.

The long-run marginal cost function for water supply was estimated from the average cost of water supply of 18 irrigation projects in the Western United States as shown below:

$$g'(z_s(0)) = 0.003785 + (3.785*10^{-11} z_s(0)) \tag{42}$$

where marginal cost is given in US$ and the initial stock of water $z_s(0)$ in m^3.

The width of the project area α is assumed to be 10^5m as specified in the surface water model of Chakravorty et al. (1995). The same seepage rate β was assumed for both cases of seepage from the canal as well as from the field for all locations. Gisser and Mercado (1973) and Gisser and Sanchez (1980) use a return flow coefficient of 0.27 for the Pecos River Basin in New Mexico. Kim et al. (1989) use 0.20 for irrigated production in the Texas High Plains. In this model, seepage rate was assumed to be 0.3 as adopted by Gisser (1983) for New Mexico.

In many groundwater studies, the marginal cost of water is approximated by the pumping cost of water and defined as a linear function of pumping lift (Burt, 1964; Gisser and Mercado, 1973; Gisser and Sanchez, 1980; Gisser, 1983; Kim et al., 1989). Caswell and Zilberman (1985, 1986) also specified marginal pumping cost as a function of lift which is an addition of actual lift and a lift converted from the energy cost of pressurization. These studies consider that the marginal cost of pumping does not depend on the amount of water extracted[15]. For simplicity, the same assumption of constant marginal cost of pumping is adopted. The marginal pumping cost, US\$0.0128/m^3 (US\$15.80/acre-foot) as estimated by Negri and Brooks (1990), excludes the cost of pressurization and is considered appropriate for this model in order to separate pumping cost from on-farm investment. Table 2.1 summarizes the value of fixed parameters used in the base models.

2.4.2 Method of simulation

The following computer algorithm was written in FORTRAN for simulation analysis. Figure 2.4 shows a flow diagram of this algorithm. First, given the initial stock of surface water $z_s(0)$, $\lambda_s(0)$ is computed from the salvage value condition (19). The initial stock of groundwater $z_g(0)$ is zero. Given $\lambda_s(0)$ and λ_g which is constant, condition (15) gives $m'(k)$ at $x=0$. The marginal reduction function derived from (41) defines the conveyance expenditure $k(0)$ and by substituting $k(0)$ into (40), water loss from the canal $a(0)$ is computed. Given $\lambda_s(0)$ and λ_g (in the case of the second model), condition (11)

[15] Kanazawa (1992) suggested in his study for Central California that the marginal pumping cost of groundwater may actually increase as the amount of pumping increases.

Table 2.1
Fixed Parameters in the Base Models

α	width of the project area	100 km	Chakravorty et al. (1995)
β	seepage rate	0.3	Gisser (1983)
a_0	base loss rate in the canal/10 km	0.4	Chakravorty et al. (1995)
I	on-farm investment in water efficiency	$0.02/m^2	University of California (1988)
h(I)	on-farm water efficiency	0.9	University of California (1988)
F	fixed cost of irrigation farming	$0.107/m^2	University of California (1988)
p	output price of cotton	$0.75/lb	Zilberman et al. (1994)
w	unit pumping cost	$0.0128/m^3	Negri & Brooks (1990)

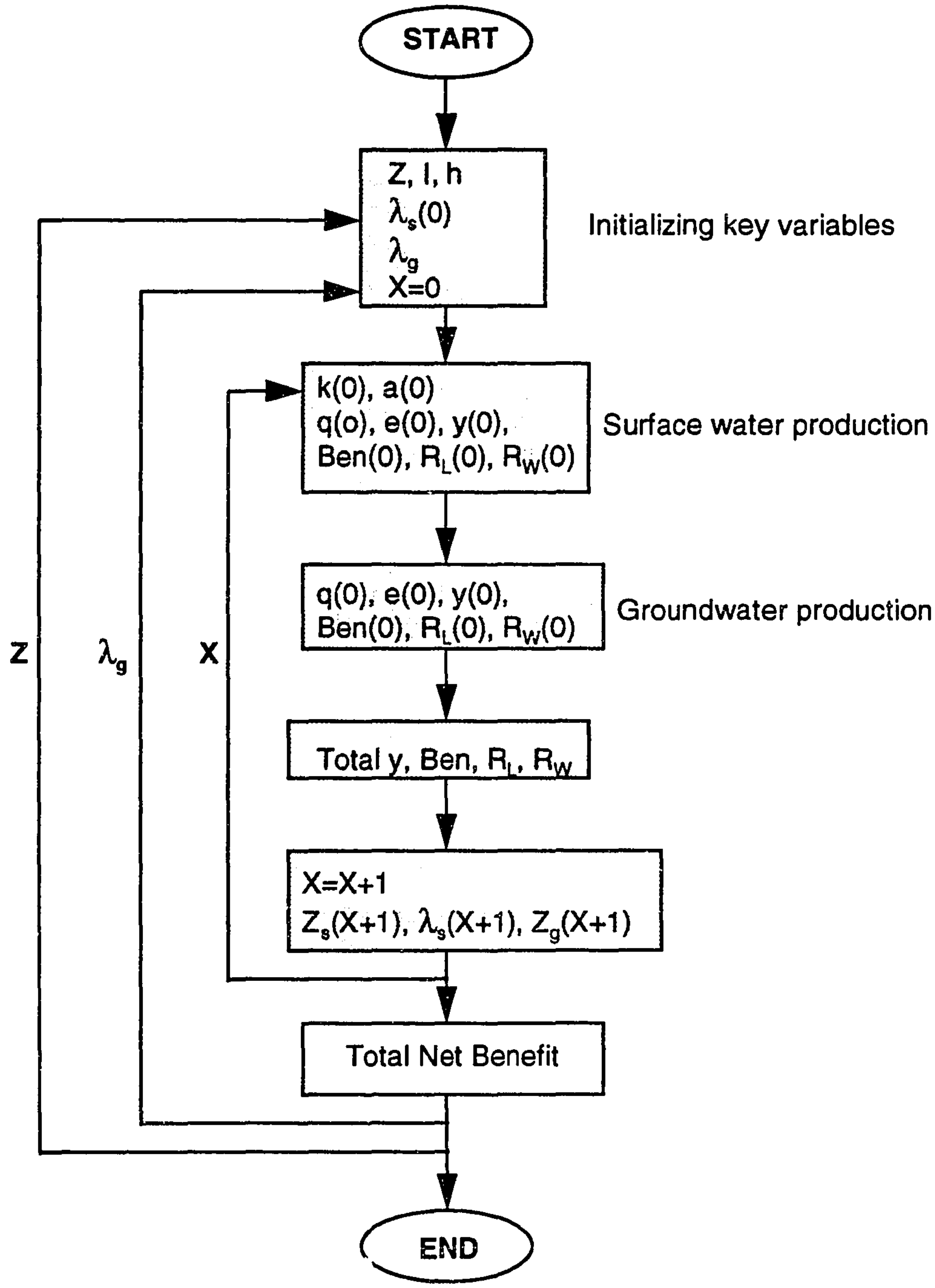


Figure 2.4
Algorithm for Static Conjunctive Water Use Model with Fixed Technology

yields $q_s(0)$, and $q_s(0)$ is used to compute e(0), y(0), $R_L(0)$, $R_W(0)$ for surface water production at x=0.

In the next step, when x=1, a(0), $\lambda_s(0)$ and λ_g are substituted into (13) to give $\lambda_s(1)$. The residual stock of surface water $z_s(1)$ is given from the state constraint (1) by subtracting the surface water use and water loss in the canal in the previous period x=0. Similarly, residual groundwater stock $z_g(1)$ is estimated from (3). Given $\lambda_s(1)$ and $z_s(1)$, the same cycle as before is repeated to yield $q_s(1)$, e(1), y(1), $R_L(1)$, $R_W(1)$ and continues for the next cycle at x=2. This cycle of surface water production terminates when either one of the following conditions are satisfied: (i) the shadow price of surface water is greater than the shadow price of groundwater, (ii) the land rent is not positive, (iii) the benefit of production is not positive, or (iv) residual surface water z_s is exhausted.

Since it is known previously that the result is a corner solution, groundwater extraction does not occur until one of four conditions mentioned above are satisfied. Once surface water use is terminated, the extraction of groundwater starts. The groundwater cycle repeats the same procedure as surface water production given $z_g(Xs)$, and λ_g. The groundwater cycle terminates when residual groundwater stock is exhausted or when either land rents or benefits are non positive. At the end of one cycle for different amounts of initial stock of water, $z_s(0)$, aggregate net benefit, land rents, and water rents from surface and groundwater production are estimated.

The optimal $z_s(0)$ and λ_g are determined simultaneously which maximize the total net benefit of the project, i.e., aggregate net benefit less cost of generating surface water at the source, which is given by (17). This algorithm for the base model was later altered to take into account cases under different assumptions.

2.5 The Optimal Model with Fixed Technology

Simulations were run for two models with seepage in the canal (hereafter FTSC) and with seepage in the canal *and* on the field (hereafter FTSCF) assuming fixed technology for modern and traditional on-farm irrigation. For a comparison, simulation results of the surface water model by Chakravorty et al. (1995) are presented with the same level of technology.

In the case of modern technology, on-farm investment, I, was assumed to be US\$0.02/m^2 so that from equation (39) the proportion of water actually used for production, h, is 0.9. This level of water efficiency represents on-farm technology between sprinkler irrigation (h=0.85) and drip irrigation (h=0.95). The results of simulation with modern technology are summarized in Table 2.2.

Comparing the two conjunctive use models, FTSCF yields a 3% larger total net benefit than that in FTSC. However, the optimal irrigated area, length of the canal and the initial stock of water are smaller by 4%, 6%, 5%, respectively, in FTSCF. It is expected that the area of groundwater use is larger in FTSCF (2km) than in FTSC (1km). Because of additional seepage on the field, FTSCF starts with a smaller optimal initial stock of water which means a lower shadow price of surface water at the head of the

Table 2.2
Simulation Results with Modern Technology
(h=0.9; I=0.02; F=0.107)

Parameter	Unit	Model		
		Seepage in the canal (FTSC)	**Seepage in the canal and on the field (FTSCF)**	**Chakravorty et al. (1995)**
Total Net Benefit	(10^8US$)	3.46	3.57	3.33
Area Irrigated	(10^3ha)	490	470	480
Xs	(km)	48	45	48
X*	(km)	49	47	n.a.
Initial Water Stock	(10^8m^3)	41	39	41
Aggr. Output	(10^8US$)	13.24	12.81	12.98
Aggr. Net Benefit	(10^8US$)	6.79	6.60	6.67
Aggr. Land Rent	(10^8US$)	.123	.602	.121
Aggr. Water Rent	(10^8US$)	6.67	6.00	6.55
k(0)	(US$/m)	198.94	198.83	199.23
k(Xs)	(US$/m)	154.24	153.14	167.00
a(0)	(10^{-3}/km)	.00112	.00136	.00059
a(Xs)	(10^{-3}/km)	2.0943	2.1957	1.089
$q_s(0)$	(m^3/m^2)	.8520	.8641	.852
q_g	(m^3/m^2)	.8515	.8636	.852*
$y_s(0)$	(US$/$m^2$)	.2650	.2668	.2650
y_g	(US$/$m^2$)	.2649	.2667	.2650

Table 2.2. (Continued)
Simulation Results with Modern Technology
(h=0.9; I=0.02; F=0.107)

Net Benefit (head)	($US\$/m^2$)	.1359	.1378	.1359
Net Benefit (tail)	($US\$/m^2$)	.1270	.1287	.1379
$\lambda_s(0)$	($US\$/m^3$)	.15897	.15140	.15897
$w + \lambda_g$	($US\$/m^3$)	.15947	.15190	.15927*
λ_g	($US\$/m^3$)	.14667	.13910	n.a.
$\lambda_s(0) - \lambda_g\beta(1-h)$	($US\$/m^3$)	n.a.	.14723	n.a.
$w + \lambda_g[1-\beta(1-h)]$	($US\$/m^3$)	n.a.	.14773	n.a.
$R_L(0)$	($10^6 US\$/m^2$)	.2495	1.2572	.2495
R_{Lg}	($10^6 US\$/m^2$)	.2069	1.2140	.2240
$R_W(0)$	($10^6 US\$/m^2$)	13.3454	12.5234	
R_{Wg}	($10^6 US\$/m^2$)	12.4888	11.6524	

Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal.

canal than that of FTSC. Therefore, a smaller aggregate output of FTSC is offset by lower costs of generating water at the source resulting in a larger total net benefit.

Not only does FTSCF have a 5% lower shadow price and 7% lower net shadow price of surface water, but the shadow price of groundwater is also 5% lower. Due to a lower shadow price in FTSCF, it is optimal to spend less on conveyance to stop seepage from the canal. As a result, the water loss rate is higher throughout the canal in FTSCF. Also lower net shadow prices of surface and groundwater in FTSCF increase water use by firms and contribute to earlier exhaustion of the water resource. Net benefit per unit land area is higher throughout the project area in FTSCF.

In FTSCF, as mentioned before, the utility and firms face different shadow prices for water resources due to a positive externality accrued to firms. For example, the shadow price of surface water at the head of the canal is US\$0.15140/m^3 for the utility and US\$0.14723/m^3 for firms. The difference, US\$0.00417/m^3, is the positive externality to water consumers due to the contribution to the groundwater stock on the production site. This difference in shadow price amounts to US\$19,600,000 in the whole project area.

Aggregate land rents are five times higher in FTSCF because of a lower net shadow price of water and higher water use and output per unit area of land. On the other hand, aggregate water rents are 10% lower and water rents per unit project are 6% lower in FTSCF. In both models, larger land rents and smaller water rents accrue to firms at the head of the project area.

As expected, the surface water model yields the smallest total net benefit;

however, the difference between FTSC and the surface water model is only 4% due to the small amount of seepage in FTSC. Conveyance expenditure in the surface water model is higher than the conjunctive use models. Water use, output, and net benefit show almost the same values as in FTSC.

The second case for fixed technology is when a traditional technology such as furrow irrigation is used. For the models, FTSC, FTSCF and the surface water model, on-farm investment, I, is zero and water efficiency, h, is 0.6. Under traditional irrigation technology, only 60% of water applied is used for production and the remaining 40% is either lost or recharges the aquifer as seepage. Fixed costs for on-farm irrigation with traditional technology is assumed to be US\$0.0535/m^2, half of modern technology. The results of simulation for traditional technology are summarized in Table 2.3.

When seepage is large, conjunctive use models show quite different results. Total net benefit is 4.9% higher in FTSC and 30.5% higher in FTSCF compared to the surface water model. Also, the area irrigated is 3% larger in FTSC and 21.2% larger in FTSCF than in the surface water model. The larger amount of seepage in FTSCF allows a larger area for groundwater production extending the length of the project area for 6 km at the tail and covering 15% of the total project area. The initial stock of water is the highest (41×10^8 m^3) in FTSCF compared to FTSC and the surface water model (39×10^8 m^3).

Because of the higher initial stock of water, FTSCF starts with a high shadow price of surface water. However, due to low water efficiency and high seepage, the net shadow price of surface water is low resulting in high water use and high output in the area for surface water production. On the other hand, water use and output in

Table 2.3
Simulation Results with Traditional Technology:
Model with Seepage in the Canal and on the Field
(h=0.6; I=0; F=0.0535)

Parameter	Unit	Model		
		Seepage in the canal (FTSC)	**Seepage in the canal and on the field (FTSCF)**	**Chakravorty et al. (1995)**
Total Net Benefit	(10^8US$)	3.82	4.75	3.64
Area Irrigated	(10^3ha)	340	400	330
Xs	(km)	33	34	33
X*	(km)	34	40	n.a.
Initial Water Stock	(10^8m^3)	39	41	39
Aggr. Output	(10^8US$)	8.80	10.43	8.55
Aggr. Net Benefit	(10^8US$)	6.85	8.09	6.67
Aggr. Land Rent	(10^8US$)	.72	1.29	.69
Aggr. Water Rent	(10^8US$)	6.13	6.79	5.98
k(0)	(US$/m)	198.83	198.87	199.15
k(Xs)	(US$/m)	47.92	164.99	90.71
a(0)	(10^{-3}/km)	.00136	.00127	.000713
a(Xs)	(10^{-3}/km)	23.130	1.2259	11.944
q_s	(m^3/m^2)	1.1726	1.2023	1.173
q_g	(m^3/m^2)	1.1721	1.1477	1.172*
$y_s(0)$	(US$/$m^2$)	.25137	.2557	.2514
y_g	(US$/$m^2$)	.25130	.2475	.2513

Table 2.3. (Continued)
Simulation Results with Traditional Technology:
Model with Seepage in the Canal and on the Field
(h=0.6; I=0; F=0.0535)

Net Benefit (head)	(US$/$m^2$)	.1959	.2002	.1959
Net Benefit (tail)	(US$/$m^2$)	.1828	.1793	.1969
$\lambda_s(0)$	(US$/$m^3$)	.15140	.15897	.15140
$w + \lambda_g$	(US$/$m^3$)	.15160	.18247	.15154*
λ_g	(US$/$m^3$)	.13880	.16967	n.a.
$\lambda_s(0) - \lambda_g\beta(1-h)$	(US$/$m^3$)	n.a.	.13861	n.a.
$w + \lambda_g[1-\beta(1-h)]$	(US$/$m^3$)	n.a.	.16211	n.a.
$R_L(0)$	(10^6US$/$m^2$)	2.0338	3.5527	2.0338
R_{Lg}	(10^6US$/$m^2$)	2.0104	.7913	2.0176*
$R_W(0)$	(10^6US$/$m^2$)	17.5541	16.4658	
R_{Wg}	(10^6US$/$m^2$)	16.2690	17.1366	

Note: n.a. = not applicable; * indicates figures at the tail; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal.

groundwater production is low because low water efficiency makes the net shadow price of groundwater high. Therefore, in the conjunctive use model, low water efficiency intensifies surface water use but reduces groundwater use. Aggregate land rents are 86% higher and water rents are 13.5% higher than in the surface water model.

2.6 The Optimal Model with High Conveyance Costs

In the previous section, the loss function (40) was assumed in the base cases of FTSC and FTSCF. Here, different loss functions are assumed to consider cases in which conveyance costs are relatively expensive. In addition to the base loss function, three different loss functions are used for simulation as below (see Table 2.4; Figure 2.5). Compared to the base loss function, conveyance expenditure becomes more expensive to reduce water loss from the canal. In the loss functions 2, 3 and 4, no investment in conveyance will result in a loss rate of 0.4/10km as in the base case. However, in loss function 2, US$400 is required to reduce water loss to zero. This maximum conveyance expenditure to attain zero water loss increases to US$1,000 and US$2,000 in loss functions 3 and 4, respectively. Technology, h, is again assumed to be 0.9 as in the previous simulation in Section 2.5.

Table 2.5 shows the results of simulation. Models with seepage in the canal and with loss function 2, 3, or 4 are called FTSC2, FTSC3, and FTSC4, respectively. As conveyance costs increase by five times in FTSC3, the optimal total net benefit, area irrigated, length of the canal and project area, initial water stock, and aggregate net

Table 2.4
Different Water Loss Functions and Conveyance Costs

Model	Water Loss Function	a=0.4	a=0.2	a=0
Base	$a = 4*10^{-5}-(4*10^{-7}k-10^{-9}k^2)$	k=0	k=150	k=200
2	$a = 4*10^{-5}-(2*10^{-7}k-0.25*10^{-9}k^2)$	k=0	k=300	k=400
3	$a = 4*10^{-5}-(8*10^{-8}k- 4*10^{-11}k^2)$	k=0	k=750	k=1000
4	$a = 4*10^{-5}-(4*10^{-8}k-10^{-11}k^2)$	k=0	k=1500	k=2000

Note: Loss rate is estimated for a 10 km length of the canal; a=water loss rate; k=conveyance expenditure per meter of the canal.
Source: Chakravorty et al. (1995)

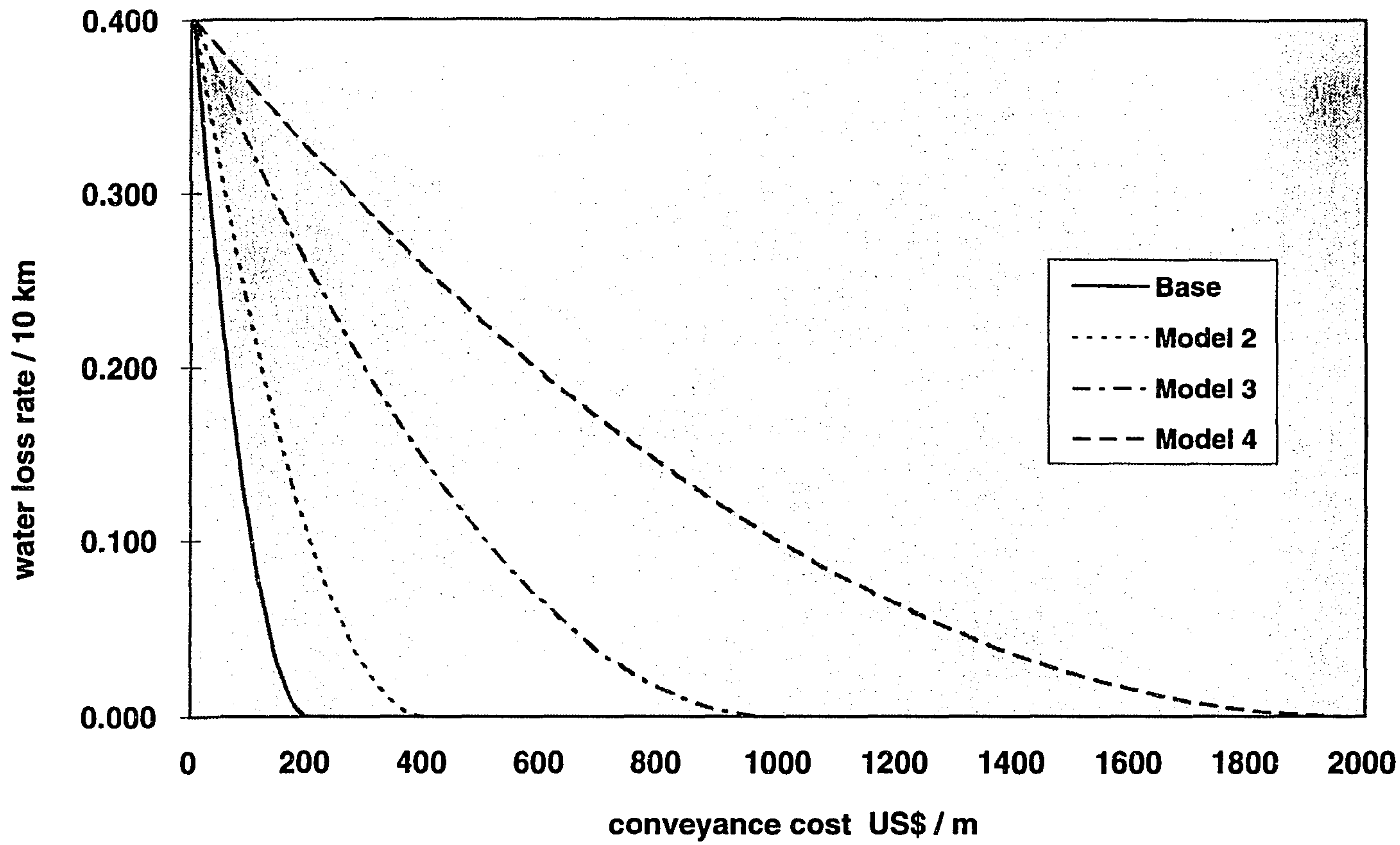


Figure 2.5
Different Water Loss Functions and Conveyance Costs

Source: Chakravorty et al. (1995)

Table 2.5
Simulation Results with High Conveyance Costs:
Model with Seepage in the Canal
(h=0.9; I=0.02; F=0.107)

Parameter	Unit	Model			
		Base (FTSC)	**2 (FTSC2)**	**3 (FTSC3)**	**4 (FTSC4)**
Total Net Benefit	(10^8US$)	3.46	3.37	3.10	2.74
Area Irrigated	(10^3ha)	490	490	460	400
Xs	(km)	48	48	45	39
X*	(km)	49	49	46	40
Initial Water Stock	(10^8m^3)	41	41	39	35
Aggr. Output	(10^8US$)	13.24	13.25	12.50	10.99
Aggr. Net Benefit	(10^8US$)	6.79	6.13	5.19	5.19
Aggr. Land Rent	(10^8US$)	.123	.119	.389	.800
Aggr. Water Rent	(10^8US$)	6.67	6.58	5.74	4.39
k(0)	(US$/m)	198.94	395.74	970.10	1844.96
k(Xs)	(US$/m)	154.24	213.08	390.24	208.87
a(0)	(10^{-3}/km)	.00112	.00453	.03577	.24037
a(Xs)	(10^{-3}/km)	2.09432	8.7351	14.8722	32.0817
$q_s(0)$	(m^3/m^2)	.8520	.8520	.8598	.8754
q_g	(m^3/m^2)	.8515	.8501	.8507	.8511
$y_s(0)$	(US$/$m^2$)	.26494	.26496	.26615	.26840
y_g	(US$/$m^2$)	.26486	.26464	.26474	.26479
Net Benefit (head)	(US$/$m^2$)	.1359	.1340	.1205	.1008
Net Benefit (tail)	(US$/$m^2$)	.1270	.1268	.1254	.1252

Table 2.5. (Continued)
Simulation Results with High Conveyance Costs:
Model with Seepage in the Canal
(h=0.9; I=0.02; F=0.107)

$\lambda_s(0)$	(US$/m^3)	.15897	.15897	.15140	.13626
$w + \lambda_g$	(US$/m^3)	.15947	.16077	.16020	.15986
λ_g	(US$/m^3)	.14667	.14797	.14740	.14706
$R_L(0)$	(10^6US$/m^2)	.2495	.2495	.8975	2.2111
R_{Lg}	(10^6US$/m^2)	.2069	.0963	.1148	.1737
$R_W(0)$	(10^6US$/m^2)	13.3454	13.1486	12.0475	10.0837
R_{Wg}	(10^6US$/m^2)	12.4888	12.5797	12.5399	12.5161

Note: Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal.

Table 2.6
Simulation Results with High Conveyance Costs:
Model with Seepage in the Canal and on the Field
(h=0.9; I=0.02; F=0.107)

Parameter	Unit	Model			
		Base (FTSCF)	**2 (FTSCF2)**	**3 (FTSCF3)**	**4 (FTSCF4)**
Total Net Benefit	(10^8US$)	3.57	3.49	3.22	2.84
Area Irrigated	(10^3ha)	470	470	440	420
Xs	(km)	45	45	42	40
X*	(km)	47	47	44	42
Initial Water Stock	(10^8m^3)	39	39	37	36
Aggr. Output	(10^8US$)	12.81	12.81	12.05	11.53
Aggr. Net Benefit	(10^8US$)	6.60	6.52	5.95	5.43
Aggr. Land Rent	(10^8US$)	.602	.598	.817	.857
Aggr. Water Rent	(10^8US$)	6.00	5.92	5.13	4.58
k(0)	(US$/m)	198.83	395.31	965.90	1854.22
k(Xs)	(US$/m)	153.14	208.08	363.12	339.87
a(0)	(10^{-3}/km)	.00136	.00550	.04652	.21253
a(Xs)	(10^{-3}/km)	2.19569	9.2082	16.2248	27.5605
$q_s(0)$	(m^3/m^2)	.8641	.8642	.8722	.8761
q_g	(m^3/m^2)	.8636	.8623	.8535	.8534
$y_s(0)$	(US$/$m^2$)	.2668	.2668	.2680	.2685
y_g	(US$/$m^2$)	.2667	.2665	.2652	.2652
Net Benefit (head)	(US$/$m^2$)	.1378	.1358	.1313	.1230
Net Benefit (tail)	(US$/$m^2$)	.1287	.1285	.1272	.1272

Table 2.6. (Continued)
Simulation Results with High Conveyance Costs:
Model with Seepage in the Canal and on the Field
(h=0.9; I=0.02; F=0.107)

$\lambda_s(0)$	(US\$/m^3)	.15140	.15140	.14383	.14005
$w + \lambda_g$	(US\$/m^3)	.15190	.15320	.16203	.16205
λ_g	(US\$/m^3)	.13910	.14040	.14923	.14925
$\lambda_s(0) - \lambda_g\beta(1-h)$	(US\$/m^3)	.14723	.14719	.13935	.13557
$w + \lambda_g[1-\beta(1-h)]$	(US\$/m^3)	.14773	.14899	.15755	.15757
$R_L(0)$	(10^{6}US\$/m^2)	1.2572	1.2605	1.9408	2.2718
R_{Lg}	(10^{6}US\$/m^2)	1.2140	1.1052	.3703	.3687
$R_W(0)$	(10^{6}US\$/m^2)	12.5234	12.3241	11.1891	10.0235
R_{Wg}	(10^{6}US\$/m^2)	11.6524	11.7435	12.3542	12.3556

Note: Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal.

benefit decline by 10%, 6%, 6%, and 5% respectively. The conveyance costs at the head of the canal are close to the maximum conveyance costs of each loss function and decrease until the end of the canal.

When conveyance costs are high, it is optimal to have a smaller initial stock of water so that the shadow price of surface water at the head is lower. This is due to the following reasons. If the shadow price is high with high conveyance costs, high water loss is associated with a high rate of increase in shadow price. Therefore, within a shorter distance, the shadow price reaches the threshold level of the shadow price of surface water where land rents become zero and no more production is feasible beyond this point. With fixed technology of h=0.9, this critical point arises when the shadow price of surface water (or the shadow price of groundwater plus pumping cost) is greater than 0.16192. Because of the lower shadow prices of both surface and groundwater associated with higher conveyance costs, water use per unit land area is also higher, resulting in higher output. However, increasing conveyance costs reduces net benefit (net of conveyance costs) with higher conveyance costs.

Aggregate land rents increase and aggregate water rents decrease as conveyance costs become more expensive. Compared to FTSC (Base), FTSC3 generated almost 6.5 times higher aggregate land rents primarily due to a 5% lower shadow price of water. High conveyance cost increases land rents at the head and decreases land rents at the tail. The opposite trend is observed for water rents. High conveyance costs tend to skew the distribution of land rents in favor of head firms and water rents in favor of the tail of the project area. Conveyance costs that are three times higher increase the difference of land rents among head and tail firms from 20% in the base model to 682% in FTSC3.

Simulation results for models with seepage in the canal *and* on the field (FTSCF, FTSCF2, FTSCF3, FTSCF4) follow the same logic as results for models with the base loss function (see Table 2.6). Compared to models with seepage only in the canal, total net benefit is larger even though the area irrigated, length of the canal, length of project area, and initial water stock are smaller. Because of a lower net shadow price, water use and output are higher in all models compared to models with seepage only in the canal.

2.7 Conclusion

This chapter defines the basic structure of a static spatial water allocation model for conjunctive use of surface and groundwater. Two models were considered. One is the model with seepage in the canal and the other is a model with seepage in the canal *and* on the field. The optimal allocation is a corner solution, i.e., firms use surface water first and then use groundwater. The shadow price of surface water increases (thus surface water use decreases) away from the source. The shadow price of groundwater (thus groundwater use) is uniform among firms. The optimal allocation of water is guaranteed as long as the utility charges firms the shadow price of surface water as well as that of groundwater per unit of water used and invest in the optimal conveyance expenditure at each location of the canal.

In the second model, seepage from the production site generates positive externalities for water consumers and as a result the net shadow price is lower in this case. Also, the model with seepage in canal *and* on the field generates different shadow prices for water resources according to the level of seepage at each point. As a result, the resource owner (i.e., the utility) and the resource user (i.e., firms) faces different shadow prices for water resources.

Simulations were run for both models assuming (i) fixed on-farm investment in water conservation, and (ii) different conveyance costs in order to analyze optimal water allocation for each case.

The simulation results with modern on-farm technology show that the model with seepage in the canal *and* on the field yields a 3% higher total net benefit with a 4% smaller project area and 5% smaller initial water stock. Also, it is optimal to invest less in conveyance when seepage is larger. The surface water model yields the smallest total net benefit; however, the difference from FTSC is only 4%. On the other hand, the simulation results with traditional on-farm technology show a 30.5% higher total net benefit compared to the surface water model. Also a large amount of seepage and thus groundwater stock extends groundwater use for 6 km at the tail of project area in FTSCF. In the conjunctive use model, low water efficiency intensifies surface water use but reduces groundwater use by firms.

These results suggest that when seepage on the field is large there is a non-negligible positive externality generated by water consumers. The utility needs to take this externality into account and charge firms for surface and groundwater resources to achieve optimal allocation. Failure to do so will result in suboptimal resource allocation and a smaller total net benefit from the water project than is optimal. This positive externality implies that when land is heterogeneous and the seepage rate differs within the project area, a larger positive externality accrues in favor of firms with leaky land, if everything else is held constant.

The simulation with high conveyance costs, which is the same as the effect of an increasing interest rate, indicates that higher conveyance expenditure causes shrinkage of the project area, total net benefit, length of the canal, and the initial stock of water. High conveyance costs tend to skew the distribution of land rents in favor of head firms and water rents in favor of tail of the project area. This implies that if maintenance of the canal is not implemented, in the long run the deterioration of the system will make conveyance more costly resulting in shrinking of the project area and worsening the distribution of land rents over time. The utility must invest in conveyance periodically to avoid this situation.

CHAPTER 3

EXTENSIONS OF THE OPTIMAL MODEL: ENDOGENOUS TECHNOLOGY AND CROP CHOICE

3.1 Introduction

In this chapter, two types of endogenous choices available to firms are considered. One type is endogenous technology, and the other is endogenous crop choice. The assumptions of fixed on-farm investment in water conservation and monocropping in the project area are relaxed to incorporate these endogenous choices. First, on-farm investment in water conservation becomes an additional decision variable for firms. Depending on the price of water, firms choose, for example, among furrow, sprinkler and drip irrigation technologies to conserve water in the field. Also, firms shift production to the crop which yields higher net benefits when water price is increasing. Given the spatially differentiated shadow price of water by the utility, firms maximize their net benefit of production by adopting the appropriate level of technology as well as the type of crop to produce.

Section 2 introduces endogenous technology for both models with seepage in the canal and with seepage in the canal *and* on the field. Section 3 tries to illustrate the endogenous crop choice in relation to shadow prices of surface and groundwater. Section 4 concludes the chapter.

3.2 Endogenous Technological Choice

The determinants of the firm's technological choice have been studied by numerous authors (Caswell and Zilberman, 1986; Lichtenberg, 1989; Negri and Brooks, 1990). Their results suggest that high cost of water and low land quality is the major driving force for adopting modern technologies such as sprinkler and drip irrigation. The purpose of this chapter is to consider the effects of spatially increasing shadow prices of water on the choice of on-farm technology, resource allocation, and total net benefit of the water project in the case of conjunctive water use.

The first part below explains specification of the problem followed by the optimal model with endogenous technology and necessary conditions for optimality. The next part shows characterization of the optimal path for each variable. The last section presents the methodology and results of the simulation. It provides a comparison with a model by Chakravorty et al. (1995) and some policy implications of this result.

3.2.1 Specification of the problem

In Chapter 2, on-farm investment in water conservation was considered exogenously given to firms. In this section, it is considered an endogenous variable. Utility and firms together endogenously choose the optimal level of on-farm investment so as to maximize total net benefit of the water project. In the following two models, one with seepage in the canal and one with seepage in the canal *and* on the field, water conservation technology, i.e., the proportion of water consumed for evapotranspiration by the crop h is a function of on-farm investment, I. Except for the endogenous technology, the same specifications mentioned in Sections 2.2 and 2.3 apply to this problem.

3.2.2 The optimal model with endogenous technological choice

The utility is assumed to choose $q_s(x)$, $q_g(x)$, $k(x)$, $I(x)$ and X, the end point of the project area, so as to maximize net benefit from the water project. In the case of a model with seepage only in the canal, the optimization problem is defined by:

$$\underset{q_s,\, q_g,\, k,\, I,\, X^*}{\text{maximize}}\ NB(z_s(0)) = \int_0^{X^*} \{[pf[(q_s+q_g)h(I)] - I - F - wq_g]\alpha - k\}dx \qquad (1)$$

subject to two state constraints:

$$z_s'(x) = -\, q_s(x)\alpha - a(x)z_s(x) \qquad (2)$$

$$z_g'(x) = \beta a(x)z_s(x) - q_g(x)\alpha \qquad (3)$$

The Hamiltonian of this problem is defined as follows, with $z_s(x)$ and $z_g(x)$ as state variables and $q_s(x)$, $q_g(x)$, $k(x)$ and $I(x)$ as control variables.

$$H\,(q_s, q_g, k, I, \lambda_s, \lambda_g) = [pf[(q_s+q_g)h(I)] - I - F - wq_g]\alpha - k$$
$$- \lambda_s\,[q_s\alpha + az_s] + \lambda_g\,[\beta az_s - q_g\alpha] \qquad (4)$$

Let q_s*, q_g*, k*, I*, λ_s*, λ_g*, and X* denote the corresponding optimal values for this optimization problem. There is again the possibility of a corner solution. Compared to the previous models in Chapter 2 in which technology is fixed, the necessary condition includes the additional marginal condition with respect to on-farm investment I, $\partial H/\partial I \leq 0$. Assume that the sufficiency conditions are met. Then the necessary conditions for optimality are given with the transversality condition as follows:

$$pf'h \leq \lambda_s \tag{5}$$

$$pf'h \leq w + \lambda_g \tag{6}$$

$$\lambda_s' = a(\lambda_s - \beta\lambda_g) \tag{7}$$

$$\lambda_g' = 0 \tag{8}$$

$$(\lambda_s - \beta\lambda_g)z_s m'(k) \leq 1 \tag{9}$$

$$pf'(q_s+q_g)h'(I) \leq 1 \tag{10}$$

$$[H\ (q_s,\ q_g,\ k,\ I,\ \lambda_s,\ \lambda_g)]_{x=X^*} = 0 \tag{11}$$

The necessary condition (10) states that the marginal benefit of increasing one unit of on-farm investment in water conservation is equal to or less than the marginal cost of on-farm investment which is unity.

In the case of a model with seepage in the canal *and* on the field, the utility maximizes the objective function (1) subject to state constraints (2) above and (12) as follows:

$$z_g'(x) = \beta a(x)z_s(x) - q_g(x)\alpha + \beta(1-h(I))(q_s(x)+q_g(x))\alpha \tag{12}$$

The Hamiltonian of this problem is given as:

$$H\,(q_s, q_g, k, I, \lambda_s, \lambda_g) = [pf[(q_s+q_g)h(I)] - I - F - wq_g]\alpha - k$$

$$- \lambda_s[q_s\alpha + az_s] + \lambda_g[\beta az_s - q_g\alpha + \beta(1-h(I))(q_s+q_g)\alpha] \tag{13}$$

Thus with an additional necessary condition for endogenous on-farm investment, the necessary conditions for optimality in this case with the transversality condition are given by:

$$pf'h \leq \lambda_s - \lambda_g\beta(1-h) \tag{14}$$

$$pf'h \leq w + \lambda_g[1-\beta(1-h)] \tag{15}$$

$$\lambda_s' = a(\lambda_s - \beta\lambda_g) \tag{16}$$

$$\lambda_g' = 0 \tag{17}$$

$$(\lambda_s - \beta\lambda_g)z_s m'(k) \leq 1 \tag{18}$$

$$pf'(q_s+q_g)h'(I) \leq 1 + \lambda_g\beta(q_s+q_g)h'(I) \tag{19}$$

$$[H\,(q_s, q_g, k, I, \lambda_s, \lambda_g)]_{x=X^*} = 0 \tag{20}$$

With additional seepage on the field, the necessary condition (19) involves an additional term $\lambda_g\beta(q_s+q_g)h'(I)$ on the left hand side of the equation which shows the marginal cost of increasing on-farm investment by one unit. When on-farm investment is increased, the positive externality of replenishing an underground aquifer decreases. The term $\lambda_g \beta(q_s+q_g)h'(I)$ reflects the value of foregone marginal benefit of the groundwater resource resulting from one more unit of on-farm investment in water conservation. Thus, in this case, the increased level of on-farm technology has a positive effect of increasing the efficient use of the water resource in production, and also a negative effect of reducing the amount of recharging groundwater stock. In other words, increased on-farm technology reduces the degree of positive externality and increases the marginal cost of water in condition (14) and (15).

3.2.3 Characterization of the optimal path for each variable

In the model with seepage in the canal, the increasing shadow price of both surface and groundwater makes on-farm investment in water conservation more attractive towards the end of the project area. Therefore, the level of on-farm investment increases away from the source. This is consistent with the empirical results of Caswell and Zilberman (1986) showing that modern irrigation technologies are more likely to be adopted with high water prices. However, in the case of seepage in the canal *and* on the field, there is a trade-off between the increased amount of effective water and the decreased positive externality of replenishing the groundwater by increasing the level of on-farm investment. Whether the investment in water conservation is profitable or not depends on the seepage rate on the field, β. The larger the seepage rate, the less profitable on-farm investment in water conservation becomes.

Characteristics of other variables are the same as mentioned in Section 2.2.3. The shadow price of surface water $\lambda_s*(x)$ increases away from the source and switches to the constant shadow price of groundwater $\lambda_g*(x)$ after Xs. As a result, surface water use $q_s*(x)$ decreases away from the source and is replaced by constant groundwater use $q_g*(x)$ after Xs. As mentioned in Section 2.2.3, the effect of an increasing shadow price is offset by the decreasing residual stock of water at location x, and as a result the optimal conveyance expenditure k*(x) decreases away from the source.

Land rents and water rents at x are now expressed with endogenous technology h(I) as a function of on-farm investment, I, in the model with seepage in the canal as follows:

$$R_L(x) = \{pf[(q_s(x)+q_g(x))h(I(x))] - \lambda_s(x)q_s(x)-(w+\lambda_g(x))q_g(x)-I(x)-F\}\alpha \quad (21)$$

$$R_W(x) = [\lambda_s(x)q_s(x)+\lambda_g(x)q_g(x)]\alpha - k(x) \quad (22)$$

and in the model with seepage in the canal *and* on the field as follows:

$$R_L(x) = \{pf[(q_s(x)+q_g(x))h(I)] - [\lambda_s(x)-\lambda_g\beta(1-h(I))]q_s(x) - (w+\lambda_g(x)[1-\beta(1-h(I))])q_g(x) - I - F\}\alpha \quad (23)$$

$$R_W(x) = \{[\lambda_s(x)-\lambda_g\beta(1-h(I))]q_s(x)+\lambda_g(x)[1-\beta(1-h(I))]q_g(x)\}\alpha - k(x) \quad (24)$$

3.2.4 Method of simulation

The basic procedure for simulation of the models with endogenous technology is the same as mentioned in Section 2.4.2. Figure 3.1 illustrates a flow diagram for this algorithm. Subroutines to determine optimal on-farm investment I for surface and groundwater production at each location x were included in the program. Given $\lambda_s(0)$, on-farm investment I(0) for surface water production is computed to satisfy condition (5) and (10) simultaneously (or (14) and (19) simultaneously in the case of a model with seepage in the canal *and* on the field). Similarly, on-farm investment for groundwater production is computed by solving condition (6) and (10) simultaneously for I given the value of λ_g (or (15) and (19) simultaneously in the case of a model with seepage in the canal *and* on the field). The same procedure applies to the model with seepage in the canal *and* on the field to define the optimal on-farm investment. Once I(0) is defined, this yields h(0) and $q_s(0)$ and the simulation cycle continues as previously mentioned in Section 2.4.2.

3.2.5 Results of simulation

Table 3.1 shows the results of simulation with endogenous technology. Let us define ETSC as the model with seepage in the canal and ETSCF as the model with seepage in the canal *and* on the field. With the optimal level of technology; total net benefit, area irrigated, and length of the canal are greater in ETSC and ETSCF than in models with fixed technology (FTSC and FTSCF with I= US\$0.02/m^2 and h=0.9).

Because of the lower initial stock of water and positive externality of additional

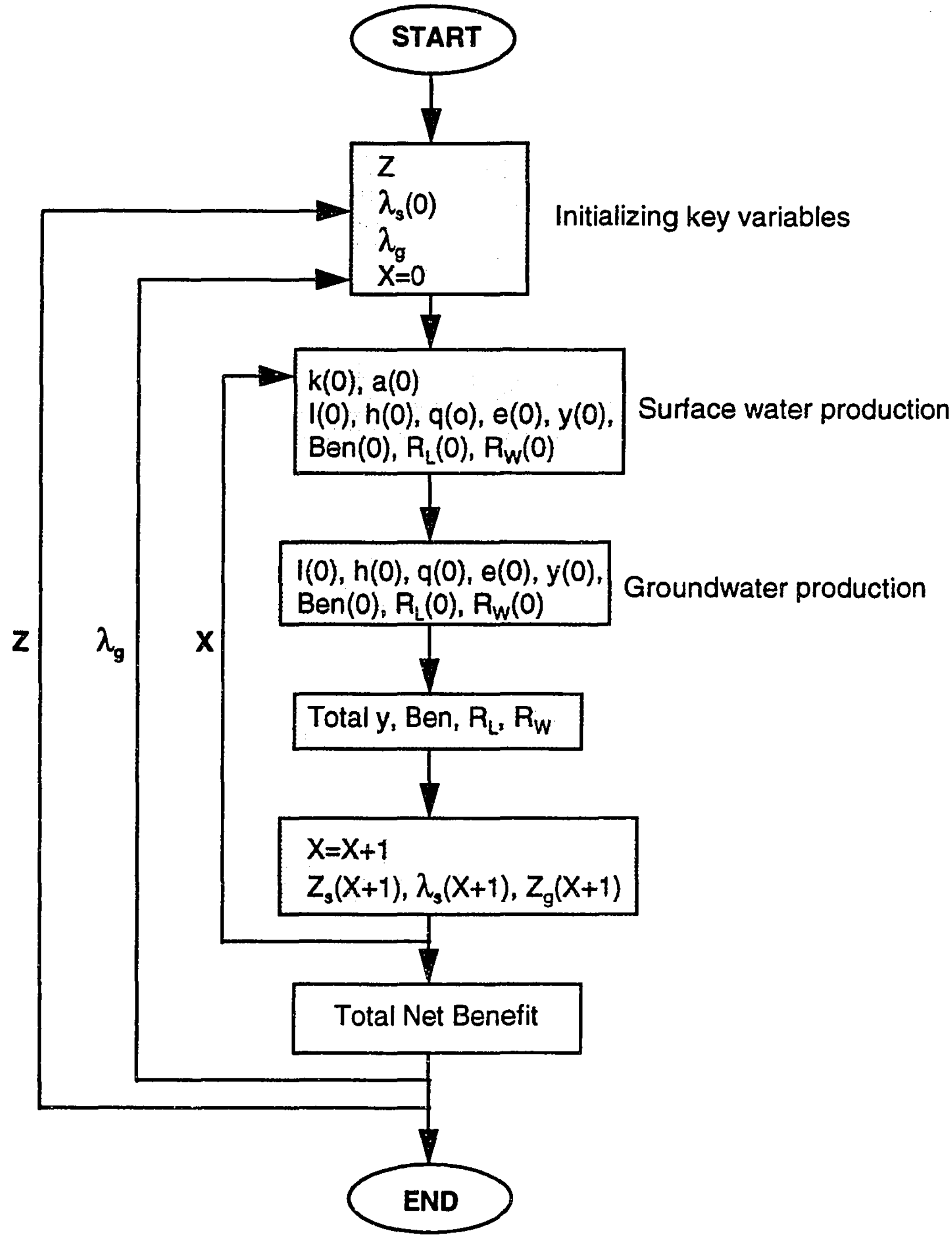


Figure 3.1
Algorithm for Static Conjunctive Water Use Model with Endogenous Technology

Table 3.1
Simulation Results with Endogenous Technology

Parameter	Unit	Model		
		Seepage in the canal (ETSC)	**Seepage in the canal and on the field (ETSCF)**	**Chakravorty et al. (1995)**
Total Net Benefit	(10^8US$)	3.47	3.57	3.34
Area Irrigated	(10^3ha)	500	480	490
Xs	(km)	49	46	49*
X*	(km)	50	48	
Initial Water Stock	($10^8 m^3$)	41	40	41
Aggr. Output	(10^8US$)	13.54	13.04	13.28
Aggr. Net Benefit	(10^8US$)	6.81	6.75	6.68
Aggr. Land Rent	(10^8US$)	.139	.462	.137
Aggr. Water Rent	(10^8US$)	6.67	6.29	6.55
k(0)	(US$/m)	198.94	198.88	199.39
k(Xs)	(US$/m)	151.32	153.47	165.07
a(0)	(10^{-3}/km)	.00112	.00123	.00059
a(Xs)	(10^{-3}/km)	2.3700	2.1651	1.24
$q_s(0)$	(m^3/m^2)	.8354	.8675	.8354
q_g	(m^3/m^2)	.8349	.8670	.8351*
$I_s(0)$	(US$/$m^2$)	.0230	.0190	.023
I_g	(US$/$m^2$)	.0230	.0190	.023*

Table 3.1. (Continued)
Simulation Results with Endogenous Technology

$h_s(0)$	$(US\$/m^2)$	.9221	.8914	.922
h_g	$(US\$/m^2)$	.9221	.8914	.922*
$y_s(0)$	$(US\$/m^2)$	.2656	.2661	.2656
y_g	$(US\$/m^2)$	.2655	.2660	.2655*
Net Benefit (head)	$(US\$/m^2)$	.1336	.1286	
Net Benefit (tail)	$(US\$/m^2)$	.1248	.1198	
$\lambda_s(0)$	$(US\$/m^3)$	.15897	.15518	.1589
$w + \lambda_g$	$(US\$/m^3)$	.15947	.15568	.1593*
λ_g	$(US\$/m^3)$	.14667	.14289	n.a.
$\lambda_s(0) - \lambda_g\beta(1-h)$	$(US\$/m^3)$	n.a	.15053	n.a.
$w + \lambda_g[1-\beta(1-h)]$	$(US\$/m^3)$	n.a	.15103	n.a.
$R_L(0)$	$(10^6 US\$/m^2)$	.2746	.9474	.28
R_{Lg}	$(10^6 US\$/m^2)$	.2328	.9036	.25*
$R_W(0)$	$(10^6 US\$/m^2)$	13.0820	12.8596	
R_{Wg}	$(10^6 US\$/m^2)$	12.2462	11.9846	

Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; In Chakravorty model, * indicates figures at the tail.

seepage on the field, ETSCF starts with a 2.4% lower shadow price of surface water than ETSC and continues with a 2.6% lower shadow price of groundwater. Therefore, water use of both surface and groundwater is 3.8% higher in ETSCF resulting in a 4% lower length of the project area.

The optimal level of on-farm investment, I, is US$0.0230/$m^2$ for the model with seepage in the canal (ETSC) and US$0.0190/$m^2$ for the model with seepage in the canal *and* on the field (ETSCF). The level of technology, h, was 0.9221 for ETSC and 0.8914 for ETSCF. The lower level of I in ETSCF can be explained by the fact that the shadow price and net shadow price of water are lower than in ETSC, and also the positive externality from additional seepage on the field makes on-farm investment in water conservation less profitable. In both cases, there is no significant difference between the head firms and tail firms on the levels of on-farm investment and technology. Compared with models of fixed technology (h=0.9; I=US$0.02/$m^2$), ETSC yields 15% higher on-farm investment and thus 2.5% higher technology than FTSC (see Table 2.1). On the other hand, the level of on-farm investment and technology is lower in ETSCF than in FTSCF.

Conveyance expenditure is slightly higher in ETSC than in ETSCF due to the relative profitability of investment in the canal lining as explained in the fixed technology case in Chapter 2. ETSCF shows land rents 3.4 times higher than ETSC, a difference that is less than the fixed technology case. Due to a 1% lower level of on-farm technology in ETSCF, aggregate land rents are 23.1% lower and water rents are 4.8% higher than in the fixed technology case (FTSCF). The opposite is true for ETSC. The 13% higher land rents and the same water rents are observed due to a higher level of on-farm investment. Spatial inequity, i.e., disparity of land rents between head firms and tail firms in the project area, decreased from 18% in ETSC to 4.8% in ETSCF when seepage occurs from the field.

Chakravorty et al. (1995) examine the case of surface water allocation with endogenous technology but without the availability of groundwater (see Table 3.1). Compared to their model, our model (ETSC) results in a greater total net benefit, area irrigated, and aggregate output with the same canal length and initial stock of water. The difference between the results of the Chakravorty model and ETSC is marginal due to the small amount of seepage from the canal. Therefore, when the amount of seepage is small, the surface water model is a good approximation of the conjunctive use model. However, when the amount of seepage is large, as in the case of ETSCF, the model indicated a 6.9% larger net benefit, 2.4% smaller initial stock of water and 2% smaller area irrigated, shorter canal length, and greater water use throughout the project area primarily due to the smaller shadow price of surface and groundwater.

Also, conveyance expenditure in conjunctive use models is less (.23% less in ETSC and .24% less in ETSCF) than in the Chakravorty model. This result may provide the reason why investment in conveyance expenditure is not preferred when groundwater is available. Additional resource availability makes the shadow price of water smaller and investment in conveyance expenditure less profitable. More than three times larger land rents accrued to ETSCF compared with the Chakravorty model. Therefore, the optimal allocation of water is likely to change depending on the magnitude of additional water available for production.

The utility can determine the conjunctive water allocation by observing canal irrigation only so far as the amount of seepage from the canal is small. However, when the amount of seepage is large, the utility needs to take into account the effects of this positive externality on the optimal shadow prices of water resources for efficient water allocation.

3.3 Endogenous Crop Choice

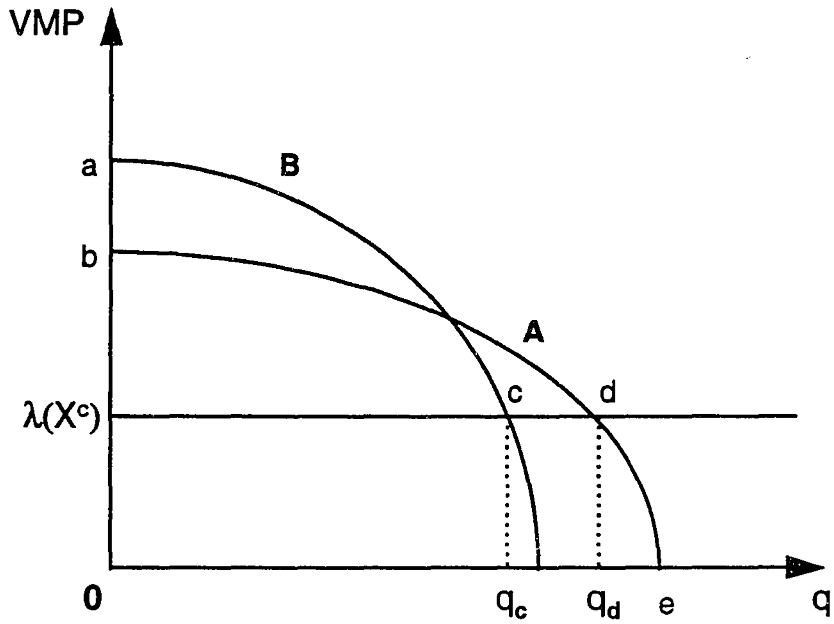
Variations in the cropping pattern are generally considered the result of land quality at the production site (Lichtenberg, 1989) or increasing scarcity and price of water resources (Kim et al., 1989). However, when two marginal value product functions intersect, even without a difference in land quality, switching from one crop to another is possible due to the spatially differentiated shadow price of water. This section will illustrate how the switching of cropping patterns occurs under the condition of homogeneous land quality. The purpose is solely to provide analytical results, thus an actual simulation for a two-crop case is not implemented.

First, specification of the problem is explained with particular attention to the shape of the marginal value product function. Second, the optimization problem and necessary condition for the case of two crops are considered. The last part discusses under which conditions switching occurs and tries to provide implications for how the results are affected by exogenous parameter changes such as output price and heterogeneous land quality.

3.3.1 Specification of the problem

In this section, the assumption of monocropping is altered to multicropping. Now firms choose an appropriate crop in order to maximize net benefit from production. Assume that two kinds of crops are available for firms to choose. Crop A is water intensive such as sorghum, corn, or soybeans; and crop B is less water intensive relative to crop A, such as oats, or barley. Let us denote the revenue function of crop A, p_Af_A, and that of crop B, p_Bf_B, where p_A and p_B are output price, f_A and f_B are productions function for crop A and crop B, respectively. It is assumed that the marginal value product functions for crop A and crop B intersect as depicted in Figure 3.2. It is crucial to have such an intersection of the marginal value product functions if switching is to occur. The reason for this assumption is as follows: If there is no intersection of the two marginal value product functions and one dominates the other, then the crop with the dominating marginal value product function has the higher net revenue throughout the feasible level of water use and switching to the other crop never occurs.

Except for this multi-cropping assumption, other specifications are the same as mentioned in Section 2.2. Exogenous technology and homogeneous land quality are assumed.



A: water intensive crop

B: less water intensive crop

$\lambda(X^c)$ **: critical shadow price**

Figure 3.2
Optimal Marginal Value Product Schedule:
Two-crop Case

3.3.2 The optimal model with endogenous crop choice

The utility is assumed to choose $q_s(x)$, $q_g(x)$, $k(x)$, X, the end point of the project area, and pf(•), the optimal revenue function for the two crops, so as to maximize net benefit from the water project. In the case of the model with seepage in the canal, the optimization problem is defined by:

$$\underset{q_s,\, q_g,\, k,\, X^*}{\text{maximize}}\ NB(z_s(0)) = \int_0^{X^*} \{[pf[(q_s+q_g)h(I)] - I - F - wq_g]\alpha - k\}dx \tag{25}$$

subject to two state constraints:

$$z_s'(x) = -\,q_s(x)\alpha - a(x)z_s(x) \tag{26}$$

$$z_g'(x) = \beta a(x)z_s(x) - q_g(x)\alpha \tag{27}$$

The Hamiltonian of this problem is defined as follows, with $z_s(x)$ and $z_g(x)$ as state variables and $q_s(x)$, $q_g(x)$, $k(x)$ as control variables.

$$H\ (q_s, q_g, k, \lambda_s, \lambda_g) = [pf[(q_s+q_g)h] - I - F - wq_g]\alpha - k$$
$$- \lambda_s\ [q_s\alpha + az_s] + \lambda_g\ [\beta az_s - q_g\alpha] \tag{28}$$

Let q_s^*, q_g^*, k^*, z_s^*, z_g^*, and X^* denote the corresponding optimal values for this optimization problem. There is again the possibility of a corner solution. Assuming that the sufficiency conditions are met, the necessary conditions for optimality are given with the transversality condition as follows:

$$pf'h \leq \lambda_s$$

$$pf'h = p_A f'_A h \quad \text{if} \quad \lambda_s \leq \lambda(X^c)$$

$$pf'h = p_B f'_B h \quad \text{if} \quad \lambda_s \geq \lambda(X^c) \tag{29}$$

$$pf'h \leq w + \lambda_g$$

$$pf'h = p_A f'_A h \quad \text{if} \quad w + \lambda_g \leq \lambda(X^c)$$

$$pf'h = p_B f'_B h \quad \text{if} \quad w + \lambda_g \geq \lambda(X^c) \tag{30}$$

$$\lambda_s' = a(\lambda_s - \beta\lambda_g) \tag{31}$$

$$\lambda_g' = 0 \tag{32}$$

$$(\lambda_s - \beta\lambda_g)z_s m'(k) \leq 1 \tag{33}$$

$$[H\,(q_s, q_g, k, \lambda_s, \lambda_g)]_{x=X^*} = 0 \tag{34}$$

where $\lambda(X^c)$ is the critical shadow price for which the net revenue, i.e., revenue minus the cost of water for both crop A (area $bd\lambda(X^c)$ in Figure 3.2) and crop B (area $ac\lambda(X^c)$ in Figure 3.2) are exactly equal. Thus X^c indicates distance from the source of canal where a switching from one crop to another occurs.

Figure 3.2 illustrates the optimal marginal value product schedule for the two-crop case. As mentioned before, crop A is more water intensive than crop B. When the shadow price is lower than $\lambda(X^c)$, firms produce crop A because the net revenue of crop A is greater than crop B. When the shadow price is higher than $\lambda(X^c)$, the net revenue of crop B dominates over that of crop A. Thereby, it is more profitable to produce crop B. In this case, the optimal marginal value product function is a combination of the two marginal product functions represented by line segments e-d and c-a in Figure 3.2. There is a discontinuity between points d and c. Therefore, the necessary conditions (29) and (30) require the optimal marginal value product schedule to determine the optimal water use for a given shadow price of water. Condition (29) states that when the shadow price of surface water is less than the critical shadow price, $\lambda(X^c)$, the shadow price of surface water is equal to or greater than the marginal value product function, $p_A f'_A h$. Also, when the shadow price of surface water is greater than $\lambda(X^c)$, the shadow price of surface water is equal to or greater than the marginal value product function, $p_B f'_B h$. A similar explanation applies to condition (30).

3.3.3 Characterization of the optimal path for each variable

As mentioned previously in Sections 2.2.3, 2.3.3, and 3.2.3, the shadow price of water increases away from the source. An increasing shadow price for surface and groundwater will switch production from the water intensive crop A to the less water intensive crop B at the critical shadow price $\lambda(X^c)$. The water use at this point jumps from q_d to q_c as depicted in Figure 3.2. However, whether switching from crop A to crop B really occurs depends on the critical shadow price of each marginal value product function for which land rents are zero. Let us denote the critical shadow price of water for crop A production for which land rents are zero, λ_{Ac}, and the critical shadow price of water for crop B production, λ_{Bc}. Three cases can be considered depending on the relative value of the three critical shadow prices.

Case 1: $\lambda(X^c) \leq \lambda_{Bc} \leq \lambda_{Ac}$; $\lambda(X^c) \leq \lambda_{Ac} \leq \lambda_{Bc}$

When the critical shadow prices of water for crops A and B are greater than the critical shadow price for the optimal marginal product function, a switch occurs when the shadow price of water reaches $\lambda(X^c)$.

Case 2: $\lambda_{Ac} \leq \lambda(X^c) \leq \lambda_{Bc}$; $\lambda_{Ac} \leq \lambda_{Bc} \leq \lambda(X^c)$

When λ_{Ac} is lower than $\lambda(X^c)$, a switch to crop B occurs at λ_{Ac} before reaching $\lambda(X^c)$. Because land rents for crop A production become zero beyond this point, producing crop A is no longer profitable. Firms have to shift to crop B at λ_{Ac}.

Case 3: $\lambda_{Bc} \leq \lambda(X^c) \leq \lambda_{Ac}$; $\lambda_{Bc} \leq \lambda_{Ac} \leq \lambda(X^c)$

When λ_{Bc} is less than $\lambda(X^c)$, switching never occurs because at $\lambda(X^c)$ producing crop B generates negative land rents.

Figure 3.3 shows the optimal spatial distribution of shadow price, surface and groundwater use, and land rents for Case 1. Thus, it is assumed that λ_{Ac} and λ_{Bc} are greater than $\lambda(X^c)$ and the optimal supply price of ground water, $w + \lambda_g$, is higher than $\lambda(X^c)$ so that switching occurs before Xs during surface water production. Discontinuity in the $q_s^*(x)$ and $R_L^*(x)$ functions is due to the shift in the marginal value product schedule for two crops.

It is interesting to examine how output price or land quality affect the optimal

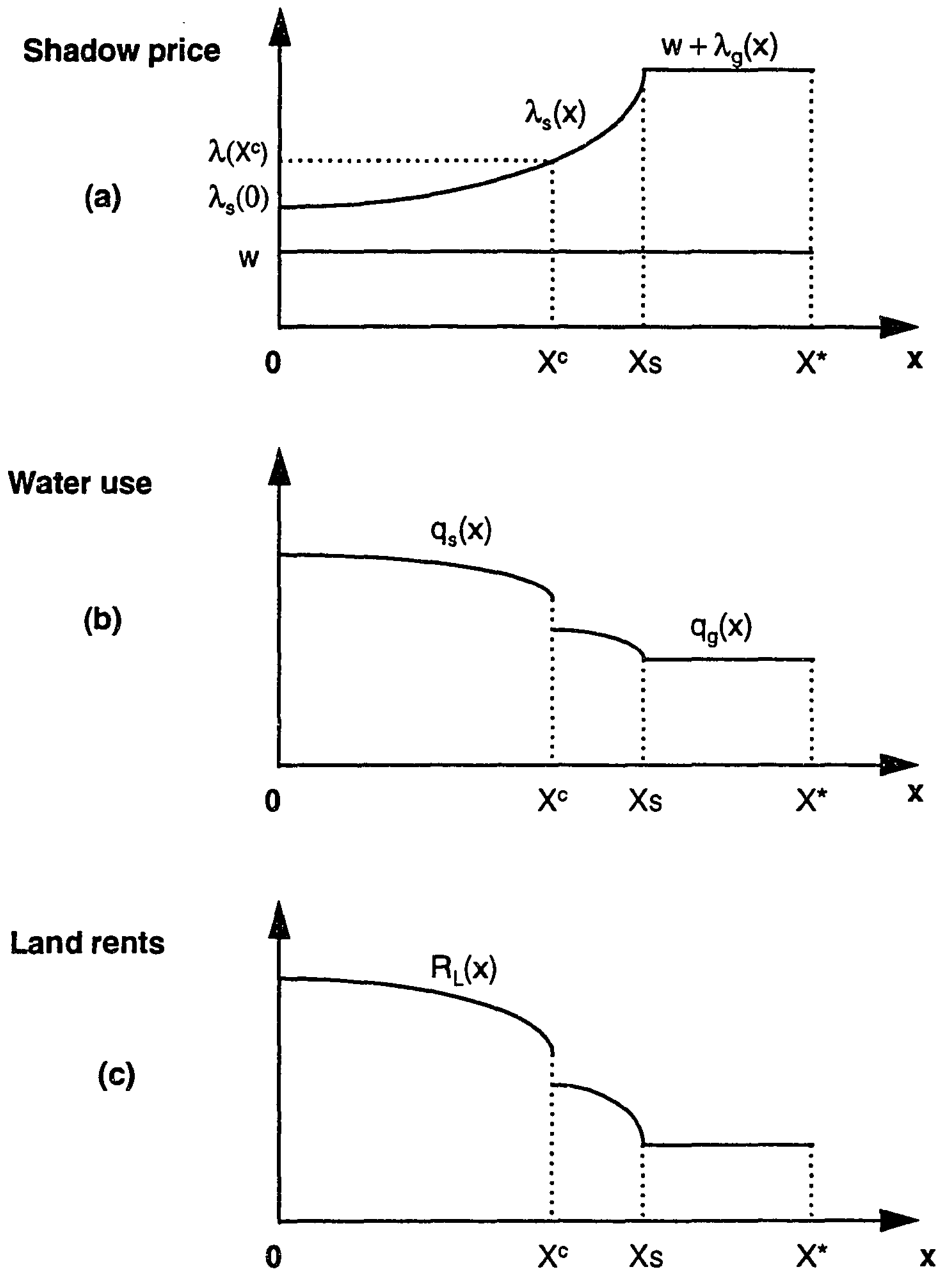


Figure 3.3
Spatial Distribution of Shadow Price, Water Use and Land Rents: Two-crop Case

choice of crop. For example, the increase in output price of crop A shifts the marginal value product function outward, i.e., the point e remains the same and the point b in Figure 3.2. shifts up. Thus the critical shadow price $\lambda(X^c)$ becomes larger in this case. In the opposite case, when output price of crop B increases, $\lambda(X^c)$ becomes smaller. Similarly, the effect of land quality on crop choice depends on the magnitude of shift in the marginal value product function and the point of the critical shadow price $\lambda(X^c)$.

3.4 Conclusion

This chapter extends the static base model of Chapter 2 by incorporating endogenous on-farm investment. Simulations were run for both models -- seepage in the canal, and seepage in the canal *and* on the field. Also, endogenous crop choice for the two crop case was discussed under homogeneous land quality and the spatially increasing shadow prices of water.

When technology is endogenous, on-farm investment in water conservation is 17% less in the model with seepage in the canal *and* on the field than in the model with seepage only in the canal due to the positive externality of additional seepage. In our models, there was no significant difference between the head firms and tail firms on the levels of on-farm investment. Land rents which accrued to firms in the case of seepage in the canal *and* on the field were more than three times larger than in the model with seepage in the canal and the model of surface water studied by Chakravorty et al. (1995). When the amount of seepage and thus groundwater stock is small, a surface water model could be a good approximation for conjunctive use models. In particular, smaller conveyance expenditure in the conjunctive use model compared to the surface water model suggests that investment in conveyance expenditure is not preferred when groundwater is available because additional resource availability makes the shadow price of water smaller and investment in conveyance expenditure less profitable.

Under homogeneous land quality and a spatially increasing shadow price of surface water, production of a water intensive crop changes to a less water intensive crop at the critical shadow price where the net revenue of the two crops are equal. Discontinuity of water use and land rents are observed at the switching point. When this switching occurs and how it is affected by exogenous parameter changes such as an output price change or heterogeneous land quality depend on the shapes of the optimal marginal value product functions for the two crops and the critical shadow prices of both production regimes when land rents are zero. Variations in the cropping pattern have been explained by land quality. However, these results suggest that even without differences in land quality, the cropping pattern theoretically shifts from water intensive crop to less water intensive crop when shadow prices are spatially increasing.

CHAPTER 4

VARIATIONS OF THE OPTIMAL MODEL: HETEROGENEOUS LAND QUALITY, EXOGENOUS PARAMETER CHANGES AND SUBOPTIMAL WATER PRICING

4.1 Introduction

One of the important exogenous factors which affects production patterns and technological choice is the quality of land. Land quality is most likely to affect productivity through fertility and the ability to maintain moisture and nutrients in the soil. Changes in output price and pumping cost also alter water use for production and thus optimal allocation of water. A high output price and low pumping cost tend to accelerate water use and depletion of groundwater resources. Depletion of the groundwater stock causes a decline of water levels and imposes to firms pumping cost externalities, i.e., a higher pumping cost. Decision making by firms is the product of multiple effects of those factors. Also, suboptimal water pricing regimes hinder the efficient allocation of water resources.

In this chapter, we consider the effects of heterogeneous land quality, changes in exogenous parameters, and suboptimal water pricing on the optimal allocation of conjunctive water use. Two base models introduced in Chapter 3, seepage in the canal or ETSC, and seepage in the canal *and* on the field or ETSCF, with endogenous technology are applied in various scenarios. Section 2 focuses on the case in which land quality is heterogeneous in the project area. Sections 3 and 4 deal with exogenous parameter changes. Section 3 shows how changes in output price affect the optimal water allocation path and the choice of technology. Section 4 similarly considers the effect of a pumping cost increase on the choice of technology. Sections 5 and 6 are concerned with suboptimal water pricing. Section 5 simulates the case when the utility charges firms a fixed price for groundwater. Section 6 shows a case when the utility charges a uniform price for water based on the marginal cost of generating water at source. Section 7 concludes the chapter.

4.2 Heterogeneous Land Quality

Land quality consists of some attributes which enhance productivity such as fertility, water-holding capacity, topography and depth of topsoil (Lichtenberg, 1989). In particular, water capacity of the topsoil is considered the best measure of soil productivity. The effect of land quality on the choice of technology and cropping pattern has been studied by numerous authors. For example, Negri and Brooks (1990) find that land with low water-holding capacity increases the likelihood of adopting sprinkler irrigation, and soil characteristics tend to dominate probabilities of selecting modern technology. Also Lichtenberg (1989) concludes in his study of the northern High Plains that land quality is one of the principal determinants of cropping patterns in the absence of irrigation, and irrigation technology alleviates a soil productivity differential. They conclude that water sensitive crops (corn, soybeans) dominate in high quality land, and less water sensitive crops (oats, barley, rye and hay) dominate in low quality land. However, the effect of heterogeneous land quality on the choice of technology with a spatial externality has not been addressed in the conjunctive use scenario.

In this section, heterogeneous land quality is introduced to the optimal model with endogenous technology of Section 3.2 to consider the effect of land quality on the allocation of water resources as well as on the choice of technology. Some policy implications follow.

4.2.1 Specification of the problem

Poor land quality is considered to decrease soil permeability, thereby affecting productivity through changes in (i) the production function, (ii) water efficiency, and (iii) the amount of seepage on the field. High quality land shifts out both the production function and water efficiency function (or water conservation parameter) and decreases the seepage rate on the field. This section considers only the first case in which land quality affects the production function. Thus, in high quality land, the same level of output is attainable with less water. Land quality is spatially heterogeneous along the canal and to the tail of the project area. Fertile lands are assumed to be concentrated at the head of the canal and land quality declines towards the tail of the project area. This is based on the observation that powerful landowners are often located at the head of water distribution systems (Repetto, 1986). Except for endogenous technology and heterogeneous land quality, the same specifications described in Sections 2.2 and 2.3

apply to this case. Both cases, seepage in the canal and seepage in the canal *and* on the field are considered.

4.2.2 Method of simulation

In order to accommodate heterogeneous land quality, the production function is multiplied by the following shift parameter assuming the highest quality soil at the head is 20% more productive than the worst soil at the tail:

$$\gamma(x) = 1.2 - 7.27*10^{-3}x + 6.61*10^{-5}x^2 \qquad (1)$$

This shift parameter for the production function, $\gamma(x)$, is a convex function of distance from the source, x, so that $\gamma' < 0$ and $\gamma'' > 0$. This shift parameter increases the production function by 1.2 times at the head of the canal and gradually decreases to 1, thus providing no change in the production function at 55 km from the source. This shift parameter not only appears in the revenue function but also in the first order conditions of the optimization problem on which this simulation model is based. Those necessary changes were made for equations in the simulation model. The method of simulation is the same as the model for endogenous technology in Section 3.2.4.

4.2.3 Results of simulation

Table 4.1 and Table 4.2 show the results of simulation models with heterogeneous

Table 4.1
Heterogeneous Land Quality: Seepage in the Canal
(Fertile Land at the Head; Endogenous Technology)

Parameter	Unit	Model	
		Base (ETSC)	**Heterogeneous land quality† (HPETSC)**
Total Net Benefit	(10^8US$)	3.47	4.45
Area Irrigated	(10^3ha)	500	490
Xs	(km)	49	48
X*	(km)	50	49
Initial Water Stock	(10^8m^3)	41	41
Aggr. Output	(10^8US$)	13.54	14.36
Aggr. Net Benefit	(10^8US$)	6.81	7.79
Aggr. Land Rent	(10^8US$)	.139	1.14
Aggr. Water Rent	(10^8US$)	6.67	6.65
k(0)	(US$/m)	198.94	198.94
k(Xs)	(US$/m)	151.32	158.93
a(0)	(10^{-3}/km)	.00112	.00112
a(Xs)	(10^{-3}/km)	2.3700	1.6870
$q_s(0)$	(m^3/m^2)	.8354	.8641
q_g	(m^3/m^2)	.8349	.8388
$I_s(0)$	(US$/$m^2$)	.0230	.0225
I_g	(US$/$m^2$)	.0230	.0223

Table 4.1. (Continued)
Heterogeneous Land Quality: Seepage in the Canal
(Fertile Land at the Head; Endogenous Technology)

$h_s(0)$	(US$/m²)	.9221	.9188
h_g	(US$/m²)	.9221	.9175
$y_s(0)$	(US$/m²)	.2656	.3231
y_g	(US$/m²)	.2655	.2611
Net Benefit (head)	(US$/m²)	.1336	.1917
Net Benefit (tail)	(US$/m²)	.1248	.1260
$\lambda_s(0)$	(US$/m³)	.15897	.15897
$w + \lambda_g$	(US$/m³)	.15947	.15937
λ_g	(US$/m³)	.14667	.14657
$R_L(0)$	(10^6US$/m²)	.2746	5.6288
R_{Lg}	(10^6US$/m²)	.2328	.3102
$R_W(0)$	(10^6US$/m²)	13.0820	13.5371
R_{Wg}	(10^6US$/m²)	12.2462	12.2948

Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; although it is not clear from the table, at each point of x the level of conveyance expenditure is the lower and the canal loss is the higher in HPETSC.

† shift parameter for production function: $\gamma(x) = 1.2 - 7.27*10^{-3}x + 6.61*10^{-5}x^2$

Table 4.2
Heterogeneous Land Quality:
Seepage in the Canal and on the Field
(Fertile Land at the Head; Endogenous Technology)

Parameter	Unit	Model	
		Base (ETSCF)	**Heterogeneous production function**† (HPETSCF)
Total Net Benefit	(10^8US$)	3.57	4.57
Area Irrigated	(10^3ha)	480	460
Xs	(km)	46	44
X*	(km)	48	46
Initial Water Stock	(10^8m^3)	40	39
Aggr. Output	(10^8US$)	13.04	13.61
Aggr. Net Benefit	(10^8US$)	6.75	7.60
Aggr. Land Rent	(10^8US$)	.462	1.597
Aggr. Water Rent	(10^8US$)	6.29	6.00
k(0)	(US$/m)	198.88	198.81
k(Xs)	(US$/m)	153.47	147.45
a(0)	(10^{-3}/km)	.00123	.00141
a(Xs)	(10^{-3}/km)	2.1651	2.7613
$q_s(0)$	(m^3/m^2)	.8675	.8989 .8754*
q_g	(m^3/m^2)	.8670	.8660 .8658*
$I_s(0)$	(US$/$m^2$)	.0190	.0188 .0185*
I_g	(US$/$m^2$)	.0190	.0190

Table 4.2. (Continued)
Heterogeneous Land Quality:
Seepage in the Canal and on the Field
(Fertile Land at the Head; Endogenous Technology)

$h_s(0)$	(US$/m^2)	.8914	.8896 .8868*
h_g	(US$/m^2)	.8914	.8914
$y_s(0)$	(US$/m^2)	.2661	.3241
y_g	(US$/m^2)	.2660	.2676
Net Benefit (head)	(US$/m^2)	.1286	.1963
Net Benefit (tail)	(US$/m^2)	.1198	.1302
$\lambda_s(0)$	(US$/m^3)	.15518	.15140
$w + \lambda_g$	(US$/m^3)	.15568	.15770
λ_g	(US$/m^3)	.14289	.14490
$\lambda_s(0) - \lambda_g\beta(1-h)$	(US$/m^3)	.15053	.14660 (.14650)
$w + \lambda_g[1-\beta(1-h)]$	(US$/m^3)	.15103	.15298 .15278*
$R_L(0)$	(10^6US$/m^2)	.9474	6.6536 1.4568*
R_{Lg}	(10^6US$/m^2)	.9036	.9133 .8800*
$R_W(0)$	(10^6US$/m^2)	12.8596	12.9791 12.8690*
R_{Wg}	(10^6US$/m^2)	11.9846	12.1395 12.1367*

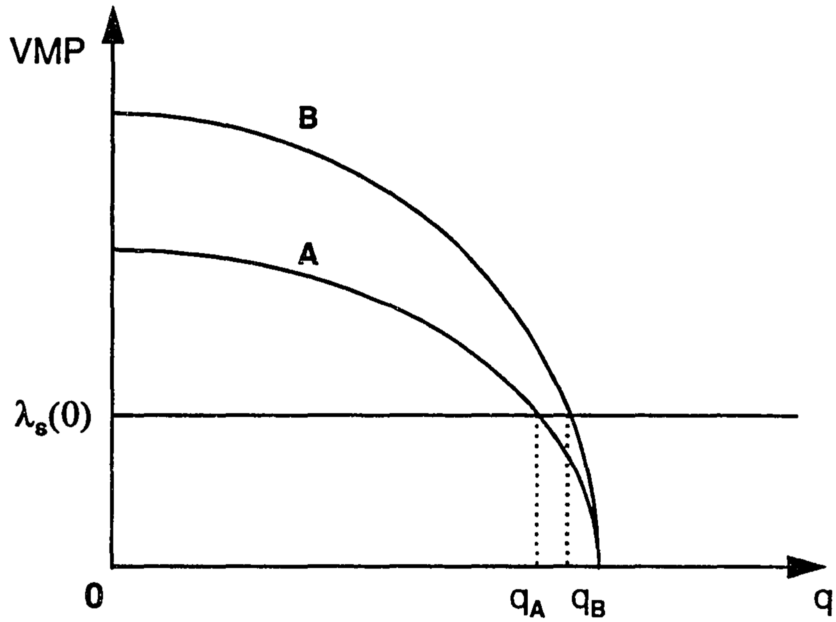
Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; * indicates figures at the tail; ( ) indicates lowest figures.

† shift parameter for production function: $\gamma(x) = 1.2 - 7.27*10^{-3}x + 6.61*10^{-5}x^2$

land quality for seepage in the canal (HPETSC) and seepage in the canal *and* on the field (HPETSCF), respectively.

In the case of HPETSC, total net benefit is 28% higher than the base model (ETSC) as expected due to the shift parameter of the production function. HPETSC has the same optimal initial stock of water, 41×10^8 m^3 and 2% less canal length and irrigated area compared to the base model, ETSC. Figure 4.1 shows the marginal value product function and the determination of optimal water use with heterogeneous land quality. A shift parameter for the production function γ is equal to 1.2 at the source, $x = 0$. This parameter shifts up the production function by 1.2 times at the source and also the marginal value product function by the same magnitude. As a result, the marginal value product function, A, for the base case proportionately moves upward to the function B. Given the same level of initial stock of water at the source and thereby the same shadow price of the initial surface water, the optimal water use with heterogeneous land quality is larger than the optimal water use for the base case. At the tail, the marginal value product function B converges to A.

As depicted in Figure 4.1, optimal water use at the source for HPETSC is higher than that of ETSC, the base case. Because of the same shadow price of surface water at the source, conveyance expenditure starts from the same level for both ETSC and HPETSC. Also, because of higher water use at the source for HPETSC, the residual stock of water decreases faster in HPETSC. The optimal conveyance expenditure is determined by the two interactive effects -- the increasing net shadow price of water, $\lambda_s - \beta\lambda_g$, and the decreasing residual stock of water, z_s. In this case, the increasing force



A: base $VMP_A = pf'$

B: heterogeneous land quality $VMP_B = \gamma(0)pf'$

$\lambda_s(0)$: shadow price of surface water at the head of canal

Figure 4.1
Marginal Value Product and Optimal Water Use with Heterogeneous Land Quality
(Head of the canal; $\gamma(0) = 1.2$)

of shadow price overwhelms the force of decreasing residual stock, and as a result, the level of conveyance expenditure is lower at each point in HPETSC. The production function which yields higher output with the same amount of water makes conveyance expenditure less profitable.

The optimal on-farm investment for water conservation spatially decreases from US\$0.0225/m^2 at the head to US\$0.0223/m^2 at the tail of the project area, which is less than the base level, US\$0.0230/m^2. As a result, water efficiency also spatially decreases from 0.9188 to 0.9175. Although it is not verified clearly by the simulation results of the base models; theoretically, on-farm investment in water conservation increases away from the source due to increasing shadow price and thus increasing scarcity of water resources towards the tail. In HPETSC, higher water use and output levels make it optimal to invest less in water conservation compared to the base case. On-farm investment declines towards the end of the project area due to an offsetting of two forces. An increasing shadow price which tends to increase on-farm investment is offset by higher and decreasing water use, resulting in decreasing on-farm investment.

Higher land rents, about 20 times the rents of the base model (ETSC), accrue to the head firm in HPETSC primarily due to a 21.6% higher output in the fertile land and low level of on-farm investment in water conservation at the head of the project area compared to the base model. Heterogeneous land quality with fertile land at the head creates a large disparity of land rents between head firms and tail firms. The disparity of land rents between head and tail is 1954% with fertile land at the head, while it is only 18% for the base model. Water rents are also slightly higher in HPETSC due to higher conveyance expenditure and lower shadow price but remained at the same level as the base case.

In the case of HPETSCF (Table 4.2) with additional seepage from the field, total net benefit and land rents are higher by 28% and 246% respectively, and the initial stock of water, length of canal, and area irrigated are less than the base case, ETSCF by 2.5%, 4.3%, and 4.2%, respectively. Heterogeneous land quality generates some irregular patterns on the net shadow price and thus on optimal water use. Figure 4.2 shows the spatial distribution of shadow price, water use, and land rents with heterogeneous land quality. In the model for seepage in the canal *and* on the field, the net shadow price over which firms optimize their production is now a function of the water efficiency parameter, h, and therefore a function of on-farm investment, I. Higher land quality makes it optimal to use more water at the head of the canal but conveyance expenditure and on-farm investment are generally lower than the base model due to the previously mentioned reason.

Relatively high initial on-farm investment and thus high water efficiency at the head offsets the increasing force of shadow price of the surface water due to seepage from the canal. As a result, net shadow price initially decreases away from the source until the land quality declines and the increasing force of the shadow price dominates at the tail of the canal (see panel (a) in Figure 4.2). A high shadow price of groundwater also has the effect of shifting the net shadow price of water further down and decreases the change in shadow price of surface water from equation (16) in Chapter 3, which is the result of the conjunctive use model. Therefore, in this case a higher shadow price of

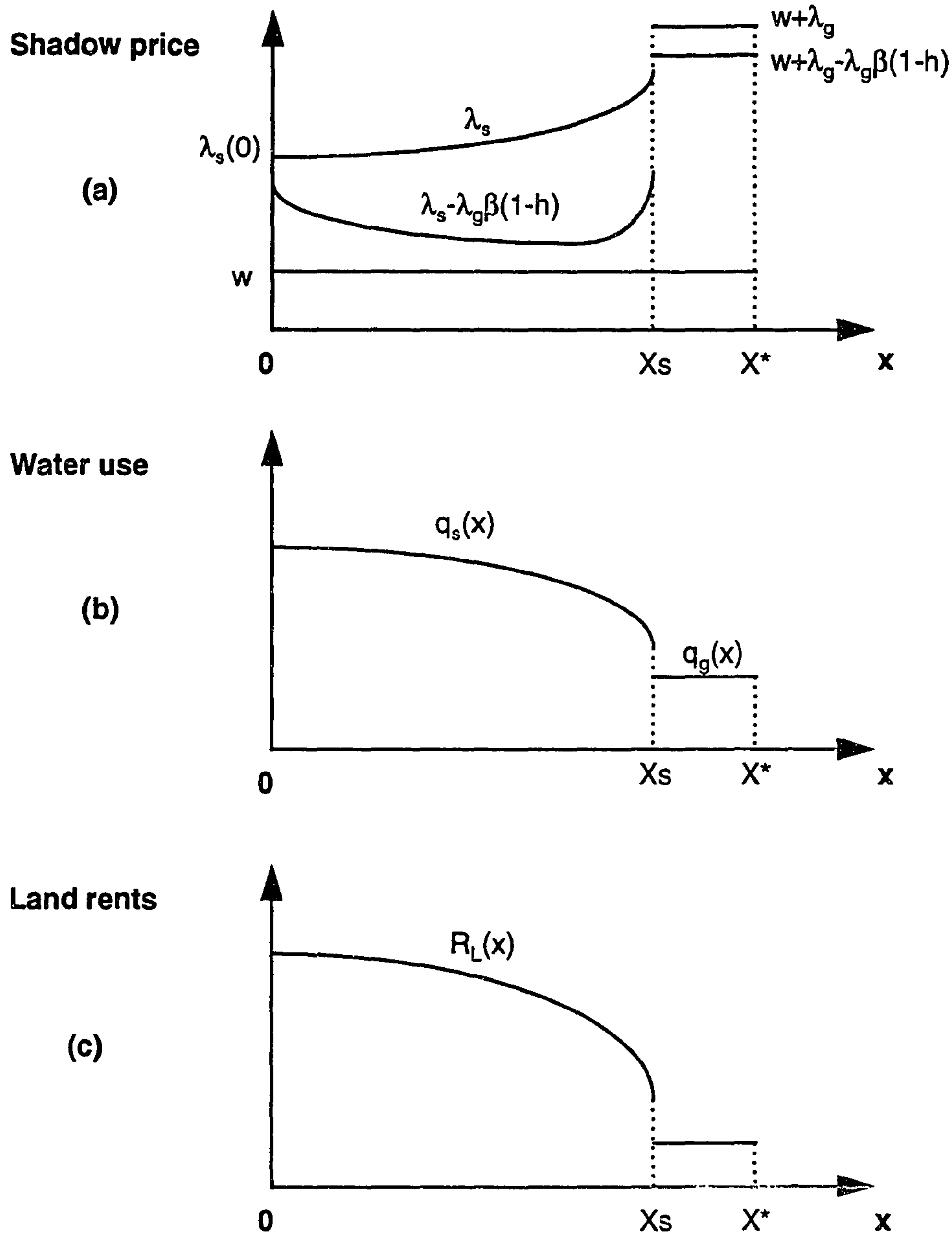


Figure 4.2
Spatial Distribution of Shadow Price, Water Use and Land Rents with Heterogeneous Land Quality
(Seepage in the Canal and on the Field; Fertile Land at the Head)

groundwater will lower the net shadow price of water and increase total net benefit. This is a counter intuitive result compared to the previous models which resulted in lower net benefit with a higher shadow price of groundwater. The resulting optimal path of shadow price of water in HPETSCF shows discontinuity at the switching point jumping from surface water to groundwater as illustrated in panel (a) in Figure 4.2. At the switching point, Xs, the residual stock of surface water is exhausted and replaced by the groundwater stock.

Because of this discontinuity of shadow price and net shadow price, optimal water use and land rents also jump down at the switching point as shown in panel (b) and (c) in Figure 4.2. Water use and land rents decrease away from the source of the canal until Xs and shift down due to a jump in the shadow price of groundwater.

The results of simulation with heterogeneous land quality when fertile land is at the head of the project area can be summarized as follows:

1) Heterogeneous land quality (higher land quality at the head) yields a 28% higher total net benefit than the base models.

2) For both models, HPETSC and HPETSCF, area irrigated, length of canal and project area shrink due to lower shadow price and higher use of surface water compared to the base models.

3) Conveyance expenditure and on-farm investment are less with heterogeneous land quality. On-farm investment decreases away from the source in HPETSC and jumps up for groundwater use at the tail in HPETSCF. A higher level of the production function due to better land quality makes these investments less profitable.

4) Higher land rents accrue to HPETSC and HPETSCF due to high output at the head generating a large disparity, 1954% in HPETSC, between head firms and tail firms.

5) In HPETSCF, high water efficiency on high quality land causes the net shadow price of surface water to initially decrease away from the source and increase at the tail. Shadow price and net shadow price generate discontinuity at the switching point from surface water use to groundwater use.

4.2.4 The effect of heterogeneous land quality on the choice of technology

The results suggest that firms invest less in water conservation when facing better land quality and a higher land quality lowers the level of on-farm investment, which is basically consistent with the observations made by Caswell and Zilberman (1986) and Negri and Brooks (1990). As shown above, the difference in land quality is immediately reflected in the difference in land rents at each location. Especially fertile land at the head of canal accelerates disparity between head firms and tail firms. This suggests that if the land quality deteriorates at the tail of the project area, low quality land may be left out from the water project in the long run. In order to alleviate the disparity, the government may have to subsidize tail firms to improve land quality or water efficiency.

One important aspect of land quality is water-holding capacity which directly influences seepage rate on the field. In our model, seepage rate is fixed and it does not vary with land quality. The model can be extended to allow less seepage in high quality land (or more seepage in low quality land). Heterogeneous land quality when fertile land is at the tail of the project area is not considered. It is expected that when fertile land is concentrated at the tail, the optimal level of on-farm investment and water use may be higher at the tail, thus lowering the shadow price at the tail and further diverging net shadow price of surface and groundwater at the switching point, Xs. The effect of heterogeneous land quality on the endogenous crop choice is also an interesting topic but not studied here.

4.3 Change in Output Price

A high output price tends to induce a higher level of optimal water use in order to increase production. The increased irrigated acreage and the use of groundwater in the western United States were largely accelerated by higher commodity prices (Adams et al., 1988). During 1987 and 1990, annual average farm prices of cotton varied about 20 per cent from the lowest year to the highest year in the United States (U.S. Department of Commerce, 1992). In this section, output price of the base model is altered to simulate the effect of output price on the optimal allocation of water and technology choice.

4.3.1 Specification of the problem and method of simulation

In both base cases, ETSC and ETSCF, the output price of cotton, US$0.75 per lb. (Zilberman et al, 1994), is increased by 1.2 and 1.5 times using a constant shift parameter, γ. These shift parameters have an effect on the revenue function exactly similar to the effect of heterogeneous land quality except that γ is constant throughout the project area. Therefore, the effect of an output price change on the marginal value product function is the same as depicted in Figure 4.1, and the constant shift continues in this case until the end of the project area. Necessary adjustments of equations for the simulation program were made with a shift parameter of output price.

4.3.2 Results of simulation

Table 4.3 and Table 4.4 show the results of simulation with higher output prices for the two base models, ETSC and ETSCF. Total net benefit is quite sensitive to the output price increase in both models.

In ETSC, total net benefit increases from 3.47 to 6.05 and 9.95 (100 million US$), representing 74% and 187% increases, when output price increases 1.2 and 1.5 times, respectively. The length of the canal also shrinks from 49 km to 46 km and the end of the project area from 50 km to 47 km as output price increases by 1.5 times. There is no effect of output price on the level of initial stock of water when seepage occurs only from the canal.

In the model with a 1.5 times higher output price, the shrinking of canal length by 6.1% is due to higher water use throughout the project area compared to the base case. As a result, aggregate output, net benefit and land rents also increase by 44.9%, 95%, and 4684% respectively, as output price increases. Conveyance expenditure and on-farm investment is smaller than the base case for the same reason as explained in the case of heterogeneous land quality. At each point x, the model with $\gamma = 1.5$ has less conveyance expenditure and a higher loss rate of the three models in Table 4.3. Higher water use and output level make it less profitable to invest in conveyance and water conservation. An

Table 4.3
Change in Output Price: Seepage in the Canal
(Endogenous Technology)

Parameter	Unit		Model	
		Base	**$\gamma = 1.2$**	**$\gamma = 1.5$**
		(ETSC)	**(ETSC)**	**(ETSC)**
Total Net Benefit	(10^8US$)	3.47	6.05	9.95
Area Irrigated	(10^3ha)	500	480	470
Xs	(km)	49	47	46
X*	(km)	50	48	47
Initial Water Stock	(10^8m^3)	41	41	41
Aggr. Output	(10^8US$)	13.54	15.83	19.62
Aggr. Net Benefit	(10^8US$)	6.81	9.38	13.28
Aggr. Land Rent	(10^8US$)	.139	2.75	6.60
Aggr. Water Rent	(10^8US$)	6.67	6.63	6.68
k(0)	(US$/m)	198.94	198.94	198.94
k(Xs)	(US$/m)	151.32	165.17	156.84
a(0)	(10^{-3}/km)	.00112	.00112	.00112
a(Xs)	(10^{-3}/km)	2.3700	1.2129	1.8627
$q_s(0)$	(m^3/m^2)	.8354	.8641	.8886
q_g	(m^3/m^2)	.8349	.8638	.8883
$I_s(0)$	(US$/$m^2$)	.0230	.0225	.0228
I_g	(US$/$m^2$)	.0230	.0225	.0228

Table 4.3. (Continued)
Change in Output Price: Seepage in the Canal
(Endogenous Technology)

$h_s(0)$	(US\$/m^2)	.9221	.9188	.9208
h_g	(US\$/m^2)	.9221	.9188	.9208
$y_s(0)$	(US\$/m^2)	.2656	.3231	.4087
y_g	(US\$/m^2)	.2655	.3231	.4086
Net Benefit (head)	(US\$/m^2)	.1336	.1917	.2769
Net Benefit (tail)	(US\$/m^2)	.1248	.1826	.2674
$\lambda_s(0)$	(US\$/m^3)	.15897	.15897	.15897
$w + \lambda_g$	(US\$/m^3)	.15947	.15927	.15937
λ_g	(US\$/m^3)	.14667	.14647	.14657
$R_L(0)$	(10^6US\$/m^2)	.2746	5.6288	13.7601
R_{Lg}	(10^6US\$/m^2)	.2328	5.6029	13.7245
$R_W(0)$	(10^6US\$/m^2)	13.0820	13.5371	13.9272
R_{Wg}	(10^6US\$/m^2)	12.2462	12.6523	13.0204

Note: In the base case, output price is US\$0.75 per lb.; n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; γ = a shift parameter for output price; although it is not clear from the table, at each point of x the level of conveyance expenditure is the lowest and the canal loss is the highest in the model with $\gamma = 1.5$.

Table 4.4
Change in Output Price:
Seepage in the Canal and on the Field
(Endogenous Technology)

Parameter	Unit	Model		
		Base	**$\gamma = 1.2$**	**$\gamma = 1.5$**
		(ETSCF)	**(ETSCF)**	**(ETSCF)**
Total Net Benefit	(10^8US$)	3.57	6.20	10.18
Area Irrigated	(10^3ha)	480	480	480
Xs	(km)	46	46	46
X*	(km)	48	48	48
Initial Water Stock	(10^8m^3)	40	41	42
Aggr. Output	(10^8US$)	13.04	15.84	20.01
Aggr. Net Benefit	(10^8US$)	6.75	9.54	13.68
Aggr. Land Rent	(10^8US$)	.462	2.93	6.75
Aggr. Water Rent	(10^8US$)	6.29	6.61	6.93
k(0)	(US$/m)	198.88	198.92	198.98
k(Xs)	(US$/m)	153.47	154.59	161.10
a(0)	(10^{-3}/km)	.00123	.00116	.00104
a(Xs)	(10^{-3}/km)	2.1651	2.0623	1.5132
$q_s(0)$	(m^3/m^2)	.8675	.8893	.9087
q_g	(m^3/m^2)	.8670	.8781	.9037
$I_s(0)$	(US$/$m^2$)	.0190	.0192	.0198
I_g	(US$/$m^2$)	.0190	.0198	.0201

Table 4.4. (Continued)
Change in Output Price:
Seepage in the Canal and on the Field
(Endogenous Technology)

$h_s(0)$	(US\$/m^2)	.8914	.8932	.8984
h_g	(US\$/m^2)	.8914	.8984	.9009
$y_s(0)$	(US\$/m^2)	.2661	.3232	.4083
y_g	(US\$/m^2)	.2660	.3223	.4079
Net Benefit (head)	(US\$/m^2)	.1286	.1950	.2796
Net Benefit (tail)	(US\$/m^2)	.1198	.1842	.2693
$\lambda_s(0)$	(US\$/m^3)	.15518	.15897	.16275
$w + \lambda_g$	(US\$/m^3)	.15568	.16667	.16666
λ_g	(US\$/m^3)	.14289	.15387	.15386
$\lambda_s(0) - \lambda_g\beta(1-h)$	(US\$/m^3)	.15053	.15404	.15806
$w + \lambda_g[1-\beta(1-h)]$	(US\$/m^3)	.15103	.16174*	.16209*
$R_L(0)$	(10^{6}US\$/m^2)	.9474	6.0027	13.7904
R_{Lg}	(10^{6}US\$/m^2)	.9036	5.3221	13.4365
$R_W(0)$	(10^{6}US\$/m^2)	12.8596	13.4998	14.1648
R_{Wg}	(10^{6}US\$/m^2)	11.9846	13.0990	13.4915

Note: In the base case, output price is US\$0.75 per lb.; n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; γ = a shift parameter for output price; * indicates figures at the tail.

increase in output price generates larger levels of land and water rents from the head to the tail of the project area. Impacts on land rents, especially, are conspicuously high.

In the case of ETSCF (see Table 4.4), an output price increase yields a higher total net benefit of 6.20 and 10.18 (100 million US$), or a 73.7% and 185% increase, when output price is increased by 1.2 and 1.5 times, respectively. However, there is no change in the length of the canal and total area irrigated. On the other hand, the optimal initial stock of water, aggregate output, land rents, and water rents increase with higher output prices.

The immediate effect of a larger initial stock of water is a larger initial net shadow price of surface water at the source. If the production function is the same, a higher shadow price of water reduces the optimal use of water. However, with an output price increase, the marginal value product function shifts up as depicted in Figure 4.1 and offsets the effect of a higher shadow price. As a result, optimal water use increases when output price increases as shown in Table 4.4.

Another effect of a higher net shadow price of water is higher conveyance expenditure and lower water loss rate as well as higher on-farm investment and higher water efficiency. When net shadow price is high, the utility invests more in conveyance expenditure and firms invest more in water conservation, as expected. Also, a higher net shadow price decreases land rents and water rents due to higher water charges by the utility. However, in this case despite higher water costs to firms, land rents and water rents increase because an increase in output price is dominating.

The simulation results with an output price increase can be summarized as follows:

1) Both models, ETSC and ETSCF, yield higher total net benefits -- increasing by 187% and 185% when output price is 1.5 times high -- which are quite sensitive to the output price increase.

2) In ETSC as output price increases, area irrigated and the length of canal shrink with the same optimal initial stock of water due to higher water use. On the other hand, in ETSCF, area irrigated and the length of canal remain the same but the initial stock of water increases.

3) In ETSC, an output price increase results in lower conveyance expenditure and on-farm investment while in ETSCF, a higher net shadow price results in higher conveyance expenditure and on-farm investment than the base models.

4) Aggregate land rents increase drastically, 4648% in ETSC and 1361% in ETSCF, as output price increases by 1.5 times due to a high net benefit at each location of the project area. There is no significant change in water rents.

4.3.3 The effects of output price on water allocation and technology choice

An increase in the output price induces more intensive use of water at each location of the project area. In ETSCF, it is possible to accommodate a larger initial stock of water and higher net shadow price because high conveyance cost lowers the rate of increase of shadow price. This suggests that a government subsidy to increase farm-gate price may have the same effect of inducing more intensive use of water as a whole.

The effect of output price on the endogenous crop choice is not considered. It is conceivable that in a multiple crop case, whether firms will shift to a crop with a higher output price depends on the shape of the two marginal value product functions and also on complementarity and substitutability of those two crops in the market.

4.4 Change in Pumping Cost

Pumping cost is another important factor in input price which alters optimal allocation of water for production. Since pumping cost consists mainly of an energy cost, any change in energy cost directly affects pumping cost. A lower pumping cost is most likely to motivate overdraft of groundwater resources. Higher input prices, on the other hand, tend to induce adoption of technology which can save costly factors of production, which is the mainstay of induced innovation hypothesis (Hayami and Ruttan, 1970; Binswanger and Ruttan, 1978). In this section, low and high pumping cost scenarios are considered to find the effect on water allocation and provide some policy implications for the choice of technology.

4.4.1 Specification of the problem and method of simulation

The same constant shift parameter, γ, from Section 4.3 is used to change pumping cost. Three scenarios are considered for both base cases, ETSC and ETSCF. The original marginal pumping cost of US$0.0128/m^3 (US$15.80/acre-foot) is reduced by 0.5 times and increased by 2 and 4 times using constant shift parameters assuming a quadrupling of energy prices as an extreme case. Except for changes in pumping cost, the same simulation method for the two base cases is used.

4.4.2 Results of simulation

Table 4.5 and Table 4.6 show the results of simulation with different pumping section, total net benefit is not very sensitive to a change in pumping cost. When pumping cost is four times that of the base case, total net benefit decreases by only 2.3% in ETSC and 1.4% in ETSCF. This is primarily due to a relatively small pumping cost compared to the supply price of groundwater.

In the case of ETSC, total net benefit, initial stock of water, the length of the canal, and area irrigated decrease for both low and high pumping cost scenarios. The initial stock of water decreases from 41×10^8 m^3 to 40×10^8 m^3 and the length of the canal shrinks from 49 km to 48 km. Also, aggregate output and net benefit decline slightly compared to the base case. Due to a lower initial stock of water at the source, the shadow price at the source starts from a lower level than the base model and this low level continues to the shadow price of groundwater.

As a result of the low shadow price of water, water use is higher throughout the project area and conveyance expenditure and on-farm investment is lower than the base model except for the case of highest pumping cost ($\gamma = 4$) in which conveyance expenditure is initially higher due to a low shadow price of groundwater. As pumping cost increases, the shadow price of groundwater decreases to restore the optimal supply price of groundwater, $w + \lambda_g$. The opposite is true for the low pumping cost case where the shadow price of groundwater increases (see Table 4.5). Aggregate land rents increase and aggregate water rents decrease slightly as pumping cost increases primarily due to a low shadow price of water.

Table 4.5
Change in Pumping Cost: Seepage in the Canal
(Endogenous Technology)

Parameter	Unit	Model			
		Base	**$\gamma = 0.5$**	**$\gamma = 2$**	**$\gamma = 4$**
		(ETSC)	**(ETSC)**	**(ETSC)**	**(ETSC)**
Total Net Benefit	(10^8US\$)	3.47	3.43	3.41	3.39
Area Irrigated	(10^3ha)	500	480	480	480
Xs	(km)	49	47	47	47
X*	(km)	50	48	48	48
Initial Water Stock	(10^8m^3)	41	40	40	40
Aggr. Output	(10^8US\$)	13.54	13.03	13.03	13.03
Aggr. Net Benefit	(10^8US\$)	6.81	6.61	6.59	6.57
Aggr. Land Rent	(10^8US\$)	.139	.29107	.29112	.29126
Aggr. Water Rent	(10^8US\$)	6.67	6.32	6.30	6.28
k(0)	(US\$/m)	198.94	198.87	198.92	198.99
k(Xs)	(US\$/m)	151.32	161.88	163.78	166.05
a(0)	(10^{-3}/km)	.00112	.00128	.00115	.00102
a(Xs)	(10^{-3}/km)	2.37002	1.4535	1.31176	1.15235
$q_s(0)$	(m^3/m^2)	.8354	.8436	.8436	.8436
q_g	(m^3/m^2)	.8349	.8432	.8432	.8433
$I_s(0)$	(US\$/m^2)	.0230	.0221	.0221	.0221
I_g	(US\$/m^2)	.0230	.0221	.0221	.0221

Table 4.5. (Continued)
Change in Pumping Cost: Seepage in the Canal
(Endogenous Technology)

$h_s(0)$	(US$/m^2)	.9221	.9161	.9161	.9161
h_g	(US$/m^2)	.9221	.9161	.9161	.9161
$y_s(0)$	(US$/m^2)	.2656	.2660	.2660	.2660
y_g	(US$/m^2)	.2655	.2659	.2659	.2659
Net Benefit (head)	(US$/m^2)	.1336	.1349	.1349	.1349
Net Benefit (tail)	(US$/m^2)	.1248	.1314	.1152	.0937
$\lambda_s(0)$	(US$/m^3)	.15897	.15518	.15518	.15518
$w + \lambda_g$	(US$/m^3)	.15947	.15559	.15559	.15549
λ_g	(US$/m^3)	.14667	.14919	.12999	.10429
$R_L(0)$	(10^{6}US$/m^2)	.2746	.5967	.5966	.5966
R_{Lg}	(10^{6}US$/m^2)	.2328	.5625	.5625	.5709
$R_W(0)$	(10^{6}US$/m^2)	13.0820	12.8930	12.8929	12.8929
R_{Wg}	(10^{6}US$/m^2)	12.2462	12.5801	10.9611	8.7950

Note: In the base case, pumping cost is US$0.0128/m^3; n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; γ = a shift parameter for pumping cost.

Table 4.6
Change in Pumping Cost:
Seepage in the Canal and on the Field
(Endogenous Technology)

Parameter	Unit	Model			
		Base	**$\gamma = 0.5$**	**$\gamma = 2$**	**$\gamma = 4$**
		(ETSCF)	**(ETSCF)**	**(ETSCF)**	**(ETSCF)**
Total Net Benefit	(10^8US$)	3.57	3.56	3.54	3.52
Area Irrigated	(10^3ha)	480	450	480	470
Xs	(km)	46	43	46	45
X*	(km)	48	45	48	47
Initial Water Stock	($10^8 m^3$)	40	38	40	39
Aggr. Output	(10^8US$)	13.04	12.28	13.03	12.79
Aggr. Net Benefit	(10^8US$)	6.75	6.43	6.72	6.54
Aggr. Land Rent	(10^8US$)	.462	.736	.443	.552
Aggr. Water Rent	(10^8US$)	6.29	5.70	6.28	5.99
k(0)	(US$/m)	198.88	198.73	198.91	198.93
k(Xs)	(US$/m)	153.47	147.46	156.642	152.73
a(0)	(10^{-3}/km)	.00123	.00160	.00118	.00115
a(Xs)	(10^{-3}/km)	2.16514	2.7600	1.8799	2.2347
$q_s(0)$	(m^3/m^2)	.8675	.8828	.8665	.8666
q_g	(m^3/m^2)	.8670	.8749	.8585	.8551
$I_s(0)$	(US$/$m^2$)	.0190	.0181	.0191	.0195
I_g	(US$/$m^2$)	.0190	.0185	.0195	.0201

Table 4.6. (Continued)
Change in Pumping Cost:
Seepage in the Canal and on the Field
(Endogenous Technology)

$h_s(0)$	(US$/m^2)	.8914	.8830	.8923	.8958
h_g	(US$/m^2)	.8914	.8868	.8958	.9009
$y_s(0)$	(US$/m^2)	.2661	.2671	.2660	.2666
y_g	(US$/m^2)	.2660	.2665	.2653	.2656
Net Benefit (head)	(US$/m^2)	.1286	.1400	.1379	.1381
Net Benefit (tail)	(US$/m^2)	.1198	.1354	.1169	.0947
$\lambda_s(0)$	(US$/m^3)	.15518	.14762	.15518	.15140
$w + \lambda_g$	(US$/m^3)	.15568	.15192	.15999	.15850
λ_g	(US$/m^3)	.14289	.14552	.13439	.10730
$\lambda_s(0) - \lambda_g\beta(1-h)$	(US$/m^3)	.15053	.14251	.15084	.14805
$w + \lambda_g[1-\beta(1-h)]$	(US$/m^3)	.15103 .15103*	.14681 .14698*	.15565 .15579*	.15515 .15531*
$R_L(0)$	(10^{6}US$/m^2)	.9474	1.6184	.9234	1.1767
R_{Lg}	(10^{6}US$/m^2)	.9036	1.2400	.5088	.5653
$R_W(0)$	(10^{6}US$/m^2)	12.8596	12.3821	12.8711	12.6306
R_{Wg}	(10^{6}US$/m^2)	11.9846	12.2998	11.1771	8.9023

Note: In the base case, pumping cost is US$0.0128/m^3; n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; γ = a shift parameter for pumping cost; * indicates figures at the tail.

In the case of ETSCF (see Table 4.6), the total net benefit decreases slightly and the length of canal and initial stock of water decline for all cases as pumping cost increases. In the low pumping cost scenario, low initial stock of water (38×10^8 m^3) causes a low net shadow price of water and high water use throughout the project area. Also due to a low net shadow price of water, conveyance expenditure and on-farm investment is lower than the base case. In ETSCF the shadow price of groundwater also decreases as pumping cost increases.

On the other hand, high pumping cost scenarios do not show general trends as to the movement of each parameter due to the interactions of variables involved. For example, when pumping cost is doubled, the net shadow price of surface water is higher than the base case because of higher on-farm investment and a lower shadow price of groundwater. However, when pumping cost is quadrupled, the net shadow price of surface water is lower than the base case due to a smaller initial stock of water and higher on-farm investment. In both cases, water use at the source is lower than the base case. On-farm investment increases as pumping cost increases. Firms tend to invest more in on-farm investment for water conservation when pumping cost is high. Thus, from the simulation results it follows that on-farm investment is higher with higher input prices, which is consistent with the induced innovation hypothesis.

In ETSCF, no general trend is observed with regard to the change in aggregate land rents. However, disparity of land rents between head and tail firms has increased. When the pumping cost grows by four times, disparity of land rents increases from 4.8% in the base model to 108%.

The simulation results with pumping cost changes are summarized as follows:

1) Total net benefits from ETSC and ETSCF all decrease slightly but they are not very sensitive to the change in pumping costs. In ETSCF, area irrigated, the length of canal and the initial stock of water decline as pumping cost increases. However, in ETSC, pumping cost has almost no effect on those parameters.

2) Water use is higher than the base model in ETSC, and lower than the base model in ETSCF. However, there is no significant change in water use when pumping cost increases.

3) On-farm investment and thus the water efficiency parameter are lower in ETSC and higher in ETSCF than the base models as pumping cost increases.

4) When pumping cost increases, aggregate land rents increase in ETSC while the change is mixed in ETSCF with greater disparity between head and tail firms (108% as compared to 4.8% in the base model).

4.4.3 The effects of pumping cost on the choice of technology

The effect of low pumping cost is higher water use, lower initial stock of water and on-farm investment in ETSCF. In the conjunctive water use model, low pumping cost increases the shadow price of groundwater and this in turn reduces net shadow price of surface water and increases net supply price of groundwater. However, low water efficiency decreases those net shadow prices. On the other hand, a higher pumping cost results in higher on-farm investment.

The effect of pumping cost on the choice of technology is less clear in ETSC.

However, in ETSCF, a trade off between on-farm investment and pumping cost can be observed. This implies that as input cost increases it is optimal for firms to invest more in on-farm investment. If government wants to save groundwater for alternative uses such as residential or industrial use, it may be sensible to impose a tax on groundwater use since the effect of taxing groundwater is similar to increasing pumping cost. Firms will then spend more on on-farm investment and use less water.

4.5 Uniform Price of Groundwater

What if the utility charges firms a shadow price of surface water but fails to estimate and to charge the optimal shadow price of groundwater? If the utility charges firms an arbitrary flat price for groundwater instead of charging a shadow price, what happens to the optimal allocation of water and the level of on-farm investment? In order to answer these questions, a fixed price of groundwater which is lower than the shadow price of the optimal base models is considered in this section.

4.5.1 Specification of the problem and method of simulation

A shift parameter is used to fix the price of groundwater at 0.8 and 0.5 times the optimal shadow price of groundwater in both models, ETSC and ETSCF. In ETSC, the optimal shadow price of groundwater, λ_g^*, is US\$0.14667/m^3 (US\$180.99/acre-foot). A shift parameter converts shadow price of groundwater to a fixed price, 0.11734 and 0.07333. Also in ETSCF, the optimal shadow price of groundwater, 0.14289 is replaced by the fixed prices 0.11431 and 0.07145. Therefore, firms maximize their production schedule according to a shadow price of surface water in surface water production, and to a supply price, i.e., a fixed price of groundwater plus a pumping cost in groundwater production. The same simulation procedure applies to this problem.

4.5.2 Results of simulation

Table 4.7 and Table 4.8 provide the simulation results with a fixed price of groundwater for ETSC and ETSCF. Total net benefit, the length of canal, and initial stock of water are sensitive to changes in groundwater price because cheap groundwater affects not only groundwater production but also surface water production through first order conditions.

In ETSC, as the charge for groundwater becomes cheaper, total net benefit, area irrigated, the length of canal and the initial stock of water decline significantly. When the fixed price of groundwater is half of the optimal shadow price, the initial stock of water decreases by 51% from 41 $10^8 m^3$ to 21 $10^8 m^3$. Due to a small initial stock of water, a low shadow price of surface water results in 14.6% higher water use from the source and it continues through the end of the project area. Thus water is used up quickly and the length of the project area shrinks from 50 km to 22 km.

Low shadow price of water and high water use reduce the optimal level of conveyance and on-farm investment. When the utility charges half of the optimal shadow price of groundwater, on-farm investment decreases by 26.1% from US\$0.0230/m^2 to US\$0.0170/m^2. The aggregate land rents increase by 1065% due to high water use and

Table 4.7
Uniform Price of Groundwater:
Seepage in the Canal
(Endogenous Technology)

Parameter	Unit	Base (ETSC)	$p_g=0.8\lambda_g^*$ (ETSC)	$p_g=0.5\lambda_g^*$ (ETSC)
			Model	
Total Net Benefit	(10^8US$)	3.47	3.25	2.89
Area Irrigated	(10^3ha)	500	380	220
Xs	(km)	49	37	21
X*	(km)	50	38	22
Initial Water Stock	(10^8m^3)	41	33	21
Aggr. Output	(10^8US$)	13.54	10.51	6.31
Aggr. Net Benefit	(10^8US$)	6.81	5.44	3.40
Aggr. Land Rent	(10^8US$)	.139	1.12	1.62
Aggr. Water Rent	(10^8US$)	6.67	4.32	1.78
k(0)	(US$/m)	198.94	198.38	196.11
k(Xs)	(US$/m)	151.32	104.21	108.05
a(0)	(10^{-3}/km)	.00112	.00262	.01510
a(Xs)	(10^{-3}/km)	2.3700	1.3845	1.9483
$q_s(0)$	(m^3/m^2)	.8354	.8766	.9571
q_g	(m^3/m^2)	.8349	.8751	.9539
$I_s(0)$	(US$/$m^2$)	.0230	.0210	.0170
I_g	(US$/$m^2$)	.0230	.0210	.0170

Table 4.7. (Continued)
Uniform Price of Groundwater:
Seepage in the Canal
(Endogenous Technology)

$h_s(0)$	(US$/m^2)	.9221	.9081	.8721
h_g	(US$/m^2)	.9221	.9081	.8721
$y_s(0)$	(US$/m^2)	.2656	.2696	.2742
y_g	(US$/m^2)	.2655	.2694	.2739
Net Benefit (head)	(US$/m^2)	.1336	.1396	.1482
Net Benefit (tail)	(US$/m^2)	.1248	.1302	.1377
$\lambda_s(0)$	(US$/m^3)	.15897	.12869	.08327
$w + \lambda_g$	(US$/m^3)	.15947	.13014	.08613
λ_g	(US$/m^3)	.14667	.11734	.07333
$R_L(0)$	(10^6US$/m^2)	.2746	2.8779	7.0473
R_{Lg}	(10^6US$/m^2)	.2328	2.7513	6.7736
$R_W(0)$	(10^6US$/m^2)	13.0820	11.0821	7.7733
R_{Wg}	(10^6US$/m^2)	12.2462	10.2680	6.9955

Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; p_g = fixed price of groundwater; λ_g* = .14667 in all models.

Table 4.8
Uniform Price of Groundwater:
Seepage in the Canal and on the Field
(Endogenous Technology)

Parameter	Unit	Model		
		Base	**p_g=0.8λ_g***	**p_g=0.5λ_g***
		(ETSCF)	**(ETSCF)**	**(ETSCF)**
Total Net Benefit	(10^8US$)	3.57	3.25	2.57
Area Irrigated	(10^3ha)	480	360	220
Xs	(km)	46	34	20
X*	(km)	48	36	22
Initial Water Stock	(10^8m^3)	40	32	21
Aggr. Output	(10^8US$)	13.04	9.99	6.30
Aggr. Net Benefit	(10^8US$)	6.75	5.31	3.48
Aggr. Land Rent	(10^8US$)	.462	1.31	1.69
Aggr. Water Rent	(10^8US$)	6.29	4.00	1.79
k(0)	(US$/m)	198.88	198.28	196.15
k(Xs)	(US$/m)	153.47	168.68	154.95
a(0)	(10^{-3}/km)	.00123	.00297	.01482
a(Xs)	(10^{-3}/km)	2.16514	.98109	2.0299
$q_s(0)$	(m^3/m^2)	.8675	.9161	1.0103
q_g	(m^3/m^2)	.8670	.9045	1.0091
$I_s(0)$	(US$/m^2)	.0190	.0170	.0130
I_g	(US$/m^2)	.0190	.0180	.0130

Table 4.8. (Continued)
Uniform Price of Groundwater:
Seepage in the Canal and on the Field
(Endogenous Technology)

$h_s(0)$	(US$/m^2)	.8914	.8721	.8254
h_g	(US$/m^2)	.8914	.8821	.8254
$y_s(0)$	(US$/m^2)	.2661	.2700	.2741
y_g	(US$/m^2)	.2660	.2698	.2740
Net Benefit (head)	(US$/m^2)	.1286	.1440	.1521
Net Benefit (tail)	(US$/m^2)	.1198	.1333	.1411
$\lambda_s(0)$	(US$/m^3)	.15518	.12491	.08327
$w + \lambda_g$	(US$/m^3)	.15568	.12711	.08253
λ_g	(US$/m^3)	.14289	.11431	.07145
$\lambda_s(0) - \lambda_g\beta(1-h)$	(US$/m^3)	.15053	.12052	.07953
$w + \lambda_g[1-\beta(1-h)]$	(US$/m^3)	.15103 .15103*	.12272 .12307*	.08050 .08050*
$R_L(0)$	(10^{6}US$/m^2)	.9474	3.5586	7.3751
R_{Lg}	(10^{6}US$/m^2)	.9036	3.3529	7.2766
$R_W(0)$	(10^{6}US$/m^2)	12.8596	10.8427	7.8386
R_{Wg}	(10^{6}US$/m^2)	11.9846	9.9736	6.8319

Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; p_g = fixed price of groundwater; λ_g* = .14289 in all models; * indicates figures at the tail.

output and the aggregate water rents decrease by 73.3% due to a low shadow price of water.

In the case of ETSCF (see Table 4.8), the movement of parameters is the same as those for ETSC. However, the total net benefit decreases by 28%, more than in ETSC, when the fixed price of groundwater is half of the shadow price. Decreasing the price of groundwater has the effect of increasing the net shadow price of water. On the other hand, the decreasing shadow price of surface water and on-farm investment and thus the water efficiency have the effect of reducing the net shadow price. In ETSCF, the latter forces are dominating and the result is a lower net shadow price and higher water use. The level of on-farm investment at the source decreases to US\$0.0170/m^2 and US\$0.0130/m^2, representing 10.5% and 31.6% decreases, when the fixed price decreases by 0.8 and 0.5 times the optimal shadow price of the base model. In ETSCF, the aggregate land rents increase by 266% due to high water use and output and the aggregate water rents decrease by 71.5% due to a low shadow price of water.

The results of simulation with fixed groundwater price are summarized as follows:
1) The total net benefit is sensitive to the fixed price of groundwater. When the price of groundwater becomes half of the optimal shadow price, the optimal initial stock of water is reduced to half and the area irrigated and the length of canal shrink to less than half for both ETSC and ETSCF.
2) Water use is 14.6% higher in ETSC and 16.5% higher in ETSCF when half of the shadow price is charged because the low shadow price of surface water and on-farm investment contribute to a low net shadow price of water.

3) Conveyance expenditure declines by 1.4% and on-farm investment declines by 26% when the fixed price of groundwater is half of the shadow price.

4) Aggregate land rents increase by 1065% in ETSC and 266% in ETSCF, and aggregate water rents decrease by 73.3% and 71.5% due to a low shadow price of surface water when the fixed price of groundwater is half of shadow price.

4.5.3 The effect of a fixed groundwater charge

When the utility charges an arbitrary fixed price of groundwater which is lower than the optimal shadow price, cheap groundwater reduces the optimal (net) shadow price of surface water as well as the (net) supply price of groundwater. As a result, conveyance expenditure and on-farm investment are lower than the optimal model. Compared to the change in pumping cost, the magnitude of change in parameters for a fixed groundwater charge is significantly large because this will decrease the (net) supply price of groundwater directly. When groundwater resources are available, the price of groundwater affects surface water production significantly. The utility should be aware of the impact of charging an arbitrarily low price for groundwater.

4.6 Uniform Price of Water

Marginal cost pricing is the key principle when considering allocative efficiency as the primary concern (Young and Haveman, 1985). However, the existence of a spatial externality, i.e., benefits from investing in conveyance expenditure that are not appropriable by individual firms, makes marginal cost pricing suboptimal. When the first-best optimal charging system is not available, it is often the case that the utility charges firms the marginal cost of water generation at the source. In other words, the utility charges firms a fixed price for water. In many developing countries, water authorities charge even less than the marginal cost, generating huge rents to farmers who are beneficiaries of the water project (Repetto, 1986). In this section, the effect of a uniform price of water is considered. The utility is assumed to charge firms a spatially uniform price per unit of water used.

4.6.1 Specification of the problem and method of simulation

A fixed cost of water is applied using two possible scenarios. One is the case in which the utility charges firms the marginal cost of water generation (MC) and the other is the case in which the utility charges half of the marginal cost of water generation (0.5MC) at the source of the canal. In order to impose the same cost of water to firms in the project area, when surface water is priced at the marginal cost of water generation, groundwater is priced at the marginal cost less pumping cost. Therefore, in surface water production, the price of surface water is equal to the marginal cost of water generation so that p_s=MC. And in groundwater production, the supply price of groundwater, i.e., the price of groundwater plus pumping cost, is equal to the marginal cost of water generation so that p_g+w=MC. This will allow the correct sequencing of water use, i.e., surface water use first and groundwater use second.

In addition, without a centralized provision for expenditures on conveyance, individual firms are assumed to receive negligible benefit from investing in canal lining. Therefore, under uniform pricing, no firms invest in conveyance, k=0, and as a result the water loss rate in the canal becomes the base loss, a_0 for the entire distance. Thus, under uniform pricing, firms maximize their net benefit, NB^f, at each location x as follows:

$$\underset{q_s,\, q_g,\, I}{\text{maximize}}\ NB^f(z_s(0)) = [pf[(q_s+q_g)h(I)] - I - F - p_s q_s - (p_g+w)q_g]\alpha \tag{2}$$

The first order conditions of this optimization problem for both ETSC and ETSCF are given below. First order conditions are the same for ETSC and ETSCF.

$$pf'h = p_s \tag{3}$$

$$pf'h = p_g + w \tag{4}$$

$$pf'h' = 1 \tag{5}$$

The utility is assumed to maximize total net benefit from the project, which is net benefit of production less water generation cost at the source, with the additional constraints as follows:

$$\underset{z_s(0)}{\text{maximize}}\ NB^*(z_s(0)) - g(z_s(0)) \tag{6}$$

subject to (3), (4), (5), k=0, and $p_s=p_g+w=g'(z_s(0))$. As shown in equations (3), (4) and (5), the first order conditions can no longer take into account the additional seepage on the field as in the base model, ETSCF (compare with the first order conditions (14), (15) and (18) in Chapter 3). As a result, individual firms face the same optimization problem for both ETSC and ETSCF, and particularly in ETSCF, firms do not optimize their production schedule based on the net shadow price of surface water and net supply price of groundwater as mentioned in the optimal model. Therefore, no allowance for spatially increasing scarcity of water nor additional seepage from the field is made in this uniform price model. Necessary adjustments for the simulation models are made to solve this problem.

4.6.2 Results of simulation

Table 4.9 and Table 4.10 show the results of simulation with a uniform price of water for the two base models, ETSC and ETSCF with MC and 0.5MC pricing scenarios. The models with uniform pricing of water are suboptimal compared to the base models. The resulting direction of movements for each parameter is the same as in the case of fixed groundwater price in the previous section except conveyance expenditure is zero in this case (see Table 4.11). However, the effect of a low water price for the entire water resource on the parameters is much greater compared to the case in the previous Section 4.5 where only groundwater price is low.

In ETSC, total net benefit, area irrigated, the length of the canal and the initial stock of water decline compared to the base model. Charging marginal cost of water generation immediately reduces total net benefit to half and the project area to less than half of the optimal model. Because there is no conveyance expenditure, seepage from the

Table 4.9
Uniform Price of Water: Seepage in the Canal
(Endogenous Technology)

Parameter	Unit	Model		
		Base	**p_e=MC**	**p_e=0.5MC**
		(ETSC)	**(ETSC)**	**(ETSC)**
Total Net Benefit	(10^8US$)	3.47	1.89	1.78
Area Irrigated	(10^3ha)	500	200	200
Xs	(km)	49	17	17
X*	(km)	50	20	20
Initial Water Stock	($10^8 m^3$)	41	24	27
Aggr. Output	(10^8US$)	13.54	5.73	5.80
Aggr. Net Benefit	(10^8US$)	6.81	3.08	3.26
Aggr. Land Rent	(10^8US$)	.139	1.25	2.12
Aggr. Water Rent	(10^8US$)	6.67	1.82	1.13
k(0)	(US$/m)	198.94	0	0
k(Xs)	(US$/m)	151.32	0	0
a(0)	(10^{-3}/km)	.00112	40.0	40.0
a(Xs)	(10^{-3}/km)	2.3700	40.0	40.0
$q_s(0)$	(m^3/m^2)	.8354	.9350	1.0589
q_g	(m^3/m^2)	.8349	.9350	1.0589
$I_s(0)$	(US$/$m^2$)	.0230	.0180	.0120
I_g	(US$/$m^2$)	.0230	.0180	.0120

Table 4.9. (Continued)
Uniform Price of Water: Seepage in the Canal
(Endogenous Technology)

$h_s(0)$	(US$/m^2)	.9221	.8821	.8120
h_g	(US$/m^2)	.9221	.8821	.8120
$y_s(0)$	(US$/m^2)	.2656	.2732	.2762
y_g	(US$/m^2)	.2655	.2732	.2762
Net Benefit (head)	(US$/m^2)	.1336	.1482	.1572
Net Benefit (tail)	(US$/m^2)	.1248	.1362	.1436
$\lambda_s(0)$	(US$/m^3)	.15897	.09463	.05299
$w + \lambda_g$	(US$/m^3)	.15947	.09463	.05299
λ_g	(US$/m^3)	.14667	.08183	.04019
$R_L(0)$	(10^{6}US$/m^2)	.2746	5.9690	10.1088
R_{Lg}	(10^{6}US$/m^2)	.2328	5.9690	10.1088
$R_W(0)$	(10^{6}US$/m^2)	13.0820	8.8478	5.6111
R_{Wg}	(10^{6}US$/m^2)	12.2462	7.6509	4.2557
Total Water Charge	(10^{8}US$)	6.7638	1.8221	.9832
Water Generation Cost	(10^{8}US$)	3.3365	1.1809	1.2774
Cost Recovery		2.027	1.543	.770

Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; p_s= price of surface water; MC = marginal cost of generating water; cost recovery = total water charge / water generation cost.

Table 4.10
Uniform Price of Water:
Seepage in the Canal and on the Field
(Endogenous Technology)

Parameter	Unit	Model		
		Base	**p_s=MC**	**p_s=0.5MC**
		(ETSCF)	**(ETSCF)**	**(ETSCF)**
Total Net Benefit	(10^8US$)	3.57	1.97	1.99
Area Irrigated	(10^3ha)	480	230	200
Xs	(km)	46	19	16
X*	(km)	48	23	20
Initial Water Stock	(10^8m^3)	40	27	25
Aggr. Output	(10^8US$)	13.04	6.52	5.80
Aggr. Net Benefit	(10^8US$)	6.75	3.45	3.27
Aggr. Land Rent	(10^8US$)	.462	1.18	2.21
Aggr. Water Rent	(10^8US$)	6.29	2.27	1.06
k(0)	(US$/m)	198.88	0	0
k(Xs)	(US$/m)	153.47	0	0
a(0)	(10^{-3}/km)	.00123	40.0	40.0
a(Xs)	(10^{-3}/km)	2.1651	40.0	40.0
$q_s(0)$	(m^3/m^2)	.8675	.9144	1.0813
q_g	(m^3/m^2)	.8670	.9144	1.0813
$I_s(0)$	(US$/$m^2$)	.0190	.0190	.0110
I_g	(US$/$m^2$)	.0190	.0190	.0110

Table 4.10. (Continued)
Uniform Price of Water:
Seepage in the Canal and on the Field
(Endogenous Technology)

$h_s(0)$	(US$/m^2)	.8914	.8914	.7980
h_g	(US$/m^2)	.8914	.8914	.7980
$y_s(0)$	(US$/m^2)	.2661	.2721	.2764
y_g	(US$/m^2)	.2660	.2721	.2764
Net Benefit (head)	(US$/m^2)	.1286	.1461	.1584
Net Benefit (tail)	(US$/m^2)	.1198	.1344	.1446
$\lambda_s(0)$	(US$/m^3)	.15518	.10598	.04921
$w + \lambda_g$	(US$/m^3)	.15568	.10598	.04921
λ_g	(US$/m^3)	.14289	.09318	.03641
$\lambda_s(0) - \lambda_g\beta(1-h)$	(US$/m^3)	.15053	n.a.	n.a.
$w + \lambda_g[1-\beta(1-h)]$	(US$/m^3)	.15103	n.a.	n.a.
$R_L(0)$	(10^{6}US$/m^2)	.9474	4.9167	10.5187
R_{Lg}	(10^{6}US$/m^2)	.9036	4.9167	10.5187
$R_W(0)$	(10^{6}US$/m^2)	12.8596	9.6903	5.3203
R_{Wg}	(10^{6}US$/m^2)	11.9846	8.5200	3.9363
Total Water Charge	(10^{8}US$)	6.4002	1.4818	1.2774
Water Generation Cost	(10^{8}US$)	3.1794	2.2789	1.0619
Cost Recovery		2.013	1.538	.831

Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; p_s= price of surface water; MC = marginal cost of generating water; cost recovery = total water charge / water generation cost.

Table 4.11
Summary of Movements for Key Parameters

	Heterogeneous Land Quality ($\gamma(0)=1.2$)		Output Price Increase ($\gamma=1.5$)		Pumping Cost Increase ($\gamma=4$)		Uniform Price of Groundwater ($p_g=0.5\lambda_g{}^*$)		Uniform Price of Water ($p_s=MC$)	
	ETSC	**ETSCF**	**ETSC**	**ETSCF**	**ETSC**	**ETSCF**	**ETSC**	**ETSCF**	**ETSC**	**ETSCF**
Total Net Benefit	↑	↑	⇑	⇑	↓	↓	↓	↓	↓	↓
Length of the Canal	↓	↓	↓	–	↓	↓	↓	↓	↓	↓
Length of Project Area	↓	↓	↓	–	↓	↓	↓	↓	↓	↓
Initial Stock of Water	–	↓	–	↑	↓	↓	↓	↓	↓	↓
Aggregate Output	↑	↑	↑	↑	↓	↓	↓	↓	↓	↓
Aggregate Land Rent	⇑	⇑	⇑	⇑	⇑	↑	⇑	⇑	⇑	⇑
Spatial Inequity	⇑	⇑	↓	↓	↓	⇑	↓	↓	no	no
Conveyance Expenditure	↓	↓	↓	↑	*	*	↓	↓	no	no
On-farm Investment	↓	↓	↓	↑	↓	↑	↓	↓	↓	–
Water Use at Head	↑	↑	↑	↑	↑	↓	↑	↑	↑	↑
Water Use at Tail	↑	↓	↑	↑	↑	↓	↑	↑	↑	↑
(Net) Shadow Price of Surface Water at Head	–	(↓)	–	(↑)	↓	(*)	↓	(↓)	↓	↓
(Net) Supply Price of Groundwater at Tail	↓	(↑)	↓	(↑)	↓	(↑)	↓	(↓)	↓	↓

Note: MC=marginal cost of generating water at the source; ETSC=seepage in the canal with endogenous technology; ETSCF=seepage in the canal and on the field with endogenous technology; ⇑ shows a more than 100% increase; – indicates no change; * indicates no global result i.e., partially larger and partially less compared to the base model; ( ) indicates net shadow price or net supply price; spatial inequity shows disparity of land rents between head firms and tail firms.

canal increases total groundwater stock available and extends groundwater production from 1 km to 3 km. The initial stock of water decreases to 24×10^8 m^3 when water price is equal to marginal cost, and to 27×10^8 m^3 when water price is equal to half of the marginal cost of water generation. Low initial stock of water further reduces marginal cost of water generation at the source.

Due to a low price of water, water use increases to 0.9350 m^3/m^2 and 1.0589 m^3/m^2 for the MC and the 0.5MC cases, respectively. Since there are no spatial differences for the supply price of water, the same amount of water is used for production throughout the project area. On-farm investment is lower than the optimal model and it decreases from US\$0.0180/m^2 to US\$0.0120/m^2 as water price declines from MC to 0.5MC.

Low water price creates super-normal land rents in the project area. Aggregate land rents increase nine times those of the base model with MC pricing even though the project area shrinks to 40 per cent of the base model. At the head of the project area, land rents are twenty times higher with MC pricing and thirty seven times higher with 0.5MC pricing. On the other hand, water rents decline due to cheap water.

As expected, the base model provides the best cost recovery, 2.027, and the figure declines to 1.543 with MC pricing. In the case of 0.5MC pricing, the resulting total water charge is less than the water generation cost, cost recovery being 0.770.

In ETSCF (see Table 4.10), the change of individual parameters is the same as ETSC. In 0.5MC pricing, total net benefit, area irrigated, length of canal and initial stock of water decline by 44%, 58%, 65%, and 37.5%, respectively. A high loss rate extends groundwater production from 1 km to 3 km at the tail of the project area. Also, water use is 24.6% higher and on-farm investment is 42% lower with the 0.5MC case compared to the base model. High and uniform land rents accrue to all firms and increase further as water becomes cheaper. Aggregate land rents increase by 155% in MC pricing and 378% in 0.5MC pricing. Similarly, cost recovery declines and in the 0.5MC scenario, the water charge cannot cover the water generation cost (0.831).

The results of simulation with uniform price of water are summarized as follows:

1) MC as well as 0.5MC pricing are suboptimal compared to the optimal models which charge shadow prices since no allowance is made for the spatially increasing scarcity of water resources and for a contribution of seepage to increasing the stock of water resources.

2) In ETSCF with 0.5MC pricing, total net benefit, area irrigated, the length of canal and the initial stock of water decline drastically by 44%, 58%, 65%, and 37.5%, respectively. Because there is no conveyance and high seepage from the canal, a larger groundwater stock extends the area of groundwater production twice at the tail of the project area.

3) Due to the low price of water, water use is 24% higher and on-farm investment is 42% lower in ETSCF with 0.5MC pricing than in the base model.

4) Cheap water generates 378% larger aggregate land rents in the project area and the aggregate water rents become 83% smaller in ETSCF with 0.5MC pricing than in the base model.

5) As the water price becomes cheap, cost recovery declines, and with 0.5MC pricing total water charges do not even cover the cost of water generation.

4.6.3 The effects of a uniform price of water

If the objective of the water authority is only to cover the cost of water generation, charging marginal cost of water generation at the source might be able to meet this purpose according to our results. However, when the utility charges a fixed price for water less than the marginal cost of water generation, it becomes difficult to recover even the cost of water generation, and the government has to continue subsidizing the cost of operation, which is quite common in many developing countries. Charging a fixed price such as marginal cost of water generation is clearly suboptimal in our models since total net benefit from the project and the area irrigated decline by half. Although a fixed price, i.e., cheap water, may be preferred by firms because it generates huge land rents to firms in the project area, in order to improve cost recovery, the charging system should be reconsidered. Our model suggests that a charging mechanism for levying the spatially differentiated shadow price will enhance optimal water use, water conservation and increase total benefit and cost recovery from the water project.

Other uniform pricing schemes which are not considered in this section include ones based on (i) the amount of output (crop tax), and (ii) the area of land utilized by each firm (land tax). Absence of spatial scarcity of water in the pricing scheme suggests that whichever uniform pricing method is used, resulting water allocation is suboptimal as shown above.

4.7 Conclusion

Simulations were run for five different scenarios. The first scenario is (i) heterogeneous land quality with fertile land at the head. The next two scenarios for exogenous parameter changes include (ii) change in output price and (iii) change in pumping cost. Tha last two scenarios deal with suboptimal water pricing such as (iv) uniform price of groundwater and (v) uniform price of water. Table 4.11 shows movements for key parameters from simulation results of these five scenarios. All movements of parameters in this table are relative to the base models, ETSC and ETSCF. Our simulation results are generally consistent with the observation of Caswell and Zilberman (1986) that modern irrigation technology is adopted when water price is high (well depth is large) and land quality is poor. A summary of simulation results is as follows:

Heterogeneous land quality with fertile land at the head has the effect of higher land rents and less conveyance expenditure and on-farm investment due to a higher level of output. In HPETSCF, shadow price and net shadow price show a discontinuity at the switching point from surface water use to groundwater use. Higher land rents accrue to firms, generating a large disparity, 1954% in HPETSC and 654% in HPETSCF, between head firms and tail firms. In order to alleviate the disparity, the government may have to subsidize tail firms to improve land quality or water efficiency.

Total net benefit is sensitive to an output price increase. When output price is 1.5 times, the ETSC simulation results in 6% shrinkage of the project area, and in ETSCF it remains the same because it can accommodate a higher initial stock of water. In ETSC, conveyance expenditure and on-farm investment are lower while in ETSCF, both are higher than the base model due to a higher net shadow price. An output price increase by 1.5 times generates 6.4% higher water use and huge, 4648% higher, land rents. This result suggests that government policy to increase farm-gate price may have the same effect of inducing more intensive use of water resources for production.

An increase in pumping cost does not significantly change total net benefit due to the relatively small pumping cost, US$0.0128/m^3, compared to supply price of groundwater. Water use is higher than the base model in ETSC and lower than the base model in ETSCF. However, there is no significant change in water use when pumping cost increases. High pumping cost is accompanied by high on-farm investment in water conservation when seepage occurs from the field. This implies that if government wishes to save water resources for alternative uses, imposing a tax on groundwater use may be an option since this policy has an effect similar to increasing pumping costs.

When the groundwater price is fixed and less than the optimal shadow price, the allocation is suboptimal. The total net benefit, area irrigated, length of canal, and the initial stock of water are all quite sensitive to the price of groundwater and decline drastically by 28%, 54%, 56%, and 47.5% respectively. When half of the optimal shadow price is charged for groundwater in ETSCF, water use is 16.5% higher and on-farm investment is 31.6% lower than the base model due to the low price of surface water. If the utility has to charge an arbitrary fixed price for groundwater which is lower than the optimal shadow price, cheap groundwater reduces the optimal (net) shadow price of surface water as well as the (net) supply price of groundwater. The utility should be aware that when conjunctive use is possible, an arbitrary low price of groundwater affects surface water production significantly.

Charging a uniform price for water is suboptimal compared to the optimal model in which the shadow price is charged. The effect of a low price of surface and groundwater is greater than the previous case in which only the groundwater price is low. A uniform price such as the marginal cost of water generation immediately reduces total net benefit to half and the project area to less than half of the optimal model. If half of the marginal cost of water generation is charged for water, total water charges cannot recover the water generation cost. Cheap water creates rent-seeking activities due to larger rents which accrue to firms and may invite strong resistance by beneficiaries to increasing the water price. A charging mechanism for levying the spatially differentiated shadow price will enhance optimal water use, water conservation and increase total benefit and cost recovery from the water project.

There are possible extensions of the models in this chapter. First, heterogeneous land quality can be considered with fertile land at the tail. Second, if a multiple crop case is considered, the effect of an output price change on the endogenous crop choice depends on complementarity and substitutability of those two crops.

CHAPTER 5

THE OPTIMAL DYNAMIC MODEL OF CONJUNCTIVE WATER USE

5.1 Introduction

An early conjunctive use model (Burt, 1964) studies optimal investment decisions over time among multiple storage facilities of water resources. Groundwater is considered not only the source of water stock but also a storage for natural runoff, incidental recharge from the canal, and artificial recharge from surface storage. Other conjunctive use models incorporate dynamics (Young and Bredehoeft, 1972; Gisser, 1983); however, the spatial aspect of surface and groundwater allocation has not been given much attention until recently. The literature which deals with spatial dynamics of water allocation is scant[16]. Kim et al. (1989) elaborates on a dynamic model of groundwater use to consider endogenous cropping patterns with a pumping cost externality. However, a spatial dimension is not given attention. This chapter attempts to fill this gap and to illustrate economic principles that govern efficient allocation of conjunctive water use over space and time.

This chapter is concerned with dynamic aspects of spatial conjunctive water use. The static spatial model discussed in Chapter 2 is extended to incorporate a dynamic dimension of water allocation. Section 2 defines the specification and the optimization

[16] For example, Takayama and Judge (1971) discuss models for intertemporal and spatial price equilibrium problems with multiple commodities and multiple regions. However, the work regarding water resource allocation problems is very scarce.

problem for the optimal spatial dynamic model. Section 3 explains the method of simulation for this dynamic extension of the spatial model. Section 4 provides the simulation results. Section 5 concludes the chapter with some policy implications.

5.2 The Optimal Dynamic Model of Conjunctive Water Use

The model considered here is a spatial dynamic optimal water allocation model for conjunctive use of surface and groundwater. The first section illustrates the specification of the problem. The next part specifies the optimization problem of the dynamic and spatial allocation of water. This is followed by the necessary conditions for this optimization problem.

5.2.1 Specification of the problem

A utility is assumed to invest optimally over three time periods in a canal irrigation project, and it charges each firm the shadow price of water in the project area. Figure 5.1 shows the water project area and an aquifer in the case of dynamic conjunctive water use. There is an aquifer underlying the project area which naturally recharges a fixed amount of water every year. Individual firms have a choice of using groundwater from the aquifer in conjunction with surface water which is distributed through the irrigation canal. There is seepage from the canal which recharges the aquifer. Also, there is a water storage facility near the project area and the utility uses a certain amount of water each year from storage to generate water in the canal. The optimal allocation

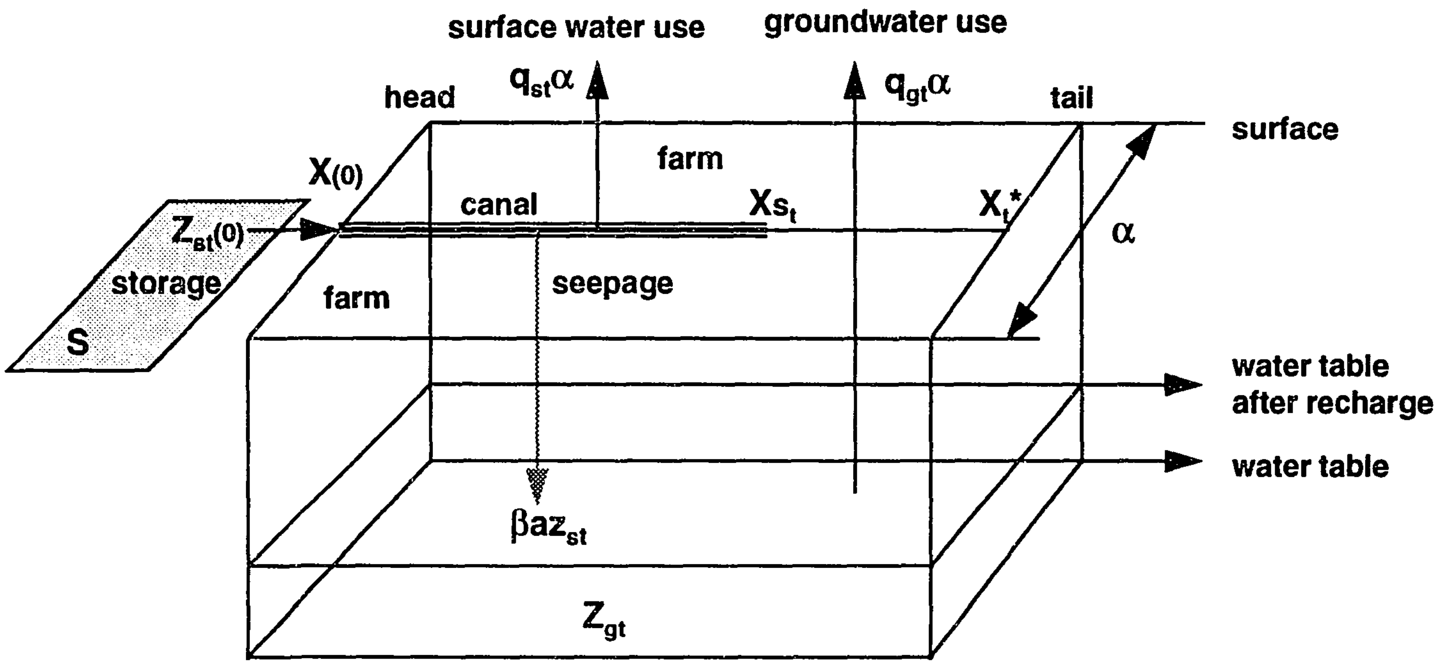


Figure 5.1. Water Project Area and an Aquifer: The Case of Dynamic Conjunctive Water Use

determines the optimal project area, the length of canal, spatial surface and groundwater use, conveyance expenditure, and the optimal initial stocks of surface water for each time period. Monocropping, homogeneous land quality, and no uncertainty are assumed. Seepage from the field is not considered in this case.

The utility endogenously chooses the amount of the initial stock of surface water $z_{st}(0)$ from a storage facility at the source (x=0) of the canal for a period t (t=1, 2, and 3). In this section, unless otherwise noted, subscripts s, g, and t denote surface water, groundwater and time period, respectively. Therefore, each function and the spatially variable parameters include a subscript t for time period. The total surface water stock available in storage is fixed and is denoted by S, and S_t indicates water stock which is remaining in storage at period t with S>0 and $S_t \geq 0$. Thus the total surface water constraint for three periods is given by:

$$S = \sum_{t=1}^{3} z_{st}(0) \tag{1}$$

Let $g(z_{st}(0))$ be the cost of generating water[17], and $g'(z_{st}(0))$ be the marginal cost of generating water at the source for time period t. The quantity of surface water use per unit land area at location x for time period t is represented by $q_{st}(x)$, groundwater use by

[17] Another interesting specification of the cost of generating water must be the case when the cost is a function of cumulative water stock extracted from the storage. In this specification, similar to a mining problem, the cost of generating water increases drastically and if one uses more surface water in storage for canal today, it becomes more costly to extract the remaining water in the next period.

$q_{gt}(x)$, and the fraction of water lost in conveyance per unit length of canal by $a_t(x)$. The residual quantity of water flowing in the canal per unit length at x is $z_{st}(x)$ for time period t. The change in the residual stock of water at each location for given period t, $z_{st}'(x)$, is expressed by the total water used by firms, $q_{st}(x)\alpha$, and the total water lost in the canal, $a_t(x)z_{st}(x)$, as follows:

$$z_{st}'(x) = -\ q_{st}(x)\alpha - a_t(x)z_{st}(x) \qquad (t=1,\ 2,\ 3) \qquad (2)$$

The water loss rate $a_t(x)$ is a function of conveyance expenditure per unit surface area of the canal $k_t(x)$ and is expressed by:

$$a_t(x) = a_0 - m(k_t(x)) \qquad (t=1,\ 2,\ 3) \text{ and}$$

$$a_0 \in [0,\ 1],\ \ m \in [0,\ a_0),\ \ a_t(x) \in (0,\ 1] \qquad (3)$$

where a_0 is the constant base loss rate and $m(k_t(x))$ is the reduction in conveyance loss rate with a given level of conveyance expenditure $k_t(x)$ for period t.

At each time period, a fraction, β, of water lost in the canal goes underground and recharges the aquifer. The change in the residual stock of groundwater at each location for a given period t is expressed by the amount of recharge from canal to the aquifer, $\beta a_t(x)z_{gt}(x)$, and the amount of extraction of groundwater, $q_{gt}(x)\alpha$. Groundwater use is allowed only in period 2 and period 3. Thus,

$$z_{g1}'(x) = \beta a_1(x) z_{s1}(x) \tag{4}$$

$$z_{gt}'(x) = \beta a_t(x) z_{st}(x) - q_{gt}(x)\alpha \qquad (t=2,\ 3) \tag{5}$$

Also, at the beginning of period 2 and period 3, there is a fixed amount of natural recharge, R, flowing into the aquifer. For period 2, the initial stock of groundwater is the fixed recharge plus seepage accumulated in period 1. Therefore, the initial stock of groundwater for each period is different and given by:

$$z_{g1}(0) = 0 \tag{6}$$

$$z_{g2}(0) = R + \int_0^{X^*_1} \beta a_1(x) z_{s1}(x)\,dx \tag{7}$$

$$z_{g3}(0) = R \tag{8}$$

where X^*_1 is the optimal length of the project area for period 1.

The same production function used in the static model is assumed for the dynamic model. The characteristics of the functional forms are the same as mentioned in Section 2.2.1 in Chapter 2 and are not repeated here.

5.2.2 The optimization problem

In summary, the water resource available for production in each period is as follows: In period 1, firms can use only surface water from the canal. There is no groundwater pumping in the first period. In period 2, firms can utilize (i) surface water, in conjunction with (ii) groundwater (fixed recharge + seepage from canal in period 1 and period 2). In period 3, (i) surface water and (ii) groundwater (fixed recharge and seepage from canal in period 3) are available.

The utility is assumed to maximize total net benefit from the water project over time and space with respect to temporal and spatial decision variables. Temporal decision variables include the amount of initial stock of surface water allocated to each period:

$$z_{st}(0) \qquad (t=1, 2, 3) \tag{9}$$

Spatial decision (control) variables are the amount of surface water use, groundwater use, conveyance expenditure at each location x, and the optimal length of project area for each period, given the initial stock of water at the source of canal as follows:

$$q_{st}(x) \qquad (t=1, 2, 3) \tag{10}$$

$$q_{gt}(x) \qquad (t=2, 3) \tag{11}$$

$$k_t(x) \qquad (t=1, 2, 3) \tag{12}$$

$$X^{*}_{t} \qquad (t=1, 2, 3) \tag{13}$$

The optimization problem is expressed as a maximization of present value of total net benefit, J_t, from the spatial water allocation problem for three periods subject to the temporal resource constraint (1), the spatial state constraints (2), (4), (5) and the initial stock constraints (6), (7) and (8) as shown below.

$$\underset{(9)(10)(11)(12)(13)}{\text{maximize}} \quad \sum_{t=1}^{3} J_t (1 + r)^{1-t} \tag{14}$$

$$= \text{maximize} \int_0^{X^*_1} \{[pf[(q_{s1})h] - I - F]\alpha - k_1\}dx - g(z_{s1}(0)) \tag{15}$$

$$+ \quad \{ \int_0^{X^*_2} \{[pf[(q_{s2}+q_{g2})h] - I - F - wq_{g2}]\alpha - k_2\}dx - g(z_{s2}(0)) \} (1 + r)^{-1}$$

$$+ \quad \{ \int_0^{X^*_3} \{[pf[(q_{s3}+q_{g3})h] - I - F - wq_{g3}]\alpha - k_3\}dx - g(z_{s3}(0)) \} (1 + r)^{-2}$$

where p is the constant output price, assuming price-taking producers; X^*_t is the optimal length of the project area for each period; I is the expenditure of on-farm investment; and F is the fixed cost of irrigated farming. A pumping cost, w, is assumed to be constant over the project area and the unit cost of conveyance is considered to be unity. The temporal and spatial decision variables should satisfy necessary conditions of respective temporal and spatial optimization problems. The following two sections consider the necessary conditions of these problems.

5.2.3 Necessary conditions for temporal optimization

Temporal optimization is expressed as a discrete optimization problem. The temporal resource constraint (1) can be rewritten in a discrete form as follows:

$$S_{t+1} = S_t - z_{st}(0) \qquad (t=1, 2, 3) \qquad (16)$$

where S_t is the water stock left in storage at period t. Equation (16) shows that the water stock in storage which will be left for the next period is the water stock for this period minus water used for canal irrigation in the same period so that S_1=S and S_4=0. Thus the utility maximizes the objective function (14), or the present value of a stream of total net benefit for three periods, with respect to decision variables, $z_{st}(0)$, δ_t, and S_t (t=1, 2, 3) subject to a temporal resource constraint (16). The Lagrangian of this problem is given below:

$$L = \sum_{t=1}^{3} J_t (1 + r)^{1-t} + \sum_{t=1}^{3} \delta_t [- S_{t+1} + S_t - z_{st}(0)] \qquad (17)$$

where δ_t is a Lagrangian multiplier at period t which provides the temporal shadow price of the surface water resource. Let $z_{st}^*(0)$, δ_t^* denote the corresponding optimal values for this optimization problem. The first order necessary conditions for optimality are given as follows:

$$\partial L/\partial z_{st}(0): \quad [\partial NB_t/\partial z_{st}(0) - \partial g(z_{st}(0))/\partial z_{st}(0)](1 + r)^{1-t} = \delta_t \qquad (18)$$

$$\partial L/\partial \delta_t : \quad S_{t+1} = S_t - z_{st}(0) \qquad (19)$$

$$\partial L/\partial S_t : \quad \delta_{t+1} = \delta_t \qquad (20)$$

Equation (18) means that the marginal benefit of using one more unit of initial surface water is equal to the marginal cost of holding one more unit of water in storage. In other words, δ_t indicates the opportunity cost of a resource which is the increased discounted stream of returns the utility would receive by using one additional unit of the surface water resource from storage. Equation (19) is simply a restatement of the resource constraint (16). Equation (20) shows that the increased return from holding one more unit of surface water today in storage is equivalent to the increased return from holding one more unit in the next period.

The marginal cost of generating water, $g'(z_{st}(0))$, is equal to the spatial shadow price of surface water at the source as from the salvage value condition explained in Chapter 2. Using this relationship and equations (18) and (20), we can derive a relationship similar to the Hotelling rule of exhaustible resource extraction (Hotelling, 1931) as follows:

$$\{(MNB_{t+1} - \lambda_{s,\,t+1}{*}(0)) - (MNB_t - \lambda_{st}{*}(0))\}/(MNB_t - \lambda_{st}{*}(0)) = r \qquad (21)$$

where $MNB_t = \partial NB_t/\partial z_{st}(0)$, $\lambda_{st}{*}(0) = g'(z_{st}(0))$ and r is the interest rate. The marginal net benefit of the water project minus the marginal cost of generating water, i.e. the shadow price of surface water at the source for period t, $(MNB_t - \lambda_{st}{*}(0))$, indicates rents of water resources generated from the project by using the resource in the form of surface and groundwater. This condition states that the rate of change of rents generated from using surface water is equivalent to the interest rate. This condition relates the initial spatial shadow price of the resource for each period with dynamic optimality conditions.

5.2.4 Necessary conditions for spatial optimization

Once the initial stock of surface water at each period is defined according to the necessary conditions of the dynamic optimization problem, it will be followed by the spatial optimization problem with a given surface water stock. Therefore, spatial allocation is constrained by the allocation of surface water for each period. Assuming that the second order sufficiency condition is well satisfied and also assuming the possibility of a corner solution, the necessary conditions for spatial optimality with the transversality condition for period 1 are given by:

$$pf'h \leq \lambda_{s1} \qquad (22)$$

$$\lambda_{s1}' = a_1(\lambda_{s1} - \beta\lambda_{g1}) \qquad (23)$$

$$\lambda_{g1}' = 0 \qquad (24)$$

$$(\lambda_{s1} - \beta\lambda_{g1})z_{s1}m'(k_1) \leq 1 \qquad (25)$$

$$[H\ (q_{s1}, q_{g1}, k_1, \lambda_{s1}, \lambda_{g1})]_{x=X^{*}_1} = 0 \qquad (26)$$

and similarly for period 2 and 3 (t=2, 3) with groundwater production:

$$pf'h \leq \lambda_{st} \qquad (27)$$

$$pf'h \leq w + \lambda_{gt} \qquad (28)$$

$$\lambda_{st}' = a_t(\lambda_{st} - \beta\lambda_{gt}) \tag{29}$$

$$\lambda_{gt}' = 0 \tag{30}$$

$$(\lambda_{st} - \beta\lambda_{gt})z_{st}m'(k_t) \leq 1 \tag{31}$$

$$[H\ (q_{st}, q_{gt}, k_t, \lambda_{st}, \lambda_{gt})]_{x=X^*_t} = 0 \tag{32}$$

where $f' = \partial f/\partial q_{st}$, $m' = \partial m/\partial k_t$ and $\lambda_{st}' = d\lambda_{st}/dx$. These optimality conditions are the same as those for the optimal model in the case of seepage in canal and fixed technology already discussed in detail in Sections 2.2.2 and 2.2.3 in Chapter 2; here we explain only the main points.

The conditions (22) and (27) state that the marginal value product, which is the marginal benefit, of surface water is equal to or less than the shadow price of surface water, which is the marginal cost of surface water production. The condition (28) similarly states that in the case of groundwater production, the marginal value product of groundwater is equal to or less than the pumping cost plus the shadow price of groundwater, which is the marginal cost of groundwater. Conditions (23) and (29) indicate that the change in shadow price of surface water is determined by the water loss rate in the canal, a_t, and the net shadow price of surface water in the canal due to seepage, $(\lambda_{st} - \beta\lambda_{gt})$. Thus, from this condition, the change in shadow price of surface water is increased by a higher loss rate and higher shadow price of surface water and decreased by a higher shadow price of groundwater. The conditions (24) and (30) state that the shadow price of groundwater does not change over space. The conditions (25) and (31) state that the marginal benefit of increasing one unit of conveyance is equal to or less than the marginal cost of conveyance, which is unity. The marginal benefit of conveyance is the increase in residual flow at location x by increasing one more unit of conveyance, $z_{st}m'(k_t)$, times the net shadow price of surface water in canal, $(\lambda_{st} - \beta\lambda_{gt})$. Finally, equations (26) and (32) show the transversality conditions for a free terminal point problem. They state that at the tail of the project area, the net benefits from the project are exactly offset by the shadow value of water at the tail.

5.3 Data and Method of Simulation

Similar to other fixed technology models, the level of on-farm investment, I, is fixed at US\$0.020/m^2 so that the water efficiency, i.e., the proportion of water delivered to the plant, h, is fixed at 0.9. The total stock constraint, i.e., the total amount of water in storage, S, is fixed as 90×10^8 m^3 (100 million cubic meters). The recharge at the beginning of period 2 and 3 is equal to 0.05*S which amounts to 4.5×10^8 m^3. The same value for other parameters, such as width of the project area (10^5m), seepage rate (0.3), fixed cost of on-farm investment (US\$0.107/m^2), output price of cotton (US\$0.75/lb), pumping cost (US\$0.0128/m^3), used in the model of seepage in canal with fixed technology (FTSC) apply in this model. The interest rate is 10%.

Figure 5.2 depicts a schematic framework of the algorithm for a 3-period dynamic conjunctive water use model. The fixed surface water stock, S, is allocated over three periods using two distribution parameters, Δ and Γ. Δ and Γ change from 0 to 1 (or 1 to 0). Initially, a portion of water from storage, ΔS, is distributed to period 1 as the

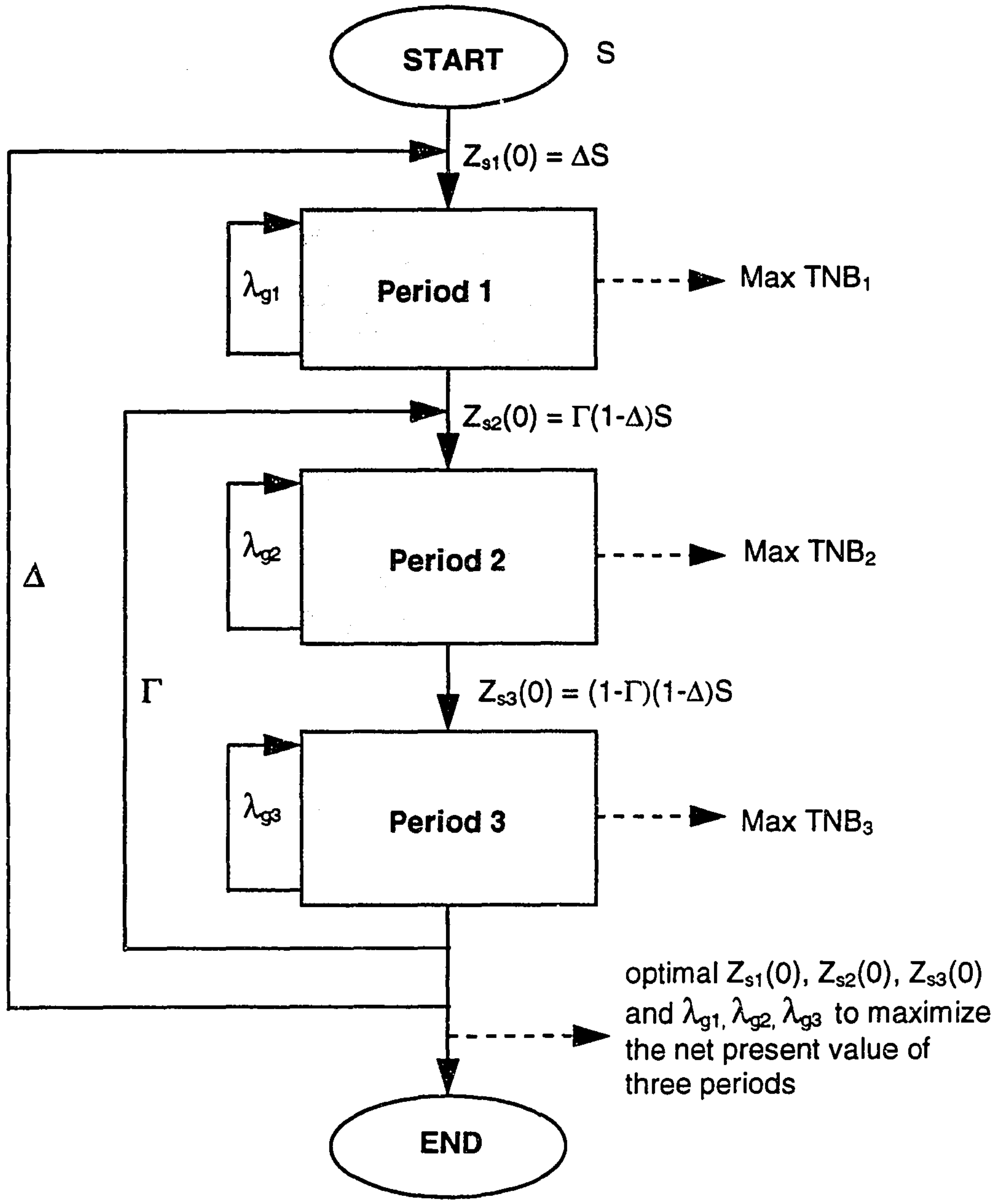


Figure 5.2
Algorithm for 3-Period Dynamic Conjunctive Water Use Model

initial stock of water into the canal. Then the remaining water stock in storage, $(1-\Delta)S$ is allocated using another distribution parameter Γ so that $\Gamma(1-\Delta)S$ is allocated to period 2, and $(1-\Gamma)(1-\Delta)S$ is allocated to period 3. Once distribution of water for three periods is determined, spatial allocation follows given the initial stock of water by simulating the optimal shadow price of groundwater which maximizes the total net benefit for each period. The algorithm for each period follows the one for the model FTSC in Figure 2.4 except groundwater production is not allowed in the first period.

When spatial allocation of water for each period defines the maximum total net benefit, present value of three periods is estimated at the end. This is the end of one cycle. After one cycle is completed, a different Γ is assumed to distribute water to period 2 and 3. When Γ reaches the maximum (or minimum) value, a different Δ is assumed and this cycle is repeated. The maximum present value defines the optimal combination of Δ and Γ which in turn defines the optimal dynamic allocation of surface water for three periods. Also, the maximum present value determines the optimal shadow price of groundwater for each period.

5.4 Results of Simulation

Table 5.1 shows the results of simulation for a 3-period dynamic conjunctive water use model. As mentioned in Sections 5.2.3 and 5.2.4, temporal optimization is governed by the Hotelling rule and the spatial optimization is controlled by the maximum principle. Furthermore, allocation of the initial stock of water is constrained by the maximum

Table 5.1
Three-Period Dynamic Conjunctive Water Use Model:
Seepage in the Canal and Fixed Recharge with Fixed Technology
(h=0.9; I=0.02; discount rate=0.10)

Parameter	Unit		Period		
		Total	**1** (surface)	**2** (surface+ ground)	**3** (surface+ ground)
Total Net Benefit	(10^8US$)		3.25	3.71	3.71
Total Net Benefit (NPV)	(10^8US$)	9.68	3.25	3.37	3.06
Area Irrigated	(10^3ha)	1120	400	360	360
Xs	(km)		40	30	30
X*	(km)		n.a.	36	36
Initial Surface Water Stock	(10^8m^3)	90	35	27.5	27.5
Allocation of Initial Water Stock		1.000	.390	.305	.305
Cost of Generating Water	(10^8US$)		2.45	1.53	1.53
Initial Groundwater Stock	(10^8US$)		0	4.503	4.500
Aggr. Output	(10^8US$)		11.00	10.06	10.06
Aggr. Net Benefit	(10^8US$)		5.72	5.23	5.24
Aggr. Land Rent	(10^8US$)		.89	1.73	1.74
Aggr. Water Rent	(10^8US$)		4.82	3.49	3.50
k(0)	(US$/m)		198.45	197.67	197.66
k(Xs)	(US$/m)		143.64	146.61	146.48
a(0)	(10^{-3}/km)		.00240	.00543	.00546
a(Xs)	(10^{-3}/km)		3.1767	2.8507	2.8641
$q_s(0)$	(m^3/m^2)		.8750 .8745*	.9049	.9049
q_g	(m^3/m^2)		n.a.	.9012	.9006

Table 5.1. (Continued)
Three-Period Dynamic Conjunctive Water Use Model:
Seepage in the Canal and Fixed Recharge with Fixed Technology
(h=0.9; I=0.02; discount rate=0.10)

Parameter	Unit	Total	Period 1	Period 2	Period 3
$I_s(0)$	(US$/m^2)		.0200	.0200	.0200
I_g	(US$/m^2)		n.a.	.0200	.0200
$h_s(0)$	(US$/m^2)		.9000	.9000	.9000
h_g	(US$/m^2)		n.a.	.9000	.9000
$y_s(0)$	(US$/m^2)		.26834	.27199	.27199
y_g	(US$/m^2)		.26827	.27159	.27152
Net Benefit (head)	(US$/m^2)		.1394	.1430	.1430
Net Benefit (tail)	(US$/m^2)		.1413	.1331	.1330
$\lambda_s(0)$	(US$/m^3)		.13664 .13714*	.10768	.10768
$w + \lambda_g$	(US$/m^3)		.16194	.11128	.11188
λ_g	(US$/m^3)		.14914	.09848	.09908
$R_L(0)$	(10^6US$/m^2)		2.1780	4.7551	4.7551
R_{Lg}	(10^6US$/m^2)		2.1343	4.4303	4.3762
$R_W(0)$	(10^6US$/m^2)		11.7580	9.5467	9.5467
R_{Wg}	(10^6US$/m^2)		11.9931	8.8750	8.9230

Note: n.a. = not applicable; Xs and X* are distances from the head of the canal; Loss rate is for a 1 km length of the canal; annual recharge of 4.5 (10^8m^3) to the aquifer is added to the initial stock of surface water for periods 2 and 3; * indicates figures at the tail.

allowable stock of water the canal can hold to produce non-negative land rents. When the initial stock of water becomes greater than 41 10^8m^3, the initial shadow price becomes too high and no production occurs due to negative land rents.

The present value of total net benefit for three periods is US$9.68 10^8 and the current value of total net benefit is US$3.25 10^8 for period 1 and US$3.71 10^8 for periods 2 and 3, which shows higher values for periods 2 and 3. However, the area irrigated, length of canal, and the initial stock of water are highest for period 1, and have the same lower values for periods 2 and 3. Out of the total stock of surface water in storage, 90 10^8m^3, 0.390 is allocated to period 1, 0.305 to periods 2 and 3. This allocation results in a higher initial shadow price of surface water at the source in period 1 compared to periods 2 and 3. The temporal allocation of the surface water resource is not sensitive to a change in the interest rate. Assuming a higher interest rate, 0.20, or lower interest rate, 0.05, does not alter the allocation of the initial stock of surface water for each period. Also, a change in the fixed recharge does not change the allocation because fixed recharge does not affect the marginal conditions[18].

A higher total net benefit accrues to periods 2 and 3 compared to period 1 despite a smaller stock of water resource including the allocation of surface water and the recharge to the groundwater for periods 2 and 3. This is because a smaller surface water allocation saves the cost of generating water at the source. Also, due to the decrease in surface water, the length of canal shrinks from 40 km in period 1 to 30 km in periods 2

[18] If recharge is a variable, for example a function of allocated initial stock of surface water for each period, then the amount of recharge will affect the marginal conditions and thus affect the allocation of the initial stock of water for each period.

and 3. And the significant amount of recharge in periods 2 and 3 to the aquifer extends the groundwater production for 6 km at the tail covering 11% of the total project area.

The allocation of a 21% higher initial stock of water in period 1 also leads to an 8.5% higher aggregate output and 9.4% higher net benefit. In addition, the higher allocation of surface water in period 1 provides a higher shadow price of surface water and as a result aggregate land rents are 48.6% lower and the aggregate water rents are 38.1% higher in period 1 compared to periods 2 and 3. As water becomes cheap, the difference between head and tail firms of land rents and water rents becomes large. The difference of land rents between head and tail firms increases from 2% in period 1 to 7.3% in periods 2 and 3.

The conveyance expenditure in periods 2 and 3 is 0.4% lower than period 1 because of a lower initial stock of water and shadow price of surface water. In period 2, conveyance expenditure is slightly higher than that in period 3 because a higher initial stock of groundwater makes the optimal shadow price of groundwater less compared to period 3. Also, a higher shadow price of surface water and groundwater in period 1 induces lower water use for firms and output, and thus lowers net benefit per unit of land in period 1. On the other hand, lower shadow prices in period 2 and period 3 generate a 2.6% higher net benefit accompanied by 3.4% higher water use at the head.

The results of simulation for a 3-period dynamic conjunctive water use model are summarized as follows.

1) The allocation of the initial stock of water is highest for period 1, 0.390, and the same amount for periods 2 and 3, 0.305; and this allocation is not sensitive to a change in the

interest rate. Fixed recharge does not affect marginal conditions of water allocation.

2) The temporal allocation of water determines the initial level of the shadow price of surface water at the source of canal for each period and the spatial allocation of water.

3) Despite a smaller allocation of the initial stock of water for periods 2 and 3, and the resulting lower shadow prices of surface water and groundwater, the total net benefit is 14% higher due to groundwater recharge and the cost saving of generating surface water. On the other hand, the area irrigated is 10% less and the length of canal is 25% less than those for period 1. Groundwater is used for 11% of total project area in periods 2 and 3.

4) A low shadow price of water provides 0.4% lower conveyance expenditure and 3.4% higher water use at the head in periods 2 and 3.

5) Aggregate land rents in periods 2 and 3 are twice the rents in period 1. Also, the difference in land rents between head and tail firms increases from 2% in period 1 to 7.3% in periods 2 and 3 due to cheap water.

5.5 Conclusion

This chapter expands the static spatial allocation of the conjunctive use model to consider a dynamic dimension. Conditions which determine temporal and spatial optimization problems were identified. Temporal allocation is governed by the Hotelling rule which determines the optimal allocation of the initial stock of water for each period. On the other hand, spatial allocation of water is constrained by the amount of the initial stock of surface water flow into the canal at each period. In this model, recharge to groundwater is fixed; therefore, the amount of groundwater does not significantly affect the temporal allocation of surface water. Also, the model is not sensitive to a change in the interest rate due to a short time horizon.

The policy implications for the above results are as follows: The optimal allocation of water results in allocating more water in the first period when fixed recharge to groundwater is available for periods 2 and 3. The utility has to be aware that a smaller allocation of water creates distributional inequity of land rents among firms due to a low shadow price of water. If the irrigation system deteriorates in later periods, this negative effect on distribution of land rents in favor of head firms may be intensified. If the utility wishes to achieve distributional equity, policy measures to compensate tail firms, for example, to use a portion of benefits from the efficient temporal allocation for compensation, would be warranted.

In this model, the conveyance cost is the same for three periods. The model can be extended by using higher loss functions so that conveyance expenditure becomes more expensive in later periods. This reflects the deterioration of the canal system over time and may be accompanied by adverse environmental problems such as waterlogging, salinization or contamination of groundwater by fertilizers and pesticides since water is a major transport mechanism of pollutants (Bogges et at., 1993). Also, if the water generating cost at the source is a function of the cumulative water resources used in the past, the allocation of water will be shifted to earlier periods to take advantage of cheaper water generation cost. Although a short time horizon does not indicate changes in allocation over time due to a change in the interest rate, if the time horizon is expanded to 10 or 20 years, the model may become sensitive to a change in the interest rate.

CHAPTER 6

CONCLUSION

6.1 Summary of Results

This study is concerned with optimal spatial allocation for the case of conjunctive use of surface and groundwater. The optimal model defines conditions which determine the spatial allocation of surface and groundwater, the level of conveyance expenditure, the level of on-farm investment in water conservation, and shadow prices of surface and groundwater.

First, the economic principles which govern the static spatial water allocation for conjunctive use of surface and groundwater were identified. Two models, seepage in the canal, and seepage in the canal *and* on the field were considered assuming fixed on-farm investment in water conservation. Due to conjunctive use, first order conditions include additional terms, compared to the surface water model, to take into account the possibility of groundwater use.

The optimal allocation of water is a corner solution, i.e., firms use surface water first and then use groundwater. The shadow price of surface water increases away from the source. On the other hand, the shadow price of groundwater is uniform among firms. Due to spatially increasing shadow prices, surface water use decreases away from the source and groundwater use flattens at the tail. The optimal allocation of water is guaranteed as long as the utility charges firms the shadow price of surface water as well as that of groundwater per unit of water used and invest in the optimal conveyance at each location of the canal.

Because of greater benefits at the head, larger rents accrue to head firms than to tail firms. In the model with seepage in the canal *and* on the field, additional seepage on the field generates positive externalities for water consumers, which reduces shadow prices of water resources by 5%. Also, seepage generates different shadow prices for the resource owner and the resource user.

Simulation results with modern on-farm irrigation technology show that the model with seepage in the canal *and* on the field yields a 3% higher total net benefit and 4% smaller project area, 5% smaller initial stock of water, and 0.1% smaller conveyance expenditure compared to the model with seepage in the canal. The surface water model yields the smallest total net benefit; however, there is only a 4% difference compared to the model with seepage in the canal. On the other hand, the simulation results with traditional on-farm technology show a 30.5% higher total net benefit compared to the surface water model. Also, groundwater production is extended to 15% of the total project area when seepage occurs on the field. In the conjunctive use model, low water efficiency intensifies surface water use but reduces groundwater use by firms.

The simulation with 500% higher conveyance costs results in shrinkage of the project area by 6%, a 10% smaller total net benefit, 7% smaller length of canal, and 5% smaller initial stock of water. High conveyance costs tend to skew the distribution of land rents by 424% compared to 3.6% in the base model in favor of head firms and water rents by 10% in favor of the tail of the project area.

The static base model is then extended by incorporating endogenous on-farm investment in water conservation. Simulations were run for both models, seepage in the canal, and seepage in the canal *and* on the field. Simulation results show that on-farm investment is 17% less in the model with seepage in the canal *and* on the field than in the model with seepage in the canal. Land rents that accrue to firms in the model with seepage in the canal *and* on the field are more than 200% larger than those in the model with seepage in the canal and those in the surface water model studied by Chakravorty et al. (1995).

When compared with the earlier results by Chakravorty et al. (1995), these results show that when the amount of seepage and thus groundwater stock is small, a surface water model could be a good approximation for conjunctive use models. In particular, 0.2% smaller conveyance expenditure at the head in the conjunctive use model compared to the Chakravorty model suggests that investment in conveyance expenditure is not preferred when groundwater is available because additional resource availability makes the shadow price of water smaller and investment in conveyance less profitable.

Analytical results were then examined for endogenous crop choice. Under homogeneous land quality and a spatially increasing shadow price of surface water, production of a water intensive crop changes to a less water intensive crop at the critical shadow price for which net revenue of the two crops are equal. Discontinuities of water use and land rents are observed at the switching point. It is found that even without differences in land quality, the cropping pattern theoretically shifts from a water intensive crop to a less water intensive crop.

With static spatial base models with endogenous on-farm investment, simulations were run for five different scenarios to analyze heterogeneous land quality, exogenous parameter changes, and suboptimal water pricing. Those are (i) heterogeneous land quality with fertile land at the head; (ii) a change in output price; (iii) a change in pumping cost; (iv) uniform price of groundwater; and (v) uniform price of water. These simulation results are generally consistent with the observations of Caswell and Zilberman (1986) that modern irrigation technology is adopted when the water price is high (well depth is great) and land quality is poor. The simulation results are as follows:

(i) When 20% more fertile land is at the head of the project area, conveyance expenditure and on-farm investment for a model with seepage in the canal *and* on the fieldis is 0.04% and 1% less, respectively, than the base model due to a 22% higher level of output at the head. More than 600% higher land rents accrue to head firms, generating a large disparity between the head and tail of the project area. Furthermore, shadow price and net shadow price show a discontinuity when surface water use switches to groundwater use.

(ii) Total net benefit is sensitive to an output price increase. In the model with seepage in the canal when output price increases 1.5 times, conveyance expenditure is the same and on-farm investment is 1% lower at the head. While in the model with seepage in the canal *and* on the field, both conveyance expenditure and on-farm investment are 0.05% and 4% higher, respectively, at the head than in the base model due to a 5% higher net shadow price. An output price increase by 1.5 times generates huge land rents, 1361% higher than the base model, throughout the project area.

(iii) An increase in pumping cost does not significantly change total net benefit because pumping cost is relatively small (8%) compared to the supply price of groundwater. In this model, there is no significant change in water use when pumping cost increases. A four times higher pumping cost is accompanied by 3% higher on-farm investment at the head when seepage occurs from the field.

(iv) When groundwater price is fixed as half of the optimal shadow price, the allocation is suboptimal. The total net benefit, area irrigated, length of canal, and initial stock of water in the model with seepage in the canal *and* on the field all decline drastically by 28%, 54%, 56%, and 48%, respectively. These parameters are all quite sensitive to the price of groundwater.

(v) Uniform water pricing is suboptimal compared to the optimal model in which the shadow price is charged. A uniform price such as the marginal cost of generating water at the source immediately reduces total net benefit by 44% and the project area by 58% of the optimal model. If less than half of the marginal cost of water generation is charged, cost recovery bocomes only 83%.

Finally, static spatial allocation of the conjunctive use model is expanded to consider dynamic dimensions. Conditions which determine temporal and spatial optimization problems are identified. Temporal allocation is governed by the Hotelling rule which determines the optimal allocation of initial stock of water for each period. Spatial allocation, on the other hand, is constrained by the amount of the initial stock of surface water that flows into the canal at each period. The simulation results show 0.39 of total water stock is distributed to period 1, 0.305 to periods 2 and 3. The amount of fixed recharge of groundwater does not affect temporal allocation of surface water. Also, the model is not sensitive to a change in the interest rate due to a short time horizon.

Here, five important results are summarized:

1) When seepage is small, the conjunctive use model does not make a significant difference. In this case, the surface water model is a good approximation of the conjunctive use model.

2) When seepage occurs from the field and conjunctive use of water is possible, there is a positive externality generated by water consumers. The shadow price of water for firms is lower than the shadow price of the utility due to a positive externality. With modern on-farm technology, conjunctive use improves total benefit by 6.9% with 17.4% less on-farm investment, compared to the surface water model by Chakravorty et al. (1995). With traditional furrow irrigation, the total net benefit increases significantly to 30.4% by conjunctive use. When seepage occurs in the canal, groundwater is used in 2.3% of the project area and additional seepage on the field increases the area for groundwater production up to 15% of the project area.

3) An output price increase, heterogeneous land quality, and a fixed price for water generate huge aggregate land rents. Land rents are quite sensitive to a change in output price. When output price becomes 1.5 times larger, aggregate land rents increase by 4684% with no seepage on the field and 1361% with seepage on the field.

4) Spatial inequity of land rents is worsened by heterogeneous land quality. When land quality is 20% higher at the head, spatial inequity increases by 1954% with no seepage on the field and 656% with seepage on the field. Except for a change in pumping cost,

conjunctive use with larger seepage on the field tend to alleviate land rents disparity between the head and tail of the project area.

5) Temporal allocation of water resources in conjunctive use is governed by the Hotelling rule variant similar to the optimal allocation rule for exhaustible resources.

6.2 Policy Implications

Simulation results with fixed on-farm irrigation technology suggest that conjunctive use improves the net benefit from the water project compared to the case where only surface water is used for production. The improvement is particularly significant, as high as 30%, when the on-farm water efficiency is low and thus the amount of seepage which replenishes the underlying aquifer is large. When conjunctive use is possible, low on-farm water efficiency on the field decreases the shadow price of surface water and increases the shadow price of groundwater resulting in high water use for surface water production and low water use for groundwater production. Improving on-farm water efficiency reduces disparity between surface water use and groundwater use.

As with the surface water model, an increasing shadow price of water and thus decreasing water use away from the source suggests that potential gains from directing a credit scheme and extension practices -- which enhance production of water-intensive crops (such as corn, soy-beans, sorghum, rice, sugar cane) and yield-increasing input use at the head when endowed with fertile land -- might be larger than the case when those efforts are distributed uniformly in the project area. In contrast, production of less-water intensive crops (such as cotton, wheat, oats, barley, rye, hay) and an investment in on-farm technology for water conservation (such as drip and sprinkler irrigation) will be more profitable at the tail of the project because of a relatively high shadow price for water.

Also, simulation results with high conveyance costs imply that if maintenance of the canal is not implemented, the deterioration of the system, in the long run, will make conveyance expenditure more costly, shrinking the project area and worsening the distribution of land rents over time. The utility needs to invest in canal conveyance periodically to avoid these adverse effects.

Distribution of land rents worsens particularly with heterogeneous land quality in favor of firms with fertile land. If an objective of the government is to alleviate disparity of land rents over the project area, the government may have to subsidize firms to improve land quality or water efficiency at the tail. A worsening of land rents distribution is also observed in favor of head firms when pumping cost increases. When seepage is large, conjunctive use of water has an effect of decreasing spatial inequity like a buffer.

Increased water use associated with an output price increase suggests that an increase in output price induces more intensive use of water for production in the project area. For example, a government policy to increase farm-gate price of commodities may have the same effect of inducing intensive water use. If the supply of surface water resources is limited, this may affect a depleting groundwater stock faster when a pumping cost externality is not the problem.

A trade-off between high pumping cost and high on-farm investment suggests that it is optimal to invest more in water conservation when pumping cost is high and seepage is large in the conjunctive use case. If the government wishes to save surface as well as groundwater resources for alternative uses such as industrial and residential sectors, imposing a tax on groundwater use may be one of the options. This policy has an effect similar to increasing pumping costs and thus inducing more investment in on-farm technology for water conservation especially at the tail. However, as shown in the model, an increase in pumping costs worsens disparity of land rents among firms. The government should be aware of the consequences of imposing a tax on groundwater use.

If the utility has to charge an arbitrary fixed price for groundwater which is lower than the optimal shadow price, cheap groundwater reduces the optimal (net) shadow price of surface water as well as the (net) supply price of groundwater. The utility should be aware that when conjunctive use is possible, an arbitrary low price of groundwater affects not only groundwater production but also surface water production significantly by inducing more intensive use of water in the project area while reducing the total benefit from the water project.

In this model, uniform pricing of water, such as charging the marginal cost of water generation at the source, creates suboptimal resource allocation. This is mainly because of a spatial externality, i.e., benefits from investing in canal conveyance are not appropriable by individual firms. As suggested by Chakravorty et al. (1995), existence of a spatial externality makes a water market regime suboptimal because firms will not make the optimal level of investment in conveyance. The same conclusion can be derived from the conjunctive use model. Furthermore, a cost recovery becomes difficult when half of the marginal cost of water generation is charged. Cheap water generates huge land rents and thus creates rent-seeking activities and may invite strong resistance to increasing water prices or charging efficiency prices.

This uniform water price model suggests that an alternative mechanism for levying the spatially differentiated shadow price as well as providing the optimal level of conveyance expenditure by the utility will enhance optimal water use, water conservation, and will increase total benefit and cost recovery from the water project. This model can be used to estimate the potential gains in benefit from improving the pricing mechanism, as well as from the optimal canal lining. As shown in simulation results, the potential gain from improving these aspects is quite large. This result also leads to immediate policy implications because by enhancing the efficient use of water in the project area, the utility can allocate saved water to other beneficial uses such as supplying water to industrial and urban sectors. Especially in the areas where water resources are scarce, changing the mechanisms for pricing water and using water more efficiently are acute issues.

Charging the spatially differentiated shadow price in order to restore efficiency may cause administrative difficulties due to high transaction costs involved. Also, charging a low price for water at the head and a high price at the tail of the project area will create spatial inequity in favor of head firms with higher rents. This problem can be partially mitigated by adopting proportional benefit taxation[19] (Chakravorty and Roumasset, 1991). A utility charges firms an equal proportion of individual rents while allocating the optimal quantities of water to each firm. Since this rule taxes rents and does not alter a firm's production schedule, it is efficient. If administrative costs are overwhelming, equal charges, i.e. uniform charge for water may be an alternative policy option.

6.3 Limitations of the Study and Future Extensions

The model presented in this dissertation has many limitations, and thus it is possible to extend it to obtain different analytical as well as numerical results.

First, one important aspect that this model does not consider and thus is worth immediate application is to include negative externalities of water use, i.e., water quality. Seepage causes not only a positive externality by adding to groundwater stock but also causes various environmental problems such as water logging and salinization. The threshold level of soil salinity with which production is feasible depends on soil structure, the underlying aquifer and the available irrigation technologies (Lee, 1989; 1993). These

[19] Chakravorty and Roumasset (1991) argue that if rationing mechanisms are available at no cost, efficient allocation of water can be achieved without using spatially differentiated water charges. They propose three charging schemes for solving spatial inequity: (i) proportional benefit taxation, (ii) equal charges and (iii) equal rents, to meet both efficiency and equity objectives. Charging equal rents is most equitable among the three; however, it is prone to encourage political pressures for extending the project area beyond an efficient boundary. On the other hand, equal charges for firms are equitable with low administrative costs, and this rule can mitigate political pressures to expand the area by limiting rents at the margin.

aspects, especially water pollution problems, can be incorporated into the conjunctive water use model. For example, if groundwater needs to be cleaned due to contamination by pesticides (e.g., groundwater pollution by pesticides from golf courses in Oahu, Hawaii), then the pumping cost and thus the supply price of groundwater becomes more expensive. Alternatively, a cost of drainage to remove excess water from the field can also be included. Incorporating those environmental variables and additional cost variables may affect results in this study significantly.

Second, in this model the marginal pumping cost is constant and any pumping cost externality is ignored. However, if the level of groundwater changes depending on the amount of water extracted, then the spatial allocation of conjunctive water use is subject to two different externalities. One is a pumping cost externality (negative) which increases the marginal pumping cost as the water level declines. The other externality is a seepage externality (positive) which decreases the marginal pumping cost by increasing the water level. Furthermore, in a dynamic setting, both externalities affect optimal water allocation in the current period and the next period.

This model is basically a first-best model, and it abstracts from considerations of the second and the third best. Second-best considerations can be modelled by incorporating transaction costs. For example, the administrative cost of charging firms the spatially differentiated shadow price is overwhelming. Once positive transaction costs are introduced, the optimal institutional choice becomes "a matter of comparative institutions" because of various economic and political factors involved (Roumasset et al., 1988). A third best model, on the other hand, includes rent seeking and strategic externalities, i.e., game theoretic considerations as mentioned in Negri (1989). If land holding of each firm is different, heterogeneous firms may generate different collusive power, e.g., larger firms at the head of the canal have more political influence over resource allocation.

Heterogeneous land quality could be specified with different water efficiency functions or different seepage rates. If seepage rate is high in low quality land, firms in low quality land should get more credit for adding to groundwater stock and be charged a lower shadow price for water. Also, the fixed cost of irrigation could vary depending on the technology and land quality. If firms face a downward sloping demand curve, the optimal allocation of water and output is subject to the elasticity of demand. In a multicropping case, substitutability and complementarity among crops affect the optimal allocation significantly.

The dynamic conjunctive water use model can be extended, using a higher loss function over time to simulate adverse environmental effects due to the deterioration of the canal system. Also, the model could incorporate a longer time horizon, the cost of generating water as a function of cumulative water extracted from storage, additional seepage from the field, variable recharge for each period, and endogenous on-farm investment.

BIBLIOGRAPHY

Adams, R. M., B. A. McCarl, D. J. Dudek, and J. D. Glyer. "Implications of Global Climate Change for Western Agriculture." *West J. Agr. Econ.* 13(1988):348-56.

Arrow, K. J. "The Organization of Economic Activity: Issues Pertinent to the Choice of Market Versus Nonmarket Allocation." *The Analysis and Evaluation of Public Expenditures: The PPB System.* vol. 1. U.S. Congress, Joint Economic Committee. Washington, D.C.: U.S. Government Printing Office, 1967, pp. 47-64.

Baumol, W. J., and W. E. Oates. *The Theory of Environmental Policy.* (2nd ed) New York: Cambridge University Press, 1988.

Binswanger, H. P., and V. W. Ruttan. *Induced Innovation: Technology, Institutions and Development.* Baltimore: Johns Hopkins University Press, 1978.

Bird, P. J. W. "The Transferability and Depletability of Externalities." *J. Environ. Econom. Management.* 14(1987):54-57.

Boggess, W., R. Lacewell, and D. Zilberman. "Economics of Water Use in Agriculture." in Carson, G. A., D. Zilberman, and J. A. Miranowski eds. *Agricultural and Environmental Resource Economics.* New York: Oxford University Press, 1993.

Bromley, D. W. *Improving Irrigated Agriculture: Institutional Reform and the Small Farmer.* World Bank Staff Working Papers, No. 531. Washington, D.C.: The World Bank, 1982.

Brookshire, D. S., and D. Whittington. "Water Resources Issues in the Developing Countries." *Water Resour. Res.* 29(1993):1883-88.

Brown, G. Jr. "An Optimal Program for Managing Common Property Resources with Congestion Externalities." *J. Polit. Econ.* 82(1974):163-73.

Brown, G. Jr., and C. B. McGuire. "A Socially Optimum Pricing Policy for a Public Water Agency." *Water Resour. Res.* 3(1967):33-43.

Brown, G. Jr., and R. Deacon. "Economic Optimization of a Single-Cell Aquifer." *Water Resour. Res.* 8(1972):557-64.

Buras, N., and S. C. Nunn. "Central Issues in the Combined Management of Surface and Groundwaters." in Custodio, E., and A. Gurgui eds. *Groundwater Economics.* Amsterdam : Elsevier, 1989.

Burt, O. R. "The Economics of Conjunctive Use of Ground and Surface Water." *Hilgardia.* 36(1964):31-111.

Burt, O. R. "Temporal Allocation of Groundwater." *Water Resour. Res.* 3(1967a):45-56.

Burt, O. R. "Groundwater Management under Quadratic Criterion Functions." *Water Resour. Res.* 3(1967b):673-82.

Casterline, G. L. *The Economics of Discrete Changes to the Technological Environment.* Ph. D. Dissertation, University of California, Berkeley, 1992.

Caswell, M., and D. Zilberman. "The Choices of Irrigation Technologies in California." *Amer. J. Agr. Econ.* 67(1985):224-34.

Caswell, M., and D. Zilberman. "The Effects of Well Depth and Land Quality on the Choice of Irrigation Technology." *Amer. J. Agr. Econ.* 68(1986):798-811.

Caswell, M., E. Lichtenberg, and D. Zilberman. "The Effect of Pricing Policies on Water Conservation and Drainage." *Amer. J. Agr. Econ.* 72(1990):883-90.

Chakravorty, U. *Optimal Resource Allocation, Pricing, Investment and Market Structure Under A Spatial Externality: The Case of Irrigation.* Ph. D. Dissertation, University of Hawaii, 1989.

Chakravorty, U., E. Hochman, and D. Zilberman. "A Spatial Model of Optimal Water Conveyance." *J. Environ. Econom. Management.* May, 1995 (forthcoming).

Chakravorty, U., and J. Roumasset. "Incorporating Economic Analysis in Irrigation Design and Management." *ASCE J. of Water Resources Planning and Management.* 120(1994):819-35.

Chakravorty, U., and J. Roumasset. "Efficient Spatial Allocation of Irrigation Water." *Amer. J. Agr. Econ.* 73(1991):165-73.

Chiang, A. C. *Elements of Dynamic Optimization.* New York: McGraw-Hill, Inc., 1992.

Cornes, R., and T. Sandler. *The Theory of Externalities, Public Goods, and Club Goods.* New York: Cambridge University Press, 1986.

Dasgupta, P. *The Control of Resources.* Cambridge: Harvard University Press, 1982.

Dinar, A. and J. Letey. "Agricultural Water Marketing, Allocative Efficiency, and Drainage Reduction." *J. Environ. Econom. Management.* 20(1991):210-23.

Dinar, A. and D. Yaron. "Influence of Quality and Scarcity of Inputs on the Adoption of Modern Irrigation Technologies." *West. J. Agr. Econ.* 15(1990):224-33.

Dorfman, R. "An Economic Interpretation of Optimal Control Theory." *Amer. Econ. Rev.* 59(1969):817-31.

Duloy, J. H., and G. T. O'Mara. *Issues of Efficiency and Interdependence in Water Resource Investments: Lessons from the Indus Basin of Pakistan.* World Bank Staff Working Papers, No. 665. Washington, D.C.: The World Bank, 1984.

Gisser, M. "Groundwater: Focusing on the Real Issue." *J. of Polit. Econ.* 91(1983):1001-27.

Gisser, M., and A. Mercado. "Economic Aspects of Groundwater Resources and Replacement Flows in Semiarid Agricultural Areas." *Amer. J. Agr. Econ.* 55(1973):461-66.

Gisser, M., and D. A. Sanchez. "Competition Versus Optimal Control in Groundwater Pumping." *Water Resour. Res.* 16(1980):638-42.

Hayami, Y., and V. W. Ruttan. "Factor Prices and Technical Change in Agricultural Development: The United States and Japan, 1880-1960." *J. of Polit. Econ.* 78(1970):1115-41.

Hotelling, H. "The Economics of Exhaustible Resources." *J. of Polit. Econ.* 39(1931):137-75.

Howe, C. W. *Natural Resource Economics: Issues, Analysis, and Policy.* New York: John Wiley & Sons, 1979.

Howe, C. W., and K. W. Easter. *Interbasin Transfers of Water: Economic Issues and Impacts.* Baltimore: Johns Hopkins Press, 1971.

Howe, C. W., D. R. Schurmeier, and W. D. Shaw, Jr. "Innovative Approaches to Water Allocation: The Potential for Water Markets." *Water Resour. Res.* 22(1986):439-45.

Howe, C. W., and Dixon, J.A. "Inefficiencies in Water Project Design and Operation in the Third World: An Economic Perspective." *Water Resour. Res.* 29(1993):1889-94.

Kanazawa, M. K. "Econometric Estimation of Groundwater Pumping Costs: A Simultaneous Equations Approach." *Water Resour. Res.* 28(1992):1507-16.

Kim, C. S., M. R. Moore, and J. J. Hanchar. "A Dynamic Model of Adaptation to Resource Depletion: Theory and an Application to Groundwater Mining." *J. Environ. Econom. Management.* 17(1989):66-82.

Kim, C. S., J. J. Hanchar, and M. R. Moore. "A New Dynamic Economic Model of Groundwater Mining." Technical Bulletin 1734, U.S. Department of Agriculture, Economic Research Service, 1981.

Laffont, Jean-Jacques. *Fundamentals of Public Economics*. Cambridge, Massachusetts: The MIT Press, 1990.

Lee, D. J. *Salinity in the Colorado River Basin: A Dynamic Modelling Approach to Policy Analysis.* Ph. D. Dissertation, University of California, Davis, 1989.

Lee, D. J., R. E. Howitt, and M. A. Mariño. "A Stochastic Model of River Water Quality: Application to Salinity in the Colorado River." *Water Resour. Res.* 29(1993):3917-23.

Lichtenberg, E. "Land Quality, Irrigation Development, and Cropping Patterns in the Northern High Plains." *Amer. J. Agr. Econ.* 71(1989):187-94.

Mapp, H. P. "Irrigated Agriculture on the High Plains: An Uncertain Future." *West J. Agr. Econ.* 13(1988):339-47.

Moore, M. R., and D. H. Negri. "A Multicrop Production Model of Irrigated Agriculture, Applied to Water Allocation Policy of the Bureau of Reclamation." *J. Agr. Res. Econ.* 17(1992):29-43.

Munasinghe, M. "Groundwater Resource Management and Environmental Protection: A Case Study of the Philippines." *Natural Resources Forum.* 15(1991):302-12.

Negri, D. H. "The Common Property Aquifer as a Differential Game." *Water Resour. Res.* 25(1989):9-15.

Negri, D. H., and D. H. Brooks. "Determination of Irrigation Technology Choice." *West. J. Agr. Econ.* 15(1990):213-23.

Nieswiadomy, M. L. "Input Substitution in Irrigated Agriculture in the High Plains of Texas, 1970-80." *West. J. Agr. Econ.* 13(1988):63-70.

Nijkamp, Peter. *Theory and Application of Environmental Economics*. Amsterdam: North-Holland Pub. Co., 1977.

O'Mara, G. T. *Issues in the Efficient Use of Surface and Groundwater in Irrigation.* World Bank Staff Working Papers, No. 707. Washington, D.C.: The World Bank, 1984.

O'Mara, G. T. "The Efficient Use of Surface Water and Groundwater in Irrigation: An Overview of the Issues." O'Mara, G. T. ed. *Efficiency in Irrigation: The Conjunctive Use of Surface and Groundwater Resources*. Washington, D.C.: World Bank, 1988.

O'Mara, G. T., and J. H. Duloy. "Modeling Efficient Conjunctive Use of Water in the Indus Basin." O'Mara, G. T. ed. *Efficiency in Irrigation: The Conjunctive Use of Surface and Groundwater Resources.* Washington, D.C.: World Bank, 1988.

Plourde, C. G. "A Simple Model of Replenishable Natural Resource Exploitation." *Amer. Econ. Rev.* 60(1960):518-22.

Provencher, B., and O. Burt. "The Externalities Associated with the Common Property Exploitation of Groundwater." *J. Environ. Econom. Management.* 24(1993):139-58.

Reisner, M. *Cadillac Desert: The American West and Its Disappering Water.* New York: Penguin Books, 1993.

Repetto, R. *Skimming the Water: Rent-seeking and the Performance of Public Irrigation Systems.* Washington, D.C.: World Resources Institute, 1986.

Roumasset, J. "The Public Economics of Irrigation Management and Cost Recovery." The World Bank, 1987.

Roumasset, J., U. Chakravorty, T. Wilson, and J. Moncur. "Efficient Principles for Water Management." Working Paper No. 2. Environment and Policy Institute, East-West Center, Honolulu, Hawaii, 1988.

Scitovsky, T. "Two Concepts of External Economies." *J. of Polit. Econ.* 62(1954):143-51.

Seierstad A., and Sydsæter K. *Optimal Control Theory with Economic Applications.* Amsterdam: North-Holland, 1987.

Shah, F., D. Zilberman, and U. Chakravorty. "Water Rights Doctrines and Technology Adoption." in K. Hoff, A. Braverman, and J. E. Stiglitz eds. *The Economics of*

Rural Organization: Theory, Practice, and Policy. New York: Oxford University Press, 1993.

Shah, F., D. Zilberman, and U. Chakravorty. "Technology Adoption and Exhaustible Resources: The Case of Groundwater Extraction." *Amer. J. Agr. Econ.* 77(1995) (forthcoming)

Solow, R. M., and W. S. Vickrey. "Land Use in a Long Narrow City." *J. Econ. Theory.* 3(1971):430-47.

Takayama, T., and G. G. Judge. *Spatial and Temporal Price and Allocation Models.* Amsterdam: North-Holland Pub. Co., 1971.

Tarlock, A. D. "An Overview of the Law of Groundwater Management." *Water Resour. Res.* 21(1985):1751-66.

Tiebout, C. M. "A Pure Theory of Local Expenditures." *J. of Polit. Econ.* 64(1956):416-24.

Todd, D. K. *Groundwater Hydrology.* New York: John Wiely & Sons, 1980.

Tolley, G. S., and V. S. Hastings. "Optimal Water Allocation: The North Platte River." *Quart. J. Econ.* 74(1960):279-95.

Tomiyama, K. "Two-Stage Optimal Control Problems and Optimality Conditions." *J. Econ. Dynamics and Control.* 9(1985):317-37.

Tsur, Y. "Managing Drainage Problems in a Conjunctive Ground and Surface Water System." in A. Dinar and D. Zilberman, eds. *The Economics and Management of Water and Drainage in Agriculture.* Boston: Kluwer Academic Publishers, 1991.

Tsur, Y. "The Stabilization Role of Groundwater When Surface Water Supplies Are Uncertain: The Implications For Groundwater Development." *Water Resour. Res.* 26(1990):811-18.

Tsur, Y., and A. Zemel. "Uncertainty and Irreversibility in Groundwater Resource Management." mimeo. University of Minnesota, 1994.

Tsur, Y., and T. Graham-Tomasi. "The Buffer Value of Groundwater with Stochastic Surface Water Supplies." *J. Environ. Econom. Management.* 21(1991):201-24.

U.S. Department of Commerce. *1987 Census of Agriculture. Volume 3. Related Surveys. Farm and Ranch Irrigation Survey (1988).* Bureau of Census, 1990.

U.S. Department of Commerce. *Statistical Abstract of the United States, 1992.* Economics and Statistics Administration, Bureau of Census, 1992.

University of California. *Associated Costs of Drainage Water Reduction.* Committee of Consultants on Drainage Water Reduction. Salinity/Drainage Task Force and Water Resources Center, 1988.

Vaux, H. J. Jr. "Economic Aspects of Groundwater Recharge." Asano, T. *Artificial Recharge of Ground Water.* Boston: Butterworth, 1985.

Wahl, R. W. *Markets for Federal Water: Subsidies, Property Rights, and the Bureau of Reclamation.* Washington, D.C.: Resources for the Future, 1989.

Wahl, R.W. "Full Cost Pricing Option." in Department of the Interior, Bureau of Reclamation. *Westside Report on Acreage Limitation: Draft Environmental Impact Statement.* Appendix G. Washington, D.C., 1985.

Wilson, T., J. Roumasset, and J. Moncur. "Optimal Mining of a Renewable Resource: The Case of Groundwater." in J. Roumasset, U. Chakravorty, T. Wilson, and J. Moncur. "Efficient Principles for Water Management." Working Paper No. 2. Environment and Policy Institute, East-West Center, Honolulu, Hawaii, 1988.

Worthington, V. E., O. R. Burt, and R. L. Brustkern. "Optimal Management of a Confined Groundwater System." *J. Environ. Econom. Management.* 12(1985):229-45.

Yaron, D., and E. Bresler. "Economic Analysis of On-farm Irrigation Using Response Functions of Crops." in H. Hillel ed. *Advances in Irrigation.* Volume 2. New York: Academic Press, 1983.

Yaron, D., and A. Dinar. "Optimal Allocation of Farm Irrigation Water during Peak Seasons." *Amer. J. Agr. Econ.* 64(1982):681-89.

Young, R. A., and J. D. Bredehoeft. "Digital Computer Simulation for Solving Management Problems of Conjunctive Groundwater and Surface Water Systems." *Water Resour. Res.* 8(1972):533-56.

Young, R. A., and R. Havemen. "Economics of Water Resources: A Survey." A. V. Kneese and J. L. Sweeney, eds. *Handbook of Natural Resource and Energy Economics.* vol. II. Amsterdam: Elsevier, 1985.

Zilberman, D., N. MacDougall, and F. Shah. "Changes in Water Allocation Mechanisms for California Agriculture." *Contemporary Economic Policy.* 12(1994):122-33.