Modeling Water Resources Management at the Basin Level

Methodology and Application to the Maipo River Basin

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Foreword

Limited water resources are increasingly constrained by growing water demand for agricultural, industrial, and domestic uses, which in turn exacerbates environmental degradation and water-quality problems. This research report develops and applies a comprehensive decision-support tool for examining these issues at the river-basin level—the natural unit of analysis for water allocation and use.

Authors Ximing Cai, Claudia Ringler, and Mark Rosegrant develop an integrated hydrologic–economic river-basin model, simulating water flows, salinity balances, and crop growth under water-allocation scenarios. One of the main advantages of the model is its ability to reflect the dynamic interactions of essential hydrologic, agronomic, and economic components and to explore both the economic and environmental consequences of a wide variety of policy choices. Illustrating this, the authors use the framework to examine a variety of water-allocation mechanisms and policy options for the Maipo River Basin in Chile. The method developed here is relevant for other water economies and water-scarce river basins.

The study also presents, for the first time, a practical application of the highly complex and changing relationship between system- and basin-level irrigation efficiencies, with important implications for water-related investments. Finally, the report studies the role of economic incentives in substituting scarce water resources for other farm-level crop inputs.

It is hoped that this model will assist water management authorities and policymakers in choosing appropriate water policies and establishing reform priorities for water resource allocation.

Joachim von Braun
Director General, IFPRI

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Summary

With increasing competition for water across sectors and regions, the river basin has been recognized as the appropriate unit of analysis for addressing the challenges of water resources management. Modeling at this scale can provide essential information for policymakers in their resource allocation decisions. A river basin system is made up of water source components, instream and off-stream demand components, and intermediate (treatment and recycling) components. The river basin is thus characterized by natural and physical processes but also by human-made projects and management policies. The essential relations within each component and the interrelations among these components in the basin can be represented in an integrated modeling framework. Integrated hydrologic and economic models are well equipped to assess water management and policy issues in a river basin setting. McKinney et al. (1999) reviewed state-of-the-art modeling approaches to integrated water resources management at the river basin scale. Based on that review, this report describes the methodology and application of an integrated hydrologic–economic river basin model.

Today we are faced largely with a “mature” water economy (Randall 1981), and most research is conducted with an explicit recognition of and focus on the need to cope with resource limits. Research has focused on a multitude of situations that might be presented in a mature water economy. Much work has been motivated by expanding municipal and industrial demands within a context of static or more slowly growing agricultural demand. More recently, expanding instream environmental demands have been added. On the supply side, conjunctive use of groundwater has been considered in addition to simple limits on surface water availability. In addition, some researchers have worked on waterlogging and water quality effects (primarily salinity). The work presented in this report examines a “complex” water economy: one in which demands grow differentially not only within but also among sectors, and one in which limited opportunities for increasing consumptive use exist. In particular, the growth of high-value irrigated crop production (such as table grapes) within the case study basin (the Maipo River Basin in Chile), together with the rapidly growing urban area, provides a rich context in which to examine the general problem of basin-level water resources management.

The methodology presented is optimization with embedded simulation. Basinwide simulation of flow and salinity balances and crop growth are embedded with the optimization of water allocation, reservoir operation, and irrigation scheduling. The modeling framework is developed based on a river basin network, including multiple source nodes (reservoirs, aquifers, river reaches, and so on) and multiple demand sites along the river, including consumptive use locations for agricultural, municipal and industrial, and instream water uses. Economic benefits associated with water use are evaluated for different demand-management instruments—including markets for tradable water rights—based on the production and benefit functions of water use in the agricultural and urban-industrial sectors. The integrated modeling framework makes use of multiple techniques, such as hydrologic modeling, spatial econometrics, geographic information system (GIS), and large-scale systems optimization. While these techniques have been adapted in other studies, this study represents a new effort to integrate them for the purpose of analyzing water use at the river-basin level.

The model's main innovative feature and advantage lie in its ability to reflect the interrelationships among essential hydrologic, agronomic, and economic components and to explore both economic and environmental consequences of alternative policy choices. The model can be used as a decision-support tool to assist water management authorities and policymakers in the selection of appropriate water policies and in the establishment of priorities for reform of institutions and incentives that affect water resource allocation.

The Maipo River Basin in Chile was chosen as the case study site in response to (1) increasing demands and competition among the major water-using sectors of agriculture, urban areas, and industries; (2) growing concerns over how these demands can be efficiently, equitably, and sustainably met; (3) increasing concerns over water pollution from agricultural, urban, and industrial users; and (4) innovative water management and allocation policies in the basin, including markets for tradable water rights.

The model is applied to the Maipo River Basin to address site-specific research questions regarding (1) the role of water rights and water rights trading in enhancing allocation efficiency; (2) the role of water use efficiency in saving water in the irrigation sector; (3) the impact of changes in physical irrigation efficiency on basin-level economic and physical efficiency; (4) the effects of hydrologic uncertainty on irrigation technology choice; and (5) the potential for substitution among water and other crop production inputs. Model applications presented thus focus on the relative benefits of alternative water allocation institutions.

The major findings of the report can be summarized as follows:

1. Modeling tool. The holistic integrated economic–hydrologic modeling framework developed for this study reflects the major hydrologic and economic processes related to water supply and demand in a river-basin context. Such a tool can be used to assist policymakers in their strategic water allocation decisions.
2. Intersectoral water transfers between irrigated agriculture and domestic and industrial uses. Under full basin optimization—assuming an omniscient decisionmaker with perfect foresight, optimizing the entire water-related basin economy, and current irrigation system and water supply charges—crop area in the basin can increase by 15 percent. Further, total crop revenue comprises an increase in high-value crops of up to 50 percent and a reduction in low-value crops, such as annual prairie and maize, of 40 percent. Under this scenario, total agricultural water withdrawal increases slightly, and domestic and industrial withdrawals almost double. This is a key and (for most contexts) surprising conclusion of the study.
3. Benefits from water rights trading with water moving into higher-valued domestic and industrial uses. When water rights can be traded, as opposed to being fixed, net farm incomes can increase substantially. Moreover, agricultural production declines only minimally as a result of water trading because economic efficiency increases. Net benefits can be even larger than under basin optimization for some irrigation districts because farmers can reap substantial benefits from selling their unused water rights during months with little or no crop production. Reducing transaction costs has significant benefits because both the volume of water traded and the benefits from trade are increased.
4. A shift from fixed to tradable water rights can lead to substantial gains in economic efficiency without prior changes in physical efficiency levels, such as water distribution/conveyance efficiency and field application efficiency.
5. Both an ideal optimal solution of basinwide water allocation, and water right trading and pricing incentives indicate that existing water and land use shift from lower-value to higher-value crops. Note, however, that additional factors like soil type and socioeconomic constraints to transfers are not taken into account in this analysis.

6. From a basin perspective, the potential for water savings from increases in water use efficiency in irrigation systems is lower than individual system efficiencies might indicate. If flow returning from an irrigation system to a water supply system can be reused in the system, then the actual or effective efficiency at this irrigation system will be higher than the traditional estimated system efficiency. This study shows that, for the Maipo River Basin, improvements in irrigation system efficiencies do increase basinwide economic efficiency over a wide range of efficiency increases. At low levels of local efficiency, improvements in system-level efficiency generate significant basinwide profits. However, when local efficiencies reach higher levels, the relative contribution to basinwide water use profits declines. At high levels of irrigation system efficiency, the contribution to basin profits from further improvements in local efficiency is minimal.
7. Tradable water rights also induce improvements in physical efficiency because it becomes more profitable for farmers to invest in improved irrigation technologies and to sell their surplus water.
8. Higher water charges result in higher basin efficiency in terms of physical indicators, such as water distribution/conveyance and field application efficiencies, and economic indicators, such as total net profit of water use and net profit per unit of water use because farmers reduce water use, shift from lower-value to higher-value crops, and shift to higher levels of irrigation technology for some crops. Moreover, incentive prices have little impact on the efficiency of irrigation systems at low levels of infrastructure development, and the improvement of physical structures can significantly strengthen the effectiveness of water prices or other economic incentives.
9. Physical and economic efficiency levels in the basin depend on the level of water being withdrawn under the current water supply and infrastructure conditions. Both physical and economic efficiency indicators improve at relatively low (but increasing) withdrawal levels compared with water needs, and increased irrigation withdrawals lead to significant increases in farmer incomes. At high withdrawal levels, both efficiency indicators decrease, but water pricing has the potential to solve this problem. In addition, appropriate physical and nonstructural improvements can enhance both physical and economic efficiency.
10. Water prices and water quality (in the form of salinity in the irrigation water) can significantly influence investments in field irrigation technology.
11. Some low-value and high-water-demanding crops are less sensitive to hydrologic uncertainty. In this study, these crops include wheat, corn, and annual forage, which require large planting areas, use large amounts of water, and are relatively less profitable in the basin.
12. Based on the uncertainty analysis, annualized capital investment per unit of crop area should be greater than US$105 per hectare but less than US$130 per hectare to maximize expected profit under the various climate scenarios and minimize the risk under the worst scenario.
13. The shift from a baseline (actual) scenario to a full optimization scenario leads to increases in both water use and other crop inputs that complement water, in particular seed and labor. This result shows that, at present, water is a constraining resource to crop production in the basin, and all other inputs are complementary to water under this scenario.
14. The shift from actual to optimized water allocation leads to a tradeoff of additional withdrawals of 301 million cubic meters and additional net profits of US$11.0 million.
15. Under economic incentives (represented by an increase in water charges by a factor of eight), a reduction in water withdrawals by 326 million cubic meters is traded against

costs of US$43.2 million for other inputs, particularly seed and labor inputs, which will ensure that profit can be maintained.

16. Substitutions between water and other crop inputs vary substantially by irrigation district, depending on the relative cropping patterns, net profit per unit area, and net profit per unit of water application. The substitutions are also related to the current levels of different inputs. If economic incentives change, the relationship between water and other inputs may move from substitute to complement or vice versa.

CHAPTER 1

Introduction

In much of the developing world, demand for water for agricultural, household, and industrial uses continues to increase rapidly, while watersheds, the irrigated land base, and the quality of water delivered to the final user are deteriorating. Scarcity of water has led to increased demand for policy reform, but many questions remain concerning the feasibility, costs, and likely effects of alternative water allocation policies in developing countries. Despite declining irrigation investments, irrigated agriculture will be called on to continue to supply a major share of growth in agricultural output in many regions of the developing world. At the same time, many developing countries will have to face severe and growing challenges to meeting rapidly growing urban and industrial demand for water resources. Water shortages are expected to worsen, especially in areas with high and growing urban density, some of which also have the lowest levels of water resources. The situation is compounded by dwindling public financial resources available for capital expenditure as the costs of new irrigation schemes increase. Thus, water used for irrigation will have to be diverted not only to meet the urban and industrial needs but also to continue to drive agricultural growth.

Waterlogging, salinization, groundwater mining, and water pollution also put increasing pressure on land and water quality. Pollution of water from industrial waste, poorly treated sewage, and runoff of agricultural chemicals, combined with poor household and community sanitary conditions, is a major contributor to human disease. In addition, as incomes grow, there will be significant increases in the demand for environmental "goods," including demand for direct allocation of water for environmental purposes. Thus, direct environmental demand for water will need to be accommodated in addition to dealing with the environmental concerns arising from urban and industrial water use.

Improved water resource policies in irrigation-dominated regions are therefore needed to (1) maintain growth in irrigated agricultural production; (2) facilitate efficient intersectoral allocation of water, including transfers of water out of agriculture; and (3) reverse the ongoing degradation of the water resource base, including the watershed, irrigated land base, and water quality. But the design and sequencing of appropriate water allocation policy reforms remain poorly understood. Moreover, because of the increasing competition for water resources, allocation has to be treated in an integrated fashion, considering not only irrigation but also household, industrial, hydropower, and environmental demand.

The interdisciplinary nature of water resource problems requires the integration of technical, economic, environmental, social, and legal aspects into a coherent analytical framework. A river basin is a natural unit for integrated water resources planning and management because water interacts with and, to a large degree, controls the extent of other natural components, such as soil, vegetation, and wildlife. Human activities that are dependent on water availability might also be best organized and coordinated within the river basin unit. Water resources management should focus on an integrated basin system that includes water supply, water demand, and intermediate components. Accordingly, policy instruments designed to make more rational economic use of water resources are likely to be applied at this level. The choice of the river basin as a unit of analysis is born of several factors: (1) it is an appropriate unit for the physical and technical management of water resources, given new developments such as sequential reservoir operations; (2) competition for water between upstream and downstream uses is growing and needs to be traced along the entire basin; (3) focus on the environmental influences of anthropogenic interventions is increasing, and such interventions should be managed at a basin scale (for example, flow regulations and diversions); (4) it is an appropriate unit for tracing the complex relationships and implications of water allocation mechanisms and policies for economic efficiency; and (5) it is the appropriate unit for water accounting (third party effects, and so on).

A river-basin system is made up of water source components, instream and offstream demand components, and intermediate (treatment and recycling) components. The river basin is characterized not only by natural and physical processes but also by human interventions and management policies. The essential relationships within and among these components in the basin can be considered in an integrated modeling framework. Combined hydrologic and economic models are well equipped to assess water management and policy issues in a river-basin setting. McKinney et al. (1999) reviewed state-of-the-art modeling approaches to integrated water resources management at the river-basin scale, with particular focus on the potential of coupled economic–hydrologic models, providing directions for future modeling exercises.

In terms of model formulation and solution approaches, integrated hydrologic–economic models can be distinguished as those with a compartment modeling approach and those with a holistic approach (McKinney et al. 1999). The compartment approach loosely connects the economic and hydrologic components, and usually only output data are transferred between components. Under the holistic approach, there is a single unit, embedding both components in a consistent model. Information transfer among hydrologic, agronomic, and economic components remains a technical obstacle in compartment modeling, whereas in holistic modeling, information transfer is conducted endogenously. However, the hydrologic side is often considerably simplified as a result of model-solving complexities.

This report presents the methodology development of an integrated economic–hydrologic river-basin model, as well as the application of this prototype to the Maipo River Basin in Chile. The model is based on a node-link river-basin network, including multiple source nodes (reservoirs, aquifers, river reaches, and so on) and demand sites, for municipal and industrial (M&I), hydropower, and agricultural water demands. In order to model water-allocation mechanisms and policies, agroclimatic variability, and multiple water uses and users, a large number of physical, economic, and behavioral relationships are incorporated into the modeling framework. They include (1) integrated water quantity and quality regulation; (2) spatial and temporal externalities resulting from the distribution of water supply and demand over time and across locations; (3) profit or benefit functions of various water uses; (4) effects of uncertainty and risk concerning both water supply and demand; (5) representation of water demand from all water-using sectors for analysis of intersectoral water allocation policies; and (6) economic incentives for water conservation and irrigation system improvement. These components are integrated into a consistent, holistic system. Its core is a multiperiod network model of the river basin, ranging from the crop root zone to the river system. The model is driven by the objective of maximizing total water use benefit from irrigation, hydropower generation, and M&I uses.

Important economic concepts that can be examined through integrated economic–hydrologic river-basin modeling include transaction costs, agricultural productivity effects of allocation mechanisms, intersectoral water allocation, environmental effects of allocations, and property rights to water for different allocation mechanisms. Moreover, successful planning and management at the river-basin scale require a foundation of comprehensive modeling in a river-basin context (see also Barrow 1998).

The Maipo River Basin in Chile was chosen as the case study site because of (1) increasing demand and competition for water among agricultural, domestic (urban), and industrial uses; (2) growing concerns over meeting such demand in an efficient, equitable, and sustainable manner; (3) increasing concerns over water pollution from agricultural, urban, and industrial users; and (4) innovative water management and allocation policies in the basin, including markets for tradable water rights. Moreover, most of the data for the model could be collected with relative ease by our collaborators in Chile (Pontifica Universidad Católica in Santiago, Chile) or developed by the research team. Particular research questions addressed in this study include: How do farmers respond to changes in the incentive structure for irrigation water? In particular, how does water marketing compare to alternative water allocation institutions? How does irrigation efficiency change in response to changes in economic incentives, infrastructure, and water availability? Does improved irrigation efficiency always lead to a decline in water consumption at the basin level? How does hydrologic uncertainty affect irrigation technology choices? To what extent can water be substituted with other agricultural inputs, such as fertilizer, labor, and machinery? In the following chapters the background of the study site is presented, the model development is described in detail, and implementation issues are discussed. The chapters thereafter address the questions listed above, based on alternative modeling scenarios and model outcomes.

CHAPTER 2

The Chilean Context and the Study Basin

Latin America, in general, and Chile, in particular, provide an appropriate setting for the development and adaptation of a prototype river-basin management model. After a phase of strong government interest and intervention in investment and management of water resources in the region, especially during the boom of the 1970s, and continuing interest in the management aspects during the recession period until the beginning of the 1990s, opportunities for the adoption of new institutional arrangements based on the concept of integrated basin water management opened up. In several countries of the region, notably Brazil, Chile, and Mexico, management of water resources through some form of river basin institution was increasingly considered the most appropriate way of internalizing the external costs of the development and use of water (Lee 1995). Moreover, Chile is a leader among developing countries in the use of market-based instruments for water allocation, an important water allocation mechanism that is and has been considered in other developing countries as well. The innovative approach to water management can also be seen in the plan by CONAMA, Chile's national environmental agency, to implement a pilot program of tradable emission permits in 2005 (Donoso and Melo 2006).

Basic Characteristics

Chile's economy has expanded at an average rate of 6.6 percent per year during 1985–2000. During the same period, agriculture grew at 4.2 percent per year (World Bank 2004). Moreover, the country has a relatively low and stable growth in population at 1.6 percent per year. As a result, GDP per capita more than doubled from US$2,577 in 1970 to US$5,300 in 2000 (1995 US$ constant prices) at 4.9 percent per year (World Bank 2004).

Chile has a total continental surface of 75.6 million hectares; 25.1 million hectares or 32.2 percent comprise productive land (11.5 million hectares of forest, 8.5 million hectares of extensive grazing land, and 5.1 million hectares of arable land). Pasture accounts for 3.2 million hectares, whereas basic staple crops are grown on about 0.9 million hectares, orchards on 0.2 million hectares, flowers and vegetables on 0.09 million hectares, and wine-producing grapes on about 0.07 million hectares. Another 0.6 million hectares is fallow at any point in time. As a result of the open trade policy of the Chilean government, the revaluation of the Chilean currency, internationally subsidized prices for agricultural commodities, and the tariffs and administrative barriers imposed by some developed countries on food imports, large land areas in Chile have gradually been concentrated in the hands of large agro-industrial exporters and several big forest companies. The area covered by large fruit farms, for example, increased from 54,000 hectares in 1973 to 235,000 hectares in 1993 (Gazmuri Schleyer and Rosegrant 1996).

The agricultural population in the country declined fairly slowly from around 24 percent in the early 1970s to 16 percent 30 years later, while the absolute population increased slightly from 2.3 million to 2.4 million people involved in agriculture. During 1975–2000, production of cereals increased at 1.8 percent per year, vegetables at 3.2 percent per year, and fruits at 4.7 percent per year (FAO 2004). This growth was achieved despite a declining share of agricultural land (arable land and permanent crops) in production. Productivity in agriculture has increased not through large infrastructure investments but by shifting land use from cattle raising and the cultivation of grains, maize, and oilseeds to increased production of fruit and wine, which returns higher income per unit of water and land (Gazmuri Schleyer and Rosegrant 1996). Agricultural exports have provided the engine for growth. Food exports as a share of merchandise exports increased from 10 percent in 1975 to an average of 27 percent per year during the 1990s (World Bank 2004). Agricultural exports rose from US$0.1 million in 1966 (1990 prices) to US$11.8 million in 1996. Chile went from being a small player in the global fruit market to becoming one of the world's largest fruit exporters in the 1990s. Table grapes are the main fruit export, but Chile also began focusing on wine exports in the 1980s and achieved important world market shares in the 1990s.

The country has a wide variety of climatic conditions, ranging from the desert climate in the north to the glacial climate to the south (see Fig. 2.1). Chile's rivers are mainly of pluvial origin in winter and glacial in the spring and summer. The runoff of the river basins in northern Chile (north of 32°S) is, as a rule, insufficient to irrigate all the land classified as irrigable. Therefore, for agricultural production to be viable, water capture and control mechanisms and water-saving irrigation techniques are necessary. In the Central Valley, particularly between the Aconcagua and Itata rivers, there are periods of severe water shortages. The majority of the population, together with most economic activity, is concentrated in this area, which can be described as a region with a typically Mediterranean climate of cool wet winters and warm dry summers. Irrigation is necessary and constitutes the largest use of water, but there is also considerable demand for urban and industrial consumption. In the southern zone, average rainfall exceeds 2,000 millimeters annually, whereas in the far south, rainfall declines to around 400 millimeters (ECLAC 1995). Total irrigated area amounts to 1.97 million hectares, of which 1.27 million hectares have permanent irrigation (85 percent or more irrigation security), and 0.7 million hectares have eventual or contingent[1] water supply (Gazmuri Schleyer 1997). Taking into account basic crops, orchards, flowers, vegetables, and wine vineyards, the irrigated crop area as a share of total crop area is about 60 percent (0.8 million hectares of irrigated area of a total of 1.3 million hectares) (Table 2.1). Approximately 75 percent of agricultural output, equivalent to 7 percent of GDP, is grown on irrigated areas (ECLAC 1995).

The Water Management System

The Chilean Water Code, introduced in 1981, entitles secure transferable water rights. The prevalent form of these rights is proportional rights over a variable flow or quantity. Rights of use can be consumptive or nonconsumptive, permanent or contingent, continuous or discontinuous, and rights might rotate among several people. The law provides for protection from detrimental third-party effects and for judiciary recourse for conflicts not solved by users' organizations or government water authorities. Water users are organized in strong and compulsory

[1]Contingent irrigation is used for areas with (seasonally) limited irrigation water supplies.

Table 2.1 Irrigated area by crop, Chile, mid-1990s

Crop category	Area (hectares)	Share irrigated (percent)
Basic crops (wheat, corn, sugarbeet, and so on)	400,347	46.5
Orchards	235,530	100.0
Flowers and vegetables	90,210	100.0
Wine-producing vineyards	66,600	90.9
Forestry (plantations, basic crop soils)	7,500	21.4
Natural and artificial pasture	599,015	18.6
Total	1,399,292	

Source: Gazmuri Schleyer 1997.

users' organizations. These water user associations are important in the enforcement of water rights and in the self-regulation of water users. Water user associations also collect fees for the construction, maintenance, and management of infrastructure. Project construction is conditional on users' prior agreement to pay the full project cost over time. This has helped shift the costs of overall water investment and management from the public to the private sector, ending huge budget deficits that had been accumulated through the construction of unprofitable water infrastructure, inefficient centralized management of irrigation systems, inefficient state-owned water services, and poor collection of water tariffs from both farmers and urban users. Government water authorities remain responsible, among other things, for water development planning, entitling original rights, keeping the National Official Water Record, approving all major hydraulic works, evaluating and assigning priority to state-financed projects for irrigation infrastructure, and fixing the maximum rates to urban water and sewage companies (Gazmuri Schleyer and Rosegrant 1996; Saleth and Dinar 2000). These changes in Chilean water management reflect a complete reversal of the historical tendency in the country toward the centralization of water development and management in one or more public agencies (Lee 1990).

The main government body responsible for water resources is the Dirección General de Aguas (DGA) of the Ministry of Public Works. Additional organizations involved include the Superintendency of Sanitary Services and the Comisión Nacional de Riego (CNR). DGA is responsible for coordinating and controlling the management of both surface and groundwater resources. Its prime responsibility is the issuing and registration of water rights. The Water Code provides for the DGA to solve most conflicts concerning water. Unresolved conflicts go to the courts for settlement (ERS 1994).

Urban water and sewerage companies were formerly highly subsidized state-owned entities. In addition, water was partially financed by a highly regressive tax system, and the poorest people had no access to public water and sewerage services. Since the early 1980s, state-owned urban services have been transformed into urban water and sewage companies that own the water rights to which the former municipal service entities were entitled (Gazmuri Schleyer and Rosegrant 1996). Some of these rights are considered to be priority rights, and consequently, volumetric withdrawals based on these rights are not reduced proportionally during times of water scarcity. Water rates are based on delivery costs, with a fair return on capital, and are reviewed every five years by the Superintendency of Sanitary Services (Hearne 1998). The coverage of potable water has risen to 99 percent in urban areas and 94 percent in rural areas from 63 percent and 27 percent, respectively, in 1970 (Gazmuri Schleyer and Rosegrant 1996).

One of the most important innovations of Chile's water policy is to allow cities to buy water without having to buy land or expropriate water. Thus, growing cities can buy rights from many farmers. As farmers mostly sell small portions of their rights and invest the financial resources obtained into enhanced irrigation technologies, agricultural production has not declined.

Although the book is not yet closed on the Chilean institutions for water management, and there is still some controversy and unfinished business regarding the benefits and potential disadvantages of this innovative allocation mechanism for the poor, farmers, and the public as a whole (Bauer 1997; ECLAC 1999), Chile's experience with markets in tradable water rights is generally considered quite successful (Hearne and Easter 1995; Gazmuri Schleyer and Rosegrant 1996; Thobani 1997; Hearne 1998). The water policy reforms together with Chile's open trade policies have fostered efficient agricultural use of water in the country. Improved water use efficiency has increased agricultural productivity and generated more production per unit of water, and trade liberalization has helped foster high-value agricultural production for exports. The market valuation of water at its scarcity value has induced farmer investment in on-farm irrigation technology that has saved water, enabling irrigation of a larger area or sale to other users. Tradable water rights also fostered investments in agriculture, allowing farmers not only to invest in and obtain financing for irrigation improvements but also for slow-maturing projects, such as the production of fruit crops and vineyards.

The Maipo River Basin

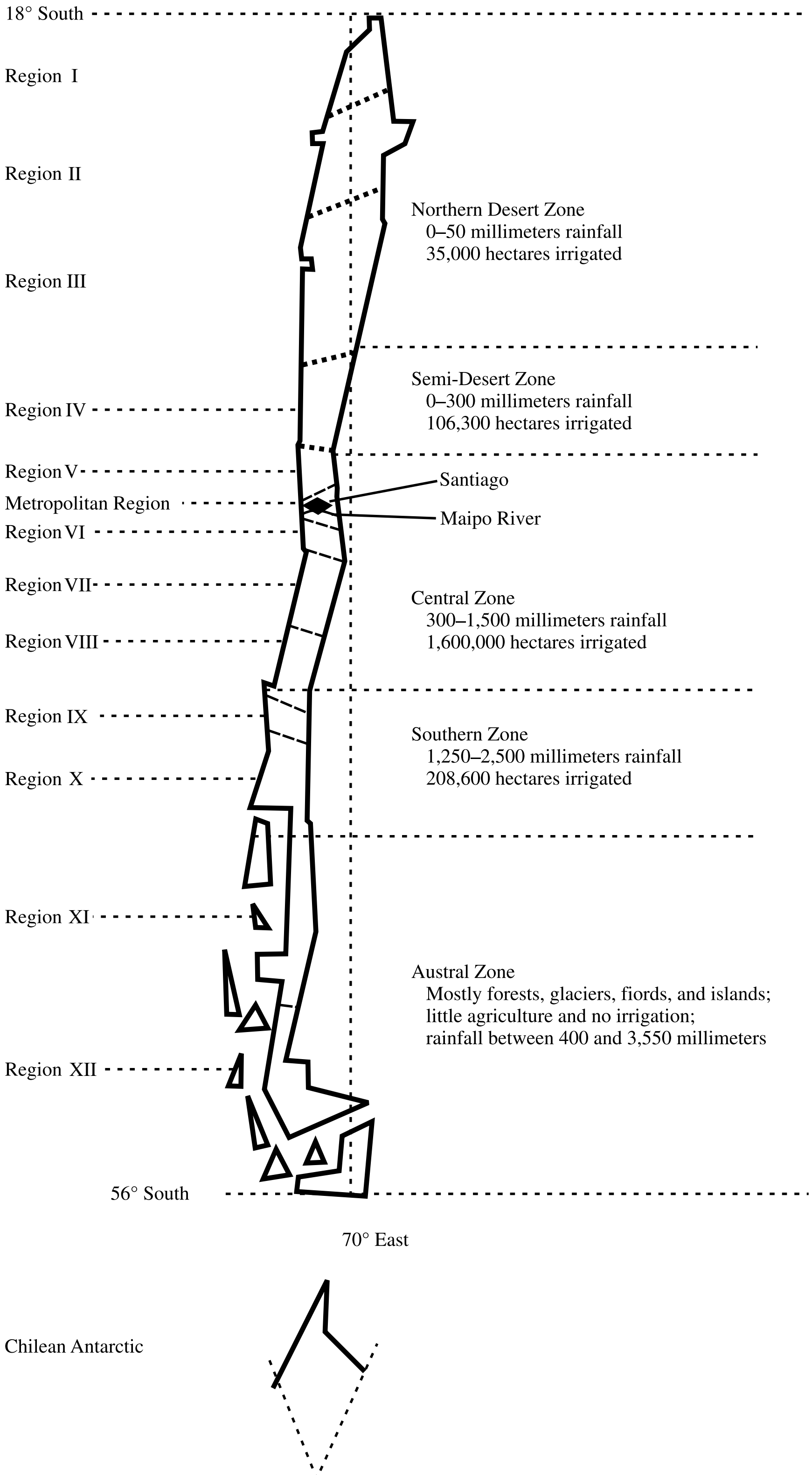
The Maipo River Basin, located in a key agricultural region in the metropolitan area of central Chile, is a prime example of a "mature water economy" (see Randall 1981) with growing water shortages and increased competition for scarce water resources across sectors. The basin is bounded to the north by the Aconcagua Basin, to the south by that of the Cachapoal, to the east by the Andes-Argentine border, and to the west by the Pacific Ocean. The basin has a catchment area of 15,549 square kilometers. It is characterized by a very dynamic agricultural sector serving an irrigated area of about 127,000 hectares and a rapidly growing industrial and urban sector, in particular in and surrounding the capital city of Santiago with a population of more than five million people. More than 90 percent of the irrigated area in this region depends on water withdrawals from surface flows. Annual flows in the Maipo River average 4,445 million cubic meters.

The Maipo enters the Pacific Ocean near the city of San Antonio, south of Valparaíso. Like other rivers in the area, the Maipo's tributaries are short and flow down steep slopes. Their volumes depend mainly on the amount of snow melt in the upper Andes. Thus, there are considerable flows in summer (November to February) and very pronounced reductions in winter (April to June). Figure 2.1 presents the geographic location of the Maipo Basin in Chile, and Figure 2.2 presents the provincial boundaries, rivers and streams, irrigated areas, and the location of the capital city in the basin.

Water Resources Availability

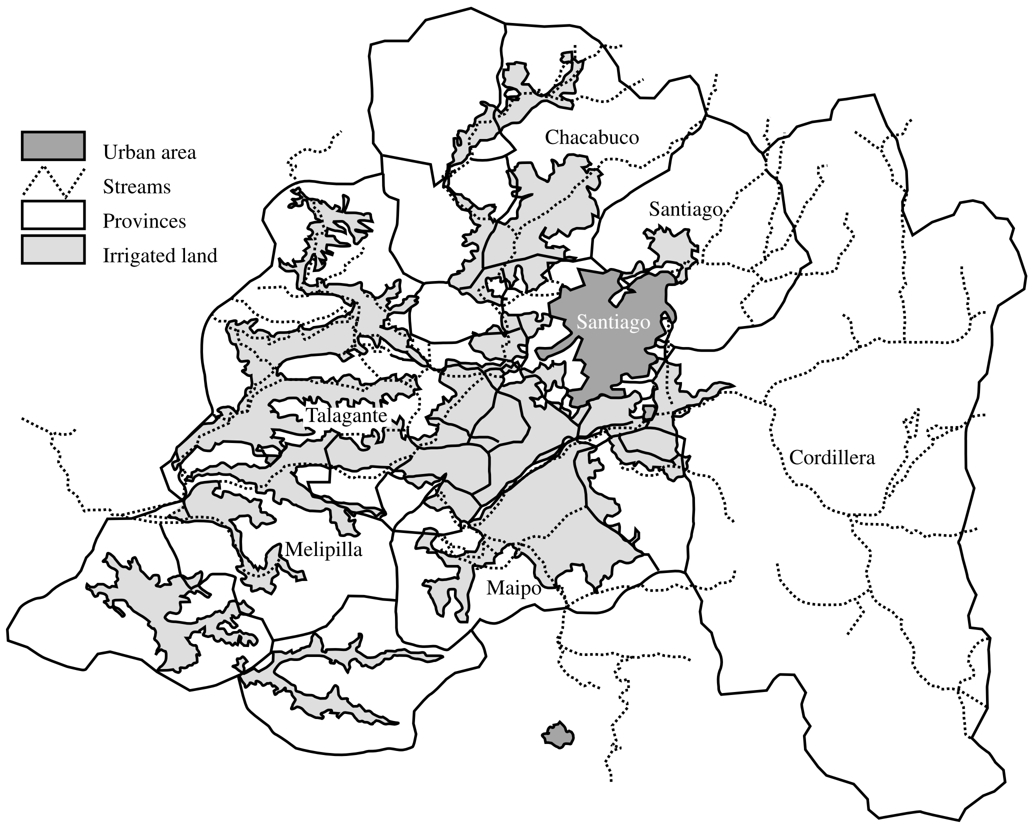
Rainfall. Figure 2.1 shows three climate zones: the northern, central, and southern zones. In the northern zone, agricultural production is not possible without irrigation because of the hydrological deficit generated by low rainfall levels. The central zone is characterized by slightly higher rainfall than the northern zone; however, agricultural production in areas with limited irrigation supplies is restricted to a few crops. The southern zone is similar to the central zone, but the hydrological deficit is lower. Basically, rainfall increases from north to south. The Maipo River Basin is located in the central zone, with its upstream area close to the

Figure 2.1 Location of the Maipo River Basin in Chile



Source: Gazmuri Schleyer and Rosegrant 1996.

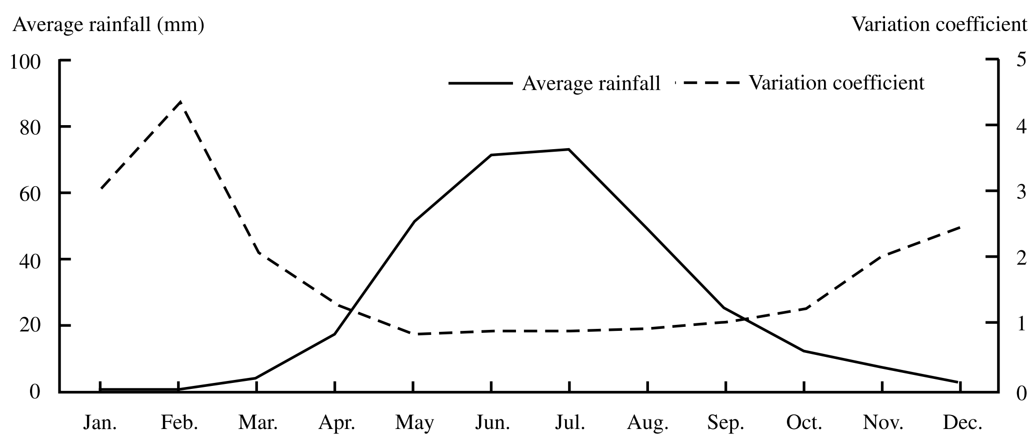
Figure 2.2 Geographic and administrative features of the Maipo River Basin



Note: Stream flow direction is from the mountainous region (Cordillera) to the coast (left side of the map).

northern zone. Figure 2.3 presents long-term (1950–98) average monthly rainfall and variation (represented by variation coefficients) at a rainfall station in Santiago. Variation is relatively high in months with low average rainfall. The lowest monthly variation coefficient is more than 0.85, and the average annual rainfall at the station is 313 millimeters.

Figure 2.3 Average monthly rainfall and variation coefficient, Santiago, Chile, 1950–98



Runoff. The river basin includes the Maipo, the Mapocho, and several smaller tributaries. River fluctuations are predominantly glacial in nature, with considerable flows in summer and very pronounced reductions in winter. Before the inflow of the rivers Yeso and Volcán, which bring 16 and 12 cubic meters per second, respectively, the Maipo carries about 30 cubic meters per second. North of the city of San José de Maipo the Colorado River carries another 26 cubic meters per second, on average. The average annual runoff discharged into the Central Valley amounts to 2,620 million cubic meters (equivalent to 83.5 cubic meters per second), rising to approximately 170 cubic meters per second in the summer and falling to 40 cubic meters per second in the winter months. The variations in daily flow vary between 80 percent and 125 percent of average monthly flows. The hourly variations are less pronounced, normally fluctuating between 90 percent and 120 percent of the daily average. In dry years, the annual runoff drops to some 2,030 million cubic meters (64.5 cubic meters per second).

The Mapocho, a tributary of the Maipo, has a catchment area of 1,005 square kilometers before its emergence into the Central Valley. Its basin lies at a lower altitude than the Maipo, and consequently, though its fluctuations depend largely on melting snow, its extreme low-water flow occurs in the autumn months. Because of the altitude of its basin, the thaws start early in spring, reach their maximum level in November, and fall off rapidly in the summer months. The average annual flow is around 250 million cubic meters (7.9 cubic meters per second), falling in dry years, with a 90 percent probability of the flow exceeding 110 million cubic meters (3.5 cubic meters per second). The daily and hourly flow variations of this river are similar to those of the Maipo. There is a regulating dam in the high cordillera on the El Yeso River, another tributary of the Maipo. The average annual volume entering this dam, which regulates not more than 10 percent of the resources of the Maipo Basin, amounts to approximately 8.3 cubic meters. This reservoir is used for industrial and drinking water only. The Maipo also possesses a natural regulation mechanism in the form of a lake, Laguna Negra, from which water is drawn for domestic and industrial uses, at an average annual rate of 2.5 cubic meters per second, with a potential of 3.0 cubic meters per second. There are no regulation works in the Mapocho Basin, nor do appropriate physical conditions exist for their construction. Renewable groundwater supplies in the basin are very limited. Groundwater is mainly extracted in the central, northern, western, and southwestern sectors of the Santiago urban area, about 10 cubic meters per second. The monthly distribution of surface water sources in the mainstream and major tributaries is shown in Table B.13 of Appendix B.

Water Uses in the Basin

Irrigation is the most significant water use in the Maipo Basin, but there is increasing competition from urban users, especially from the growing metropolitan area of Santiago. Actual water (withdrawal) demands for agricultural, domestic, and industrial uses at the off-take level in the Maipo River Basin are shown in Table 2.2. As can be seen, agriculture accounts for virtually all the water withdrawals in the provinces of Cordillera and Maipo and the basin areas of Melipilla, Talagante, and San Antonio, whereas in the capital region domestic and industrial water demands combined account for more than 80 percent of withdrawals. Irrigated area in the Maipo Basin has been gradually declining as a result of increasing demand by the domestic and industrial sectors for both water and land resources. By the mid-1970s, urban Santiago had already encroached on more than 30,000 hectares of productive irrigated land (Court Moock, Baeza Sommers, and Gómez Díaz 1979). By 2000, the urban area of Santiago had expanded to 55,000 hectares. However, the

Table 2.2 Water demand at the offtake level by hydrologic unit, Maipo River Basin, mid-1990s

Hydrologic units	Total (million cubic meters)	Agriculture (million cubic meters)	Domestic (million cubic meters)	Mining/ industry (million cubic meters)	Demand agriculture/ total (percent)
25[a]	873.3	119.9	512.8	240.7	13.7
26[b]	81.3	76.1	0.2	4.9	93.6
27[c]	1,189.5	1,171.4	17.7	0.5	98.5
Total	2,144.2	1,367.4	530.7	246.1	63.8

Source: Donoso 1997.
[a]Includes the provinces of Santiago and Chacabuco.
[b]Includes the provinces of Maipo and Cordillera.
[c]Includes 0.15, 0.80, and 0.05 percent of the provinces Talagante, Melipilla, and San Antonio, respectively.

closeness to the capital city also provides a profitable outlet for high-value crop production both for local markets and for the dynamic export sector.

Irrigation in the Basin. According to Anton (1993), agricultural areas for basic crops and pastures are irrigated by flooding, with low efficiency of water use because of losses through infiltration and evaporation. Estimates of irrigation efficiency range from 20 to 60 percent depending on local conditions.

Irrigated area is expected to slightly decline in the future because of increasing competition from Santiago for the limited water and land resources. However, despite the ongoing and projected future reduction in crop area, irrigated farming still represents an important land use in the vicinity of Santiago. The basin includes eight large irrigation districts with areas varying between 1,300 and 45,000 hectares (Table 2.3).

Municipal Water Use. Santiago is located in the upper basin of the Maipo River, on a major tributary, the Mapocho. At 3.8 percent per year, the rate of demographic growth in the capital city of Santiago has been slower than those in other large metropolitan centers in Latin America. However, growth is substantial, and the city is the country's economic center. The physical form of Santiago is dictated by the outlying hills of the Andean Cordillera and the coastal range. Originally, the city of Santiago depended on the local rivers for water, especially the Mapocho and the Zanjón de la Aguada, and to a lesser degree on a number of wells that provided water to areas farther from the river channels. With increased urban development, the urban structures have continually encroached on surrounding irrigated land. As a result, numerous canal systems have been absorbed into the city. Although Santiago is situated in the valley of the Mapocho River, the Maipo has for some time become the source of the bulk of the public water supply, and the irrigation canals drawing water from the Maipo, particularly the San Carlos canal, contribute more than half the flow of the Mapocho through the city. The average flows of the Mapocho are far too small to be significant to the modern city (Anton 1993). Table 2.4 presents the monthly volume of municipal surface withdrawals in the Maipo River Basin by hydrologic unit. Although withdrawals do not vary substantially, they are highest during January–March and rise November to December. The variation is most prevalent in the capital region. The distribution loss as a percentage of total water diversion was estimated at 29 percent in 1993, 27 percent in 2000, and was expected to decline to 25 percent by 2005 (Donoso 2001).

Santiago's former water supply distributor, Empresa Metropolitana de Obras

Table 2.3 Irrigation districts in the Maipo/Mapocho Basin

Area	Section	Communities	Irrigated area (hectares)
A	Maipo 1° section	San José de Maipo, Peñaflor, Maipú, Lo Espejo, Paine, Buin, San Bernardo, Calera de Tango, Puente Alto, Pirque, La Florida, La Granja, La Cisterna, Colina, Quilicura, Conchalí, Lampa, Barrancas, Renca, Las Condes, Ñuñoa, La Reina, and Talagante	45,236
B	Maipo 2° section	Isla de Maipo, Paine, and Melipilla	16,600
C	Maipo 3° section	Melipilla	25,330
D	Mapocho before San Carlos channel	Barnechea, Vitacura, and Las Condes	1,278
E	Mapocho between San Carlos channel and Maipo River	Lo Prado, Maipú, Curacaví, María Pinto, Mallarauco, and Melipilla	33,954
F	Angostura River	Codegua, Mostazal, and Paine	2,672
G	Estero Puangue	Curacaví, María Pinto, and Melipilla	3,657
H	Estero Chacabuco, Lampa, Rungue, Tiltil, Colina Alto, and existing drilling in Colina, Polpaico, Tiltil, and Lampa		15,913

Source: Donoso 1997.

Sanitarias (EMOS) was reformed during 1989–90 through a regulatory framework that transformed it into a quasi-concession. Tariffs were set to ensure at least a 7 percent return on assets, a regulating agency was created, and EMOS was given the right to appeal the regulator's tariff decisions. This reform generated significant benefits because (1) Chile has a long tradition of private water rights, shaped by early recognition that water is a scarce and tradable private good; (2) the reformed regulatory framework was designed to attract private investors to the water system and motivate them to operate efficiently and expand the system; (3) Chile's unique electoral institutions sustained this framework under state operation after democracy was restored; and (4) Chile's strong bureaucratic norms and institutions (permitting little corruption), combined with Santiago's relatively low-cost water system, permitted prices that effectively increased quasi-rents for investing in the system, while minimizing the risk of inefficiency or monopoly rents (Shirley, Xu, and Zuluaga 2000).

EMOS was privatized in 1999, when Aguas de Barcelona (Agbar) and Suez Lyonnaisse des Eaux acquired 51.2 percent of the company to form Aguas Andinas. In 2003, the government transferred its remaining shares in Aguas Andinas (36.1 percent) and other water supply companies to the company (Matus et al. 2004). Aguas Andinas serves approximately 6 million people and treats about 70–75 percent of domestic sewage. In 2004, it produced 546 million cubic meters of drinking water, compared with 478 million cubic meters in 1995.

Aguas Andinas obtains water from the following sources: the Maipo River (20.5 cubic meters per second), El Yeso reservoir

Table 2.4 Municipal surface water withdrawals by hydrologic unit, Maipo River Basin (cubic meters)

Period	Hydrologic unit 25[a]	26[b]	27[c]	Total
January	54,121	28.7	1,090	55,240
February	46,961	17.7	2,226	49,204
March	48,110	26.7	1,816	49,952
April	44,202	23.0	1,952	46,177
May	41,408	21.5	1,147	42,577
June	35,326	18.1	2,084	37,429
July	37,661	16.4	890	38,567
August	33,673	15.5	998	34,686
September	39,299	16.1	1,145	40,460
October	39,879	18.5	1,363	41,260
November	45,114	20.9	1,269	46,403
December	46,997	24.0	1,689	48,711
Median	41,167	20.1	1,435	42,622
Annual	512,751	247.2	17,667	530,665

Source: Donoso 1997.
[a]Includes the provinces of Santiago and Chacabuco.
[b]Includes the provinces of Maipo and Cordillera.
[c]Includes 0.15, 0.80, and 0.05 percent of the provinces Talagante, Melipilla, and San Antonio, respectively.

(260 million cubic meters), Laguna Negra (600 million cubic meters), Laguna Lo Encañado (50 million cubic meters), and wells (150 of them providing approximately 3.5 cubic meters per second in the capital area and 1.5 cubic meters per second in the surrounding areas). Most of the surface water is withdrawn from the river at the company's own intake gate or through the adjacent Canal San Carlos (Hearne 1998). Smaller towns are solely provided with groundwater. During a normal year, surface water sources are used because groundwater sources entail pumping costs. In periods of water shortages, groundwater is added as a supply source to maintain some storage in El Yeso. Average water tariffs for urban users in the Maipo Basin in 1997 are shown in Table 2.5.

Industrial Consumption. Supplies for industrial consumption are drawn from the drinking-water distribution networks as well as from privately owned wells and, in a few cases, from irrigation canals. The requirements of this sector have either been

Table 2.5 Average water tariffs, April 1997

Company	Group supplied	Fixed charge (US$ per month)	5 cubic meters per month[a] (US$ per cubic meter)[a]	15 cubic meters per month (US$ per cubic meter)[a]	30 cubic meters per month (US$ per cubic meter)[a]	50 cubic meters per month excess consumption (US$ per cubic meter)[a]
EMOS	1[b]	1.84	1.087	0.843	0.781	0.757
EMOS	2[c]	2.47	1.035	0.704	0.623	0.589
Maipu	1	2.43	0.845	0.522	0.441	0.407
Santo Domingo	1	1.67	1.851	1.320	1.185	1.133
Manquehue	1	2.86	1.015	0.632	0.536	0.498
Lo Castillo	1	1.56	0.716	0.508	0.455	0.433
Los Dominicos	1	1.39	0.704	0.517	0.472	0.453
Servicomunal	1	2.99	1.149	0.718	0.644	0.608
ESVAL	4[d]	2.87	1.346	0.963	0.867	0.829

Source: Donoso 1997.
Notes: Results are based on an exchange rate of 417.58 Chilean pesos to one U.S. dollar. EMOS indicates Empresa Metropolitana de Obras; ESVAL indicates Empresa de Servicios Sanitarios de Valparaíso.
[a]Includes potable water service and sewerage charges.
[b]Includes communities in Santiago.
[c]Includes rural areas served by EMOS.
[d]Includes communities San Antonio and Cartagena–San Sebastián served by ESVAL.

Table 2.6 Hydropower stations, Maipo River Basin

Station	Owner	Installation	Flow (cubic meters per second)	Height (meters)
Alfalfal	Chilegener Sociedad Anonima	1991	30.0	721
Maitenes	Chilegener Sociedad Anonima	1923 and 1989	11.3	180
Queltehues	Chilegener Sociedad Anonima	1928	28.1	213
Volcán	Chilegener Sociedad Anonima	1944	9.1	181
Puntilla	Compañía Manufacturera de Papeles y Cartones	NA	18.8	92
Los Bajos	Carbomet Energía	NA	16.4	63
Carena	Compañía Manufacturera de Papeles y Cartones	NA	11.2	102
La Ermita	Compañía Minera Disputada de Las Condes	NA	3.0	140
Florida	Sociedad de Canalistas del Maipo	1909	22.0	98
Planchada				

Note: The Planchada hydropower station ceased operation about 1989. NA indicates that data were not available.

partially included in those already mentioned or are obtained independently.

In 1997, the industrial and mining water demand in the Maipo Basin was estimated at 279 million cubic meters.

Hydroelectricity. The existing electric-power-generating stations are run-of-the-river stations and therefore do not adversely affect other users, particularly as there are no significant fisheries in the basin. The only dam and reservoir, El Yeso, is currently solely used for municipal water supply. Table 2.6 gives an overview on the existing run-of-the river hydropower stations.

Challenges for Water Allocation in the Basin

Water policymakers in the Maipo River Basin face several challenges. Agricultural areas for staple crops and pastures still use flood irrigation, with low efficiency of water use because of infiltration and evaporation losses. As a result of increasing competition from urban demands for the limited water and land resources, decreases in irrigated area are expected in the future. However, in spite of probable future declines, the production of high-value crops will continue to present an important land use in the vicinity of Santiago.

Problems of Water Quantity

Lack of sufficient water availability to ensure continued growth of all water-using sectors has been discussed for many years in the Central Valley. During the 1970s it was proposed to increase the water supply by means of diversion from the Cachapoal River, the next larger river to the south. This diversion would have satisfied the needs of metropolitan Santiago, the maintenance and even the expansion of irrigated areas, and further dilution of waste discharges, but it was never implemented (Court Moock, Baeza Sommers, and Gómez Díaz 1979).

Problems of Water Quality

With most water resources in the Maipo Basin fully utilized and demand continuing to grow unabated, particularly for domestic and industrial water uses, water available for waste dilution has declined dramatically in the basin. Water quality levels vary markedly between the Maipo and Mapocho rivers. The Maipo River basically bypasses the city of Santiago and is fed by glacial melt, but it contains high levels of certain minerals. The Mapocho has significant upstream mining activities and flows through Santiago, where it has basically been transformed into a sewage canal. Following the construction of the El Trebal and La Farfana treatment plants in 2001 and 2003, respectively, 75 percent of all domestic sewage in metropolitan Chile is now treated, and water quality levels have improved.

Upstream, the Maipo River has a high pH value, and some tributaries contain sulfur and calcium. Salinity levels in that reach are slightly elevated (800–1,300 millimhos per centimeter). Moreover, levels of calcium, iron, and magnesium are elevated. Water quality levels are much lower in the middle and lower reaches of the river as a result of untreated sewage, liquid or solid industrial effluent, and pollution from runoff of agricultural chemicals. The highest levels of fecal coliforms can be found at the confluence of the Mapocho and Puangue rivers and close to the mouth of the Maipo River.

The Mapocho River has high levels of calcium sulfate and low salinity levels that increase as the river passes through Santiago. The pH value reaches 7.78 at the confluence with the Maipo River. Levels of arsenic and iron are at acceptable levels, but nitrate levels are generally high as a result of point and nonpoint discharges into the river. High levels of boron limit some crop production in the Arrayan area and also in Talagante, while elevated levels of copper upstream make Mapocho water unsuitable for drinking or irrigation purposes, but levels gradually decline as the water flows downstream.

In the past, irrigation of vegetable crops with city sewage was an important health hazard (Anton 1993). New regulations on irrigation and sewage treatment have largely eliminated this problem. Prior to sewage treatment, the government had to spend large sums to decontaminate arable lands. In 1990, for example, 130,500 hectares were contaminated. Between 1990 and 1993, significant investments—amounting to US$39.3 million—were made, which allowed 12,700 hectares to be decontaminated; about 117,800 contaminated hectares remained (Bolelli 1997). Little is known about pesticide contamination in the Maipo River Basin. The point-source pollution from industrial operations in the basin has had significant adverse effects on the health of the river, given the large number of industrial operations and the many years of untreated industrial discharge. In particular, dissolved, suspended, and sedimentable solids, biological oxygen demand, nitrogen, phosphorous, oils and grease, and total and fecal coliform rates have been high (CADE–IDEPE 2004). Because of its low sodium content and medium-to-high salinity level, Maipo water is satisfactory for irrigation purposes in well-drained soils. The copper and arsenic content in Mapocho water, however, can be harmful for agricultural uses.

Other contributors to poor water quality include upstream deforestation, soil erosion as a result of deforestation and other unsustainable land use practices, and significant extraction of sand from river beds. In the coming years, both climate variability and climate change will likely become important contributors to adverse river water quality.

Water Allocation Mechanisms

In semiarid regions such as the Maipo Valley, where water is a limiting factor for development, enhanced efficiency in all uses becomes critical. Physical efficiency is measured in terms of output per unit of input: in this case agricultural or industrial production or urban domestic supply services per cubic meter of water entering the system. The process is generally one of substituting factors, that is, capital or labor, in the form of improved technologies, for water. Reducing agricultural water demands would clearly improve the flexibility of any management authority in dealing with conflicts and competition, which will inevitably arise as the multiple demands on water intensify with development.

The policy instruments available for demand management include (1) enabling conditions, which are actions to change the institutional and legal environment in which water is supplied and used (for example, reform of water rights, privatization of utilities, and laws pertaining to water user associations); (2) market-based incentives, which directly influence the behavior of water users by providing incentives to conserve on water use (such as pricing reform and reduction in subsidies on urban water consumption, water markets, effluent or pollution charges, and other targeted taxes or subsidies); (3) nonmarket instruments, such as restrictions, quotas, licenses, and pollution control; and (4) direct interventions, such as conservation programs, leak detection and repair programs, and investment in improved infrastructure (Bhatia, Cestti, and Winpenny 1995). The precise nature of water policy reform and the policy instruments to be deployed vary from country to country, depending on the underlying conditions such as the level of economic development and institutional capability, the relative water scarcity, and the level of agricultural intensification. The mix of policy instruments will also vary from river basin to river basin, depending on the structural development of the different sectors in the region, prevailing rights to natural resources, relative water shortages, and other basin-specific characteristics. Therefore, no single recipe for water policy reform can be applied universally, and additional research is required to design specific policies within any given country, region, and basin. However, some key elements of a demand management strategy can be identified. The process of reallocating water from agriculture to other uses, for example, can likely be better managed through the reform of existing administrative water management organizations, through the use of incentive systems, such as volumetric water prices and markets in tradable water rights, and through the development of innovative mixed systems of water allocation.

Many studies have shown that prices do play a decisive role in the behavior of water users, and pricing reform is certainly an important instrument for saving water in urban areas. The choice between administered prices and markets should be largely a function of which system has the lowest administrative and transaction costs. Markets for tradable water rights can reduce information costs because the market bears the costs and generates the necessary information on the value and opportunity costs of water. Second, in existing irrigation systems, the value of the water right is often inherently reflected in the value of the irrigated land. In this case, water fees could be considered as an expropriation of the traditionally free access to water. Markets in tradable water rights empower the water user by requiring user consent to any reallocation of water and compensating the user for any water transferred. Moreover, they provide security to the water user. If well-defined rights are established, the water user can benefit from investments in water-saving technologies. In addition, a system of marketable rights to water induces water users to consider the full opportunity cost of water, including its value in alternative uses, thus providing incentives to economize on the use of water and gain additional income through the sale of saved water. Finally, a properly managed system of tradable water rights provides incentives for water users to internalize (or take account of) the external costs imposed by their water use, reducing the pressure to degrade resources. Market allocation can provide flexibility in response to water demands, permitting the selling and purchasing of water across sectors, across districts, and across time by opening opportunities for exchange where they are needed. The outcomes of the exchange process reflect the water scarcity condition in the area with water flowing to the uses where its marginal value is highest (Rosegrant 1997). Markets also provide the foundation for water leasing and option contracts, which can quickly mitigate acute, short-term urban water shortages while maintaining the agricultural production base (Michelsen and Young 1993).

Establishment of markets in tradable property rights does not imply free markets in water. Rather, the system would be one of managed trade, with institutions in place to protect against third-party effects and potential negative environmental effects that are not eliminated by the change in incentives. The law forming the basis for the allocation of water through tradable rights should be simple and comprehensive; clearly define the characteristics of water rights and the conditions and regulations governing the trade of water rights; establish and implement water rights registers; delineate the roles of the government, institutions, and individuals involved in water allocation and the ways of solving conflicts between them; and provide cost-effective protection against negative third-party and environmental effects that can arise from water trades (Rosegrant and Binswanger 1994; Rosegrant 1997).

Water allocation systems in the real world will most likely be mixed both in ownership (combining aspects of public and private ownership of water supply infrastructure and water rights) and in overriding water allocation principles (combining administrative/regulatory approaches with market/incentive-based approaches). Decentralization and privatization will increasingly create systems with public ownership and management down to a certain level in the distribution system and user-based ownership below that level. For water market systems to be efficient and equitable, judicious regulation will be required.

The Chilean Water Law of 1981 established the basic characteristics of property rights over water as a proportional share over a variable flow or quantity. Rights can be consumptive or nonconsumptive; their exercise can be permanent or contingent, continuous or discontinuous; and rights may alternate among several people. Changes in allocation of water within and between sectors are realized through markets in tradable water rights (Gazmuri Schleyer and Rosegrant 1996). More recently, a series of reforms of the current Water Law have been proposed. The proposed reforms concern, in particular, water rights to nonconsumptive instream uses such as environmental and hydropower generation.

In the Maipo River Basin, water transactions are carried out within river sections. The Maipo River, for example, is divided into three sections, and the Mapocho River into five sections. Some of these sections are overseen by a Junta de Vigilancia (Water User Association). Table 2.7 presents an example of the shareholders of the first section of the Mapocho River.

A comprehensive analysis of all water transactions in the Maipo Basin is not available. However, an examination of the water register of Santiago County provides a picture of the magnitude and type of transactions undertaken. During 1993/94, the water register of Santiago County, which covers 12,000 hectares of irrigated land, had 587 permanent transactions inscribed. Some 13 percent were between farmers, representing 94 percent of the transferred water; 85 percent were agriculture–urban, representing about 3 percent of the transferred water; and 2 percent were agriculture–mining, representing 1 percent of the transferred water. The amount of water involved in transactions was about 3 percent of the total water rights held, indicating an active water market. Agriculture–urban sales are numerous, but of very small size compared with sales within agriculture (Gazmuri Schleyer and Rosegrant 1996). In the Pirque Canal, one of 10 canals in the first section of the Maipo River, a total of 56 permanent transactions were recorded during 1994–98, corresponding to 1.1 percent of total rights in the canal. Buyers included 1 agricultural company, 2 industries, 34 investment and other service companies, and 19 individuals, whereas vendors included 3 agricultural companies, 14 service companies, and 39 individuals.

Most transactions carried out in the basin are temporary rentals of water, or water swaps between nearby farmers with different water requirements during different periods. Renting or swapping water offers greater flexibility for irrigation and increases efficiency. These farmer-to-farmer water rentals take place only between farmers irrigating from the same or nearby canals because of excessive transaction costs of long-distance trades. They do not have to be

Table 2.7 Main water rights holders, first section, Mapocho River, September 1999

Name	Permanent right	Contingent right
Compañía Minera Disputada de Las Condes	4,063.0	500.0
Empresa de Agua Potable Aguas Cordillera Sociedad Anonima	1,358.7	500.0
Canal El Bollo	805.3	26.8
Inversiones Libardon Sociedad Anonima	500.0	
Canal Vitacura	426.5	6.5
Canal La Dehesa	411.7	
Canal Unidos	103.5	
Canal Bajo Potrerillos	90.0	90.0
Canal Alto Potrerillos	50.0	60.0
Ilustre Miunicipalidad de Las Condes	41.0	
Empresa de Agua Potable Valle Nevado Sociedad Anonima		105.0
Corporacion de Adelanto de Farellones	26.0	
Empresa de Agua Potable El Colorado Sociedad Anonima	17.7	
Sociedad Agrícola Las Condes Ltda.	12.0	
Andrés Maira Rojas	12.0	
Canal Lo Matta	8.8	
Empresa de Agua Potable y Alc. La Leonera Sociedad Anonima	8.0	
Asociación de Vecinos La Parva	8.0	
Inmobiliaria Dominicos Oriente Sociedad Anonima	7.5	
Sociedad de Andariveles de Cordillera Sociedad Anonima	4.3	8.0
Asociación Cristiana de Jóvenes (YMCA)	3.3	1.7
Distribución y Servicio D&S Sociedad Anonima	2.5	
Comunidad Campos France	2.0	
Miguel Limmer Pfeilstetter	1.5	
Otros Usuarios (five individuals)	0.9	0.8
Total	7,964.3	1,298.8

Source: Donoso 1999.

Notes: Section one of the Mapocho River extends from the Cordillera mountains to the flow of Canal San Carlos into the Mapocho River. Major tributaries are the Molina and San Francisco rivers and the Arrayan stream. Not all rights are used, and irrigation and domestic use rights are differentiated.

registered in the respective Water Registry (Fernando Peralta Toro, personal communication, December 2000).

Romano and Leporati (2002) examine the consequences of water trading in the Limari River in northern Chile during 1981–97. The study shows that the market is active, albeit imperfect with barriers to entry and asymmetric information. The authors report that the share of farmer water rights declined over time, with adverse effects on farm production and incomes, whereas water rights in the nonagricultural sectors increased. However, the authors do not answer the question if the institution of water rights trading accelerated or slowed this development in that region.

This study, by developing and applying an integrated economic–hydrologic policy analysis tool to the Maipo River Basin, allows examining the effect of alternative water allocation institutions on water demand and use by sector and farmer profits, including the role of tradable water use rights. The policy analysis tool combines economic relationships that represent the behavior of the various water use sectors with a reasonably detailed physical setting depicting the basin hydrology, water supply facilities, water availability and water quality, and water use systems. Chapter 3 presents the modeling framework.

CHAPTER 3

Modeling Framework

The development of an integrated economic–hydrologic modeling framework at the basin scale can be almost infinitely complicated. Therefore, it is essential to make sensible choices at the outset to determine the priority variables, parameters, and processes to be handled by the model. Any model of this type might include the following essential elements:

- Consistent accounting for water storage and flows, diversions at each location and sector, actual consumptive use of water by location and sector, and return flows to the river system
- Integrated accounting of the flow and generation of pollutants through the river basin
- Representation of the demand for water and the economic benefits from water use at each demand site (irrigation district, municipal and industrial [M&I] use, and other sites), and of the effect of water and soil pollutants on the economic benefits from water use by location and sector
- Consideration of both instream and off-stream water uses, where instream uses include flows for waste dilution, the environment, and hydropower generation, and off-stream uses include water diversion for agricultural, municipal, and industrial water uses
- Incorporation of institutional rules and policies that govern water allocation for each sector at each location, including priority allocations, customary practices, water rights, water prices, restrictions on trading, and so forth, identified based on research regarding the institutions for water allocation in place (institutions can be represented as constraints in the model, and effects of institutions on benefits from water use can be assessed by alteration or elimination of the rules)

The development of such an empirical model therefore should concentrate on (1) the hydrologic/mechanistic characteristics of water allocation in the river basin and (2) the representation of economic benefits and environmental consequences of water use in the agricultural and nonagricultural sectors in the basin. The valuation of instream uses is not included explicitly in the modeling framework; instream water requirements are represented as constraints.

A geographic information system (GIS)–based database was developed for the modeling work. It provides a complete depiction of the physical and thematic characteristics of the river basin. GIS coverages include administrative boundaries, rivers and streams, reservoirs, irrigated area, and soil distribution. The attributes associated with these features are stored in tabular form in ArcView (GIS software). Hydrologic parameters, for example, monthly average precipitation, temperature, net radiation, and soil water surplus are also represented by geographic themes. GIS also provides the means to calculate reference crop evapotranspiration and effective rainfall for individual crops based on empirical relationships (Doorenbos and Pruitt 1977).

Model outputs are stored as attributes in the node and link features of the river basin network represented in the GIS coverage and visualized display functions and spatial analysis functions are provided for the outputs. A detailed description of the GIS-based database is provided by McKinney and Cai (2002).

The River Basin Network

The river basin model is developed as a node-link network with nodes representing physical entities and links the connection between these entities. Figure 3.1 shows the schematic basin network of the Maipo River Basin. Nodes in the network include source nodes, such as river reaches and tributaries, reservoirs, groundwater aquifers, and demand nodes for irrigation (*irr-d*), M&I areas (*m&i-d*), and hydropower production (*pwst*) (other instream ecological demand sites can be included if necessary). These nodes are spatially connected to the basin network. Spatial elements for the hydrologic component are delineated so that the spatial variability of water resources and demands are sufficiently reflected, while maintaining the boundaries and continuation of the hydrologic system. Major reservoirs and aquifers are identified as separate source nodes, whereas smaller reservoirs are neglected, and those of equal purpose on the same tributary are aggregated into a single reservoir.

Tributaries associated with major reservoirs, those with water outlet(s) to demand sites, and those with major flow contribution are identified as separate nodes. Features on the main river that need to be identified include (1) the confluence of tributaries with the main river; (2) the location of reservoirs; (3) the offtakes from and return flow sites to the river; (4) the locations of importance for ecological and environmental flows and water quality, such as the outflow to the sea; and (5) additional river reaches for an adequate resolution of the flow balance.

Demand nodes are aggregated based on (1) the distribution of water demands, (2) the water conveyance/distribution system, and (3) administrative boundaries. Large cities are treated as separate M&I demand sites. Irrigation demand sites are delineated considering the boundaries of both the water distribution system and administrative units.

The node-link network originates from the traditional reservoir system (Loucks, Stedinger, and Haith 1981) that relates a single reservoir (source node) with a single water demand site (demand node) or to multiple reservoirs and multiple demand sites along a river reach or within a sub-basin, and finally to various source nodes and various demand nodes in the scope of an entire basin, as described above. Several water management models use the basin network as the underlying foundation, including the Interactive River–Aquifer Simulation model (IRAS) (see Loucks, Taylor, and French 1996) and the Water Evaluation and Planning System (WEAP) developed by the Stockholm Environment Institute–Boston Center (SEI 2005). Compared with those models, the river basin model presented here incorporates additional details, focusing, in particular, on the economic behavior of various water users.

Hydrologic, agronomic, and economic components or processes that are linked to specific nodes and links in the basin network structure are described in the following sections.

Hydrologic Processes

Hydrologic processes considered in the model are shown in Figure 3.2. They include reservoir operations, flow distribution, conveyance and recycling, irrigation water use, and interactions between surface and groundwater. Figures 3.3 and 3.4 describe the water balance at the crop field level and the balance at M&I demand sites, respectively.

The major hydrologic relations include

- flow distribution and conveyance and salt transport and balance from river outlets/reservoirs to crop fields or municipal sites;

Figure 3.1 The Maipo River Basin network

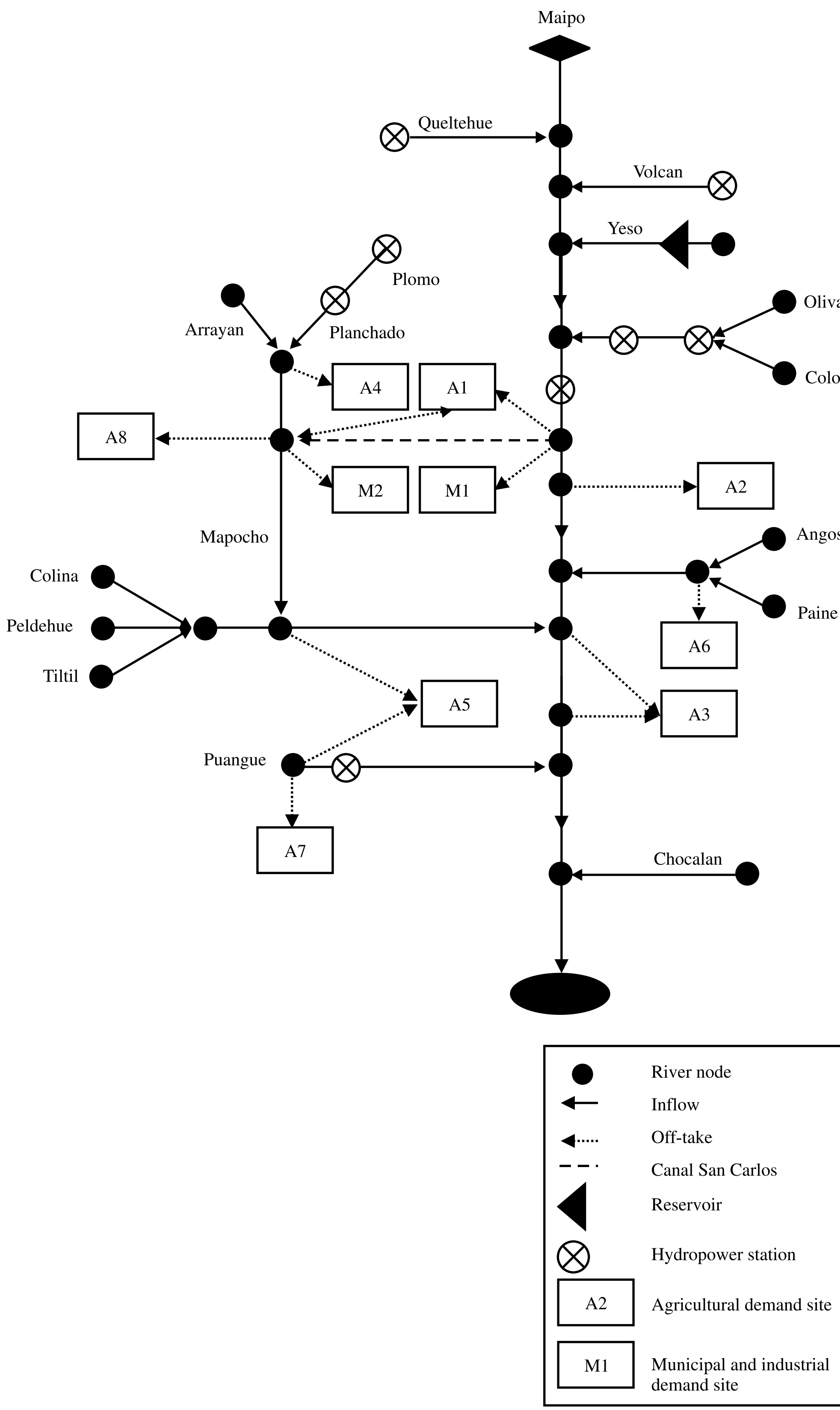


Figure 3.2 Conceptual framework of a basin model—Hydrologic processes and water uses

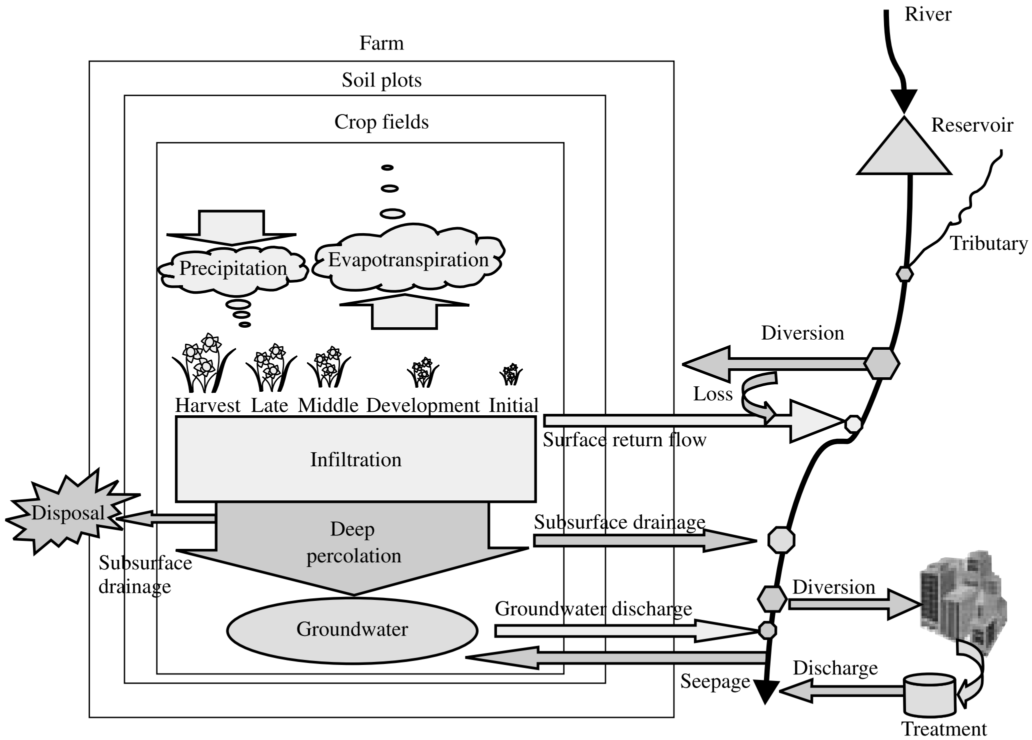
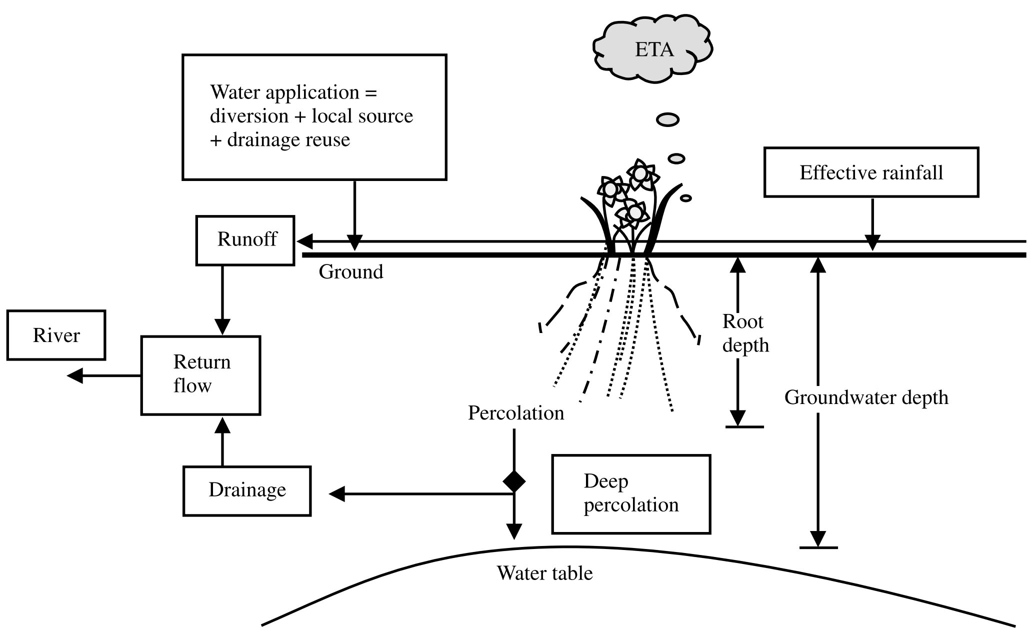
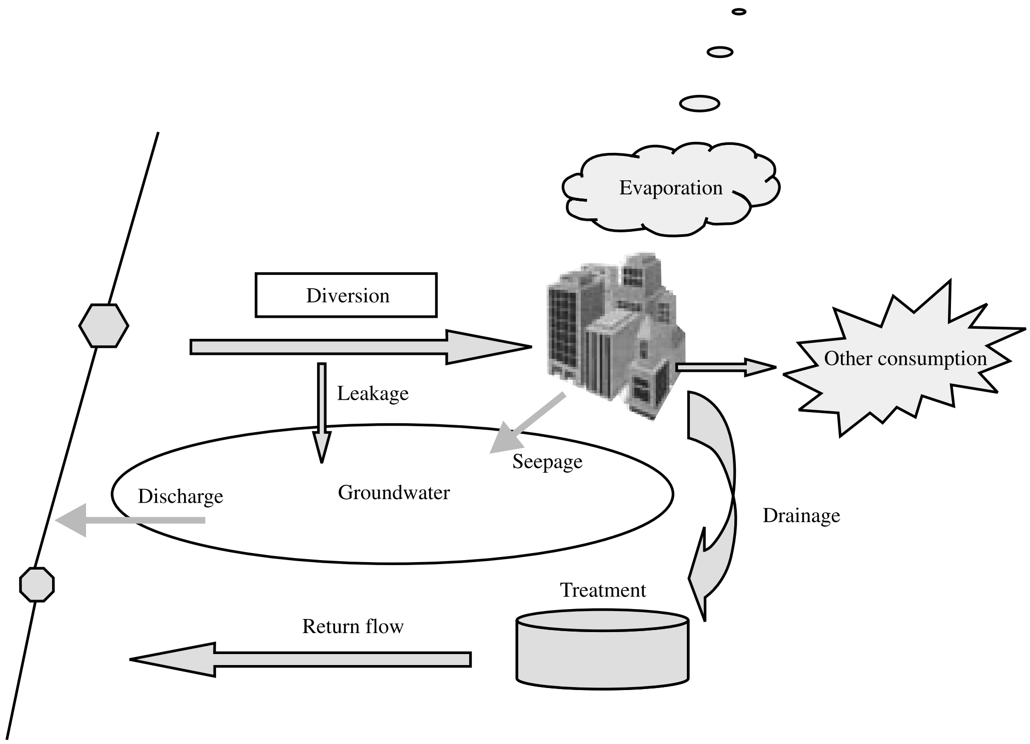


Figure 3.3 Hydrologic processes considered in the crop field



Note: ETA indicates actual crop evapotranspiration.

Figure 3.4 The relationship between municipal and industrial sites and the hydrologic components



- recharge to and discharge from surface and groundwater;
- crop evapotranspiration from fields;
- effective rainfall (rainfall stored in the crop root zone, which can be used for crop growth);
- water balance in the crop root zone, including surface runoff, percolation, drainage, and groundwater abstraction;
- water balance in M&I demand sites, including water distribution, seepage or leakage, drainage, and treatment;
- return flow from irrigated and M&I areas; and
- hydropower generation.

The mathematical expressions for these relations are described in detail in Appendix A. For groundwater sources, a single aquifer or tank is assumed for each demand site. Monthly water balances and yearly salinity balances are calculated for each tank, considering inflows to the tank (natural recharge, deep percolation, surface water seepage) and outflows from the tank (pumping, subsurface drainage). No connections between tanks are considered. A description of the hydrologic and agronomic relationships is also provided in Cai, McKinney, and Lasdon (2003).

The rainfall-runoff process is not included in the model. Water supply is assumed to start from rivers and reservoirs, and effective rainfall is calculated externally to the model and input to the model as a constant parameter.

Economic Components

Crop Yield and Irrigation Profit Functions

A highly generalized crop yield function that incorporates water quantity and quality, and irrigation technology is adapted for the river basin model. Relationships among the yield parameters for the various crops have been determined based on a crop simulation model adapted from Letey and Dinar (1986) (see also Dinar and Letey 1996), and coefficients for the various crops have been estimated through regression analysis based on a number of simulations under various combinations of water application, irrigation technology, and water quality. The yield function is specified as a nonlinear function of water application, irrigation technology, and water quality, that is,

$$y = \frac{y_a}{y_m} = a_1 + a_2 \cdot w + a_3 \ln w, \qquad (3.1)$$

where $w = WF/ET;$ $a_1 = b_1 + b_2u + b_3c;$ $a_2 = b_4 + b_5u + b_6c;$ $a_3 = b_7 + b_8u + b_9c;$ WF is the water applied to the crop field (millimeters); ET is crop potential evapotranspiration (millimeters); Y_a is crop yield (metric tons per hectare); Y_{max} is maximum attainable yield (metric tons per hectare); a_1, a_2, and a_3 are regression coefficients; b_1–b_9 are regression coefficients; c is the salt concentration in water application (grams per liter); and u is the Christiansen Uniformity Coefficient (CUC) (Christiansen 1942), which is used as a proxy for field irrigation technology.

The CUC value (typically within a range of 50–100) for a given field varies by irrigation system, technology, and management (Dinar and Letey 1996, 54).

A typical production function for wheat in the Maipo River Basin based on this crop model is shown in Figure 3.5. Figure 3.6 presents relative yield versus relative water under three salinity levels (with constant CUC or $u = 70$), also for wheat. As expected, relative yield is lower at higher levels of salinity. Figure 3.7 shows the same relationship under three levels of irrigation technology (with constant salinity concentration in the irrigation water of 1.0 grams per liter). Again, relative yield is highest under the highest level of CUC, which represents a higher level of irrigation technology. The

Figure 3.5 Production function, crop (wheat) yield versus water application (indicator of irrigation technology, Christiansen Uniformity Coefficient CUC = 70, salinity = 0.7 grams per liter)

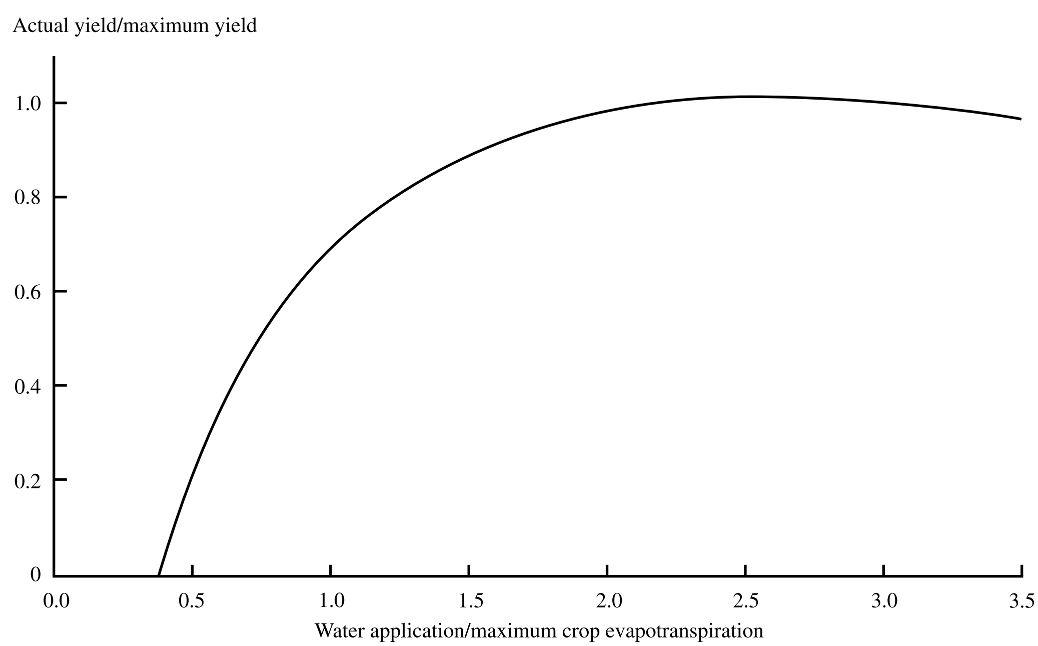
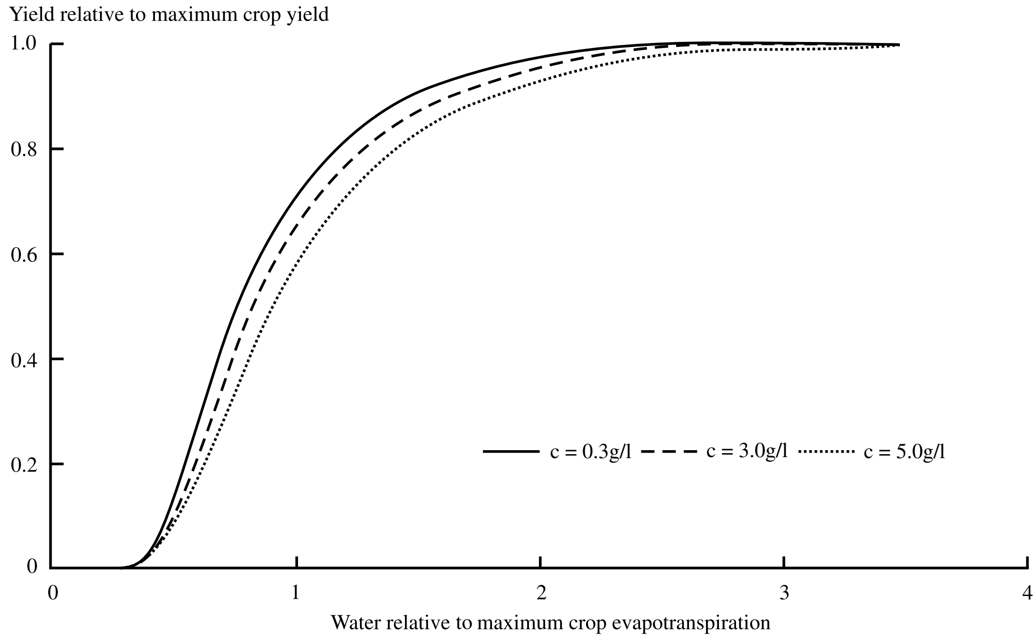
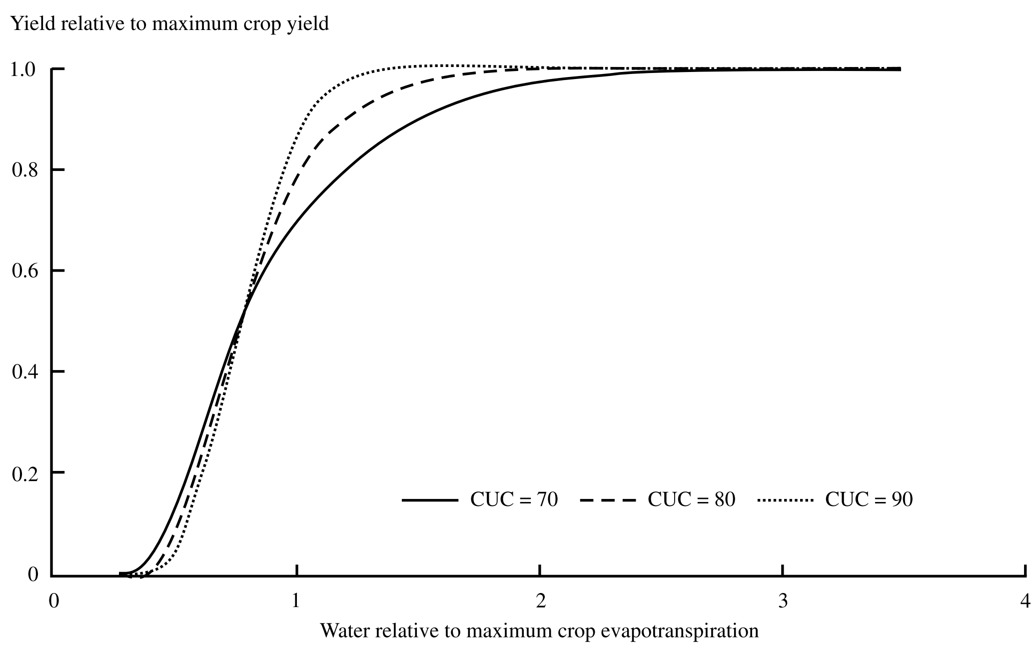


Figure 3.6 Yield salinity relationship, example of wheat



Note: c indicates the salt concentration.

Figure 3.7 Yield versus crop water use under different levels of irrigation technology (Christiansen Uniformity Coefficient [CUC]), example of wheat



regression coefficients for 15 irrigated crops in the Maipo River Basin are presented in Table B.8 of Appendix B.

The derivative of crop yield (y) with respect to water (w) is:

$$y'_w = b_4 + b_5 u + b_6 c + (b_7 + b_8 u + b_9 c)/w, \quad (3.3)$$

and according to the first-order condition, $y'_w = 0$, the optimal water application (w^*) with given u and c is:

$$w^* = -(b_7 + b_8 u + b_9 c)/(b_4 + b_5 u + b_6 c). \quad (3.4)$$

Figure 3.8a plots w^* versus u for a given value of salinity or c (c = 0.3 grams per liter), and Figure 3.8b plots w^* versus c for a given value of CUC or u (u = 70) for irrigated wheat. As can be seen, w^* decreases with u and increases with c, which shows a substitution between water and irrigation technology and a substitution between water quantity and water quality (that is, if water with high salinity is applied, then a larger amount of water is needed for salt leaching in order to generate the same crop yield.

The first derivatives of y with respect to u and c are shown in the following two equations, respectively:

$$y'_u = b_2 + b_5 \cdot w + b_8 \cdot \ln(w), \text{ and} \quad (3.5)$$

$$y'_c = b_3 + b_6 \cdot \ln(w). \quad (3.6)$$

As an example, Figures 3.9a and 3.9b present the first derivatives of y of corn and grapes with respect to u and c, respectively, versus water application (relative to potential crop ET). As expected, y'_u is positive, and y'_c is negative. The relationship between y'_u and w is concave, and the curve for y'_c versus w is convex. Marginal yield increases with irrigation technology and reaches a peak value at approximately w = 1.5, that is, when water application is about 1.5 times the crop potential ET for both corn and grapes. The marginal yield decreases with salinity and for grapes reaches a low point at about w = 1.0, when water application is close to the crop potential ET. At water ap-

Figure 3.8a Relationship between optimal water application and field irrigation technology under given value of irrigation salinity, example of wheat (c = 0.3 grams per liter)

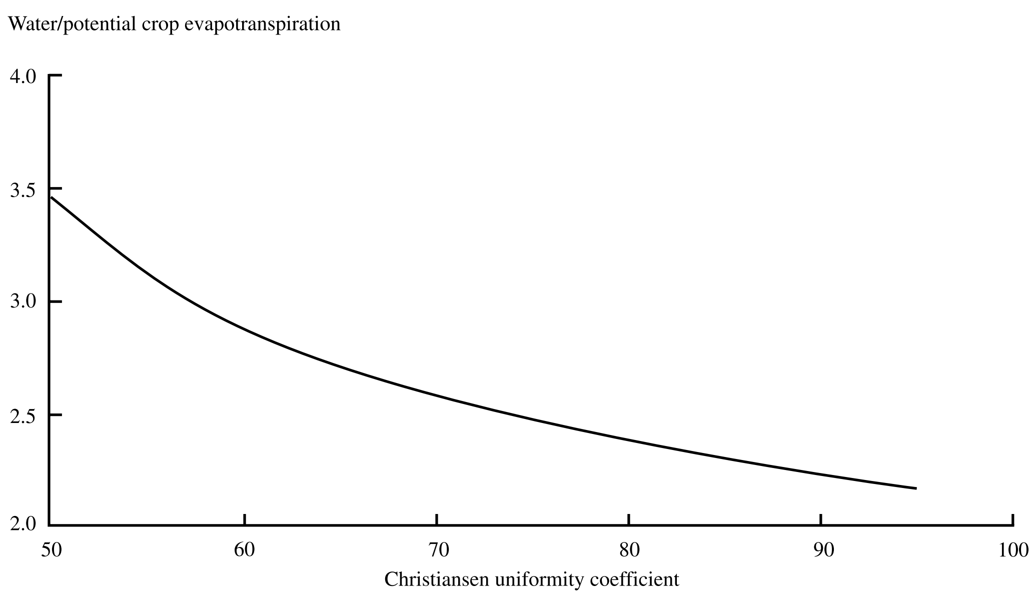
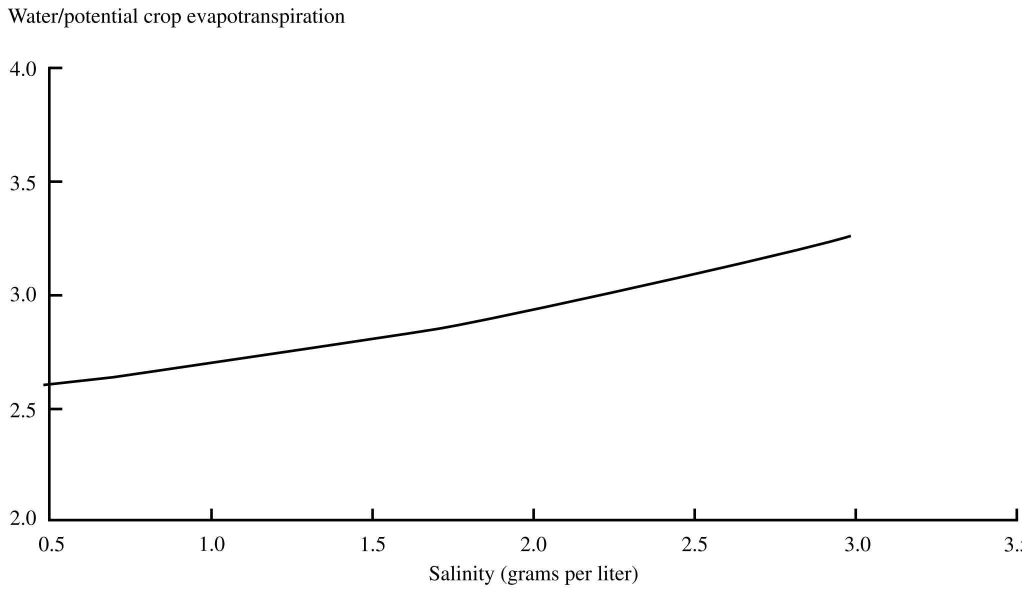


Figure 3.8b Relationship between optimal water application and irrigation salinity under given value of field irrigation technology, example of wheat (u = 70)



plication levels where $w < \mathrm{ET}$, no water can be used for salt leaching, and soil salinity accumulates with increasing water application. Only after $w \geq ET$ can a fraction of water be used for salt leaching, and the effect of salinity declines with an increased leaching fraction. For corn, on the other hand, marginal yield continues to decline even at higher levels of water application, but at lower rates.

Figure 3.9a Relationships between first partial derivative of crop yield with respect to irrigation technology (y'_u), for corn and grapes, and water use relative to maximum crop evapotranspiration (w)

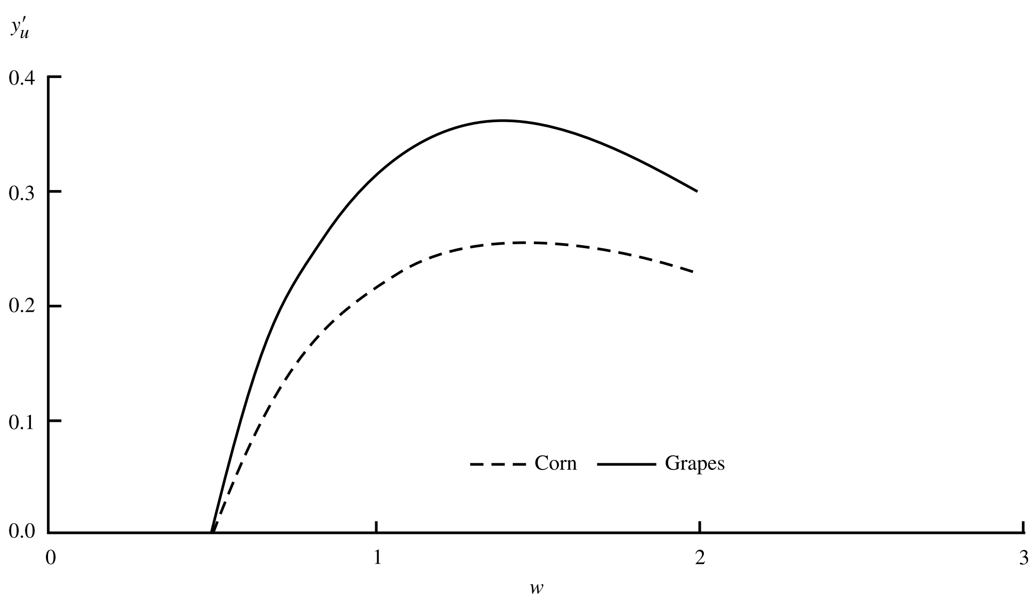
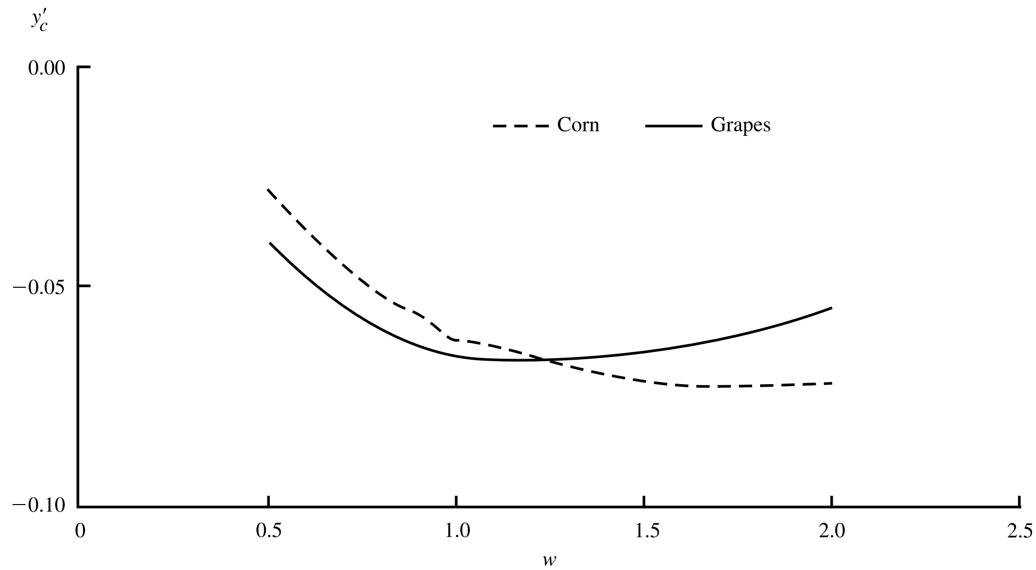


Figure 3.9b Relationships between first partial derivative of crop yield with respect to salinity (y_c') for corn and grapes, and water use relative to maximum crop evapotranspiration (w)



The second partial derivatives of y with respect to w and to u or c are shown in equations 3.7 and 3.8, respectively:

$$y''_{wu} = b_5 + b_8/w, \text{ and} \tag{3.7}$$

$$y''_{wc} = b_6 + b_9/w. \tag{3.8}$$

Figures 3.10a and 3.10b present the second derivatives of y of corn and grapes for the relationship between w (relative to crop ET) and u and between w and c, for corn and grapes, respectively. The second derivative of yield with respect to irrigation technology, y'_{wu}, is positive but declines with increased water application. Thus, at low levels of water application, irrigation technology contributes relatively more to marginal crop yield; this contribution declines at increased water application. The second derivative of yield with respect to salinity in the irrigation water, y'_{wc}, is negative but increases with increased water application. Thus, at low levels of water application, the damage to marginal crop yield caused by salinity (in the applied water) is high; and damage is reduced with increased water application.

The function for profits from irrigation (VA) is calculated as gross crop profits minus crop planting costs and water fees:

$$\begin{aligned} VA^d = & \sum_{cp} ACP^{d,cp} Y^{d,cp} p^{d,cp} \\ & - \sum_{cp} ACP^{d,cp}(fc^{d,cp} + tc^{d,cp}) \\ & - \sum_{pd} (ws^d_{pd} \cdot wps^d + wg^d_{pd} \cdot wpg^d) \end{aligned} \tag{3.9}$$

where ACP is the irrigated area for each crop at each demand side, Y is irrigated yield, p is crop price, fc is fixed crop cost, tc is irrigation technology cost, ws is surface water, wg is groundwater, and wps and wpg are the respective water prices.

$$tc = \mathrm{k}_0 \cdot 10^{(-\mathrm{k}_1 \cdot tek)}. \tag{3.10}$$

Crop yield is calculated as a function of seasonal relative water (to maximum crop evapotranspiration), salinity in irrigation water, and irrigation technology. Equation 3.10 calculates the cost for irrigation technology following Dinar and Letey (1996). Irrigation technology is represented by CUC, and k_0 and k_1 are regression

Figure 3.10a Relationship between second partial derivative of crop yield to water and irrigation technology ($y''_{w,u}$) for corn and grapes, and water use relative to maximum crop evapotranspiration (w)

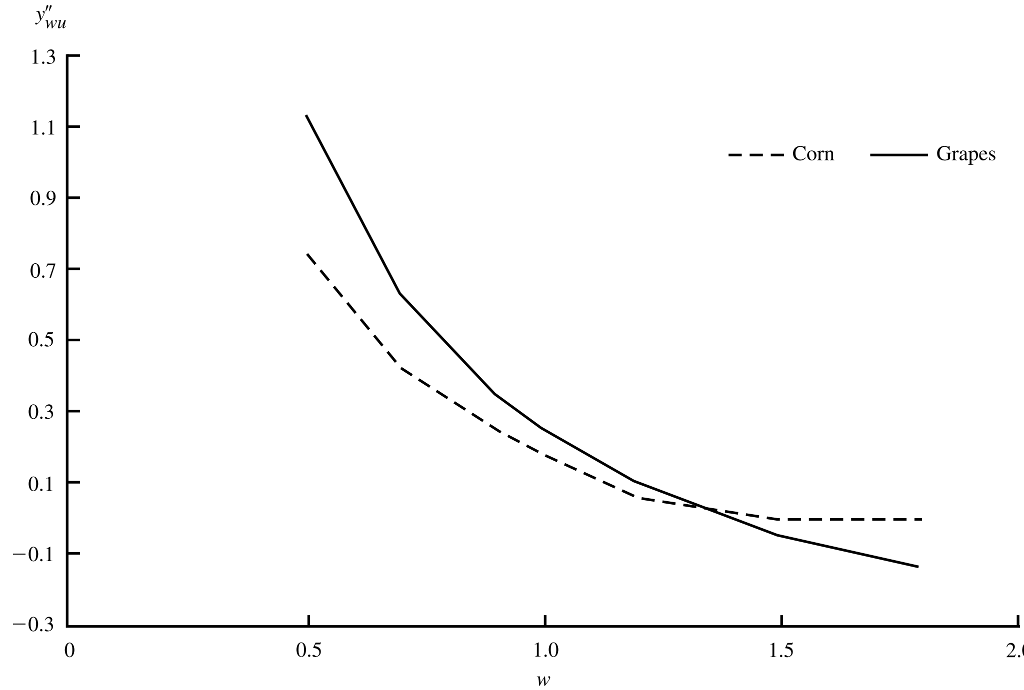
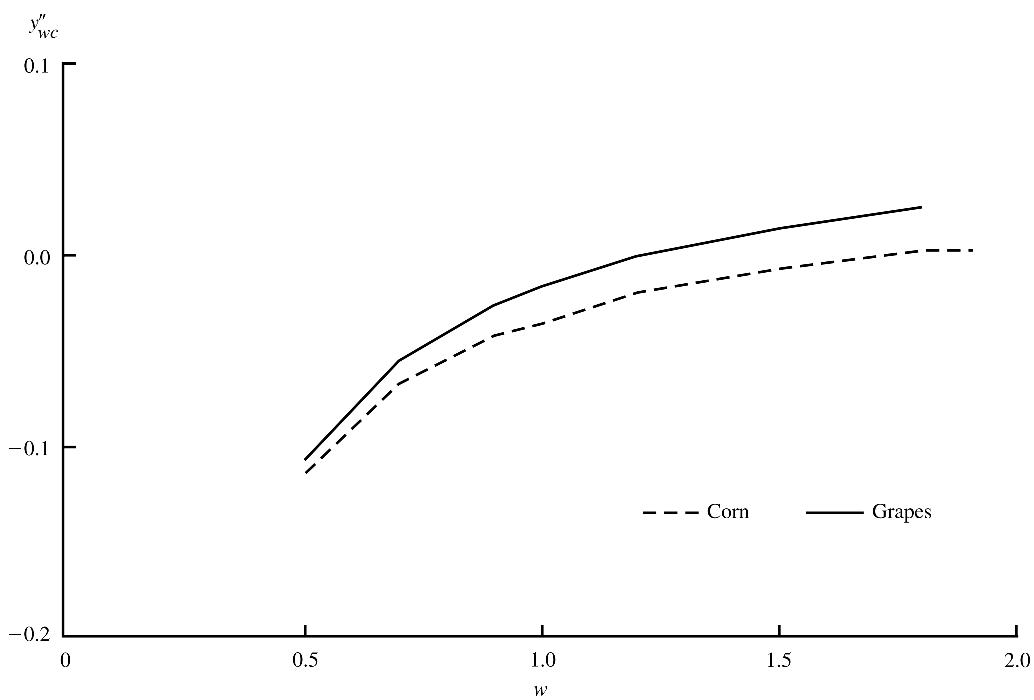


Figure 3.10b Relationship between second partial derivative of crop yield with respect to water and salinity ($y''_{w,c}$) for corn and grapes, and water use relative to maximum crop evapotranspiration (w)



coefficients. The CUC is explained in detail in Appendix A.

Alternative Crop Yield Specification

An alternative specification for the crop yield function has been developed based on an agricultural production survey carried out in the Maipo River Basin. Crop yield has been estimated as a function of several agricultural inputs, including irrigation investment, application of fertilizer, pesticides, machinery, labor, and water. In order to establish a relationship between agricultural inputs and crop yield, a quadratic production function is chosen because of its properties of decreasing marginal returns to additional inputs and substitutability of inputs. The quadratic function is expressed as follows:

$$y(x_1, x_2, .. x_i ..) = [\alpha_1, \alpha_2, .. \alpha_i ..]\begin{bmatrix} x_1 \\ x_2 \\ .. \\ x_i \\ .. \end{bmatrix} - [x_1\ x_2\ ...\ x_i\ ...]\begin{bmatrix} \gamma_{11} & \gamma_{12} & .. & \gamma_{1i} & .. \\ \gamma_{21} & \gamma_{22} & .. & \gamma_{2i} & .. \\ & & & & \\ \gamma_{i1} & \gamma_{i2} & .. & \gamma_{ii} & .. \\ .. & .. & & & \end{bmatrix}\begin{bmatrix} x_1 \\ x_2 \\ .. \\ x_i \\ .. \end{bmatrix}. \quad (3.11)$$

where $\boldsymbol{x_i}$ represents crop inputs, $\boldsymbol{\alpha}$ is the vector of linear coefficients, and $\boldsymbol{\gamma}$ is the vector of cross-item coefficients.

The crop production survey was carried out during the months of August to October 1999 by the Catholic University of Chile for a total of 300 households in the Metropolitan Region as well as in other areas located within the Maipo River Basin.

Because of the limited number of samples available from the survey, conventional econometric estimates would be restricted by the ill-posed or ill-conditioned data sets. As a result, the quadratic yield function shown in equation 3.11 was estimated using the generalized maximum entropy (GME) approach (Golan, Judge, and Miller 1996; Mittelhammer, Judge, and Miller 2000). GME combines incomplete information and plausible assumptions and derives new information, which is normally not accessible from traditional analytic approaches. GME was used for regression analysis with incomplete samples first by Golan, Judge, and Miller (1996). The program that calculates the yield functions applied for this study was originally developed by Richard Howitt of University of California at Davis, and Arnaud Reynaud of INRA (Institute National de la Recherche Agronomique) in France. This approach enables the estimation of flexible form yield function parameters for the case of limited small sample information. The model uses first-order conditions derived from the desired model structure and a yield function as estimating equations. Major assumptions relate to the range of marginal input costs (ratio of input cost to crop price). Details of the GME program can be found in Howitt and Msangi (2002). The values of the coefficient vectors $\boldsymbol{\alpha}$ and $\boldsymbol{\gamma}$ can be found in Table B.10 of Appendix B.

The derivative of crop yield with respect to water is:

$$\begin{aligned} y'_w = \alpha_w - (2\gamma_{w,w} \cdot w + \gamma_{w,i} \cdot i \\ + \gamma_{w,f} \cdot f + \gamma_{w,p} \cdot p \\ + \gamma_{w,m} \cdot m + \gamma_{w,l} \cdot l + \gamma_{w,s} \cdot s), \end{aligned} \quad (3.12)$$

and according to the first-order condition, $y'_w = 0$, the optimal water application (w^*) at any given level of other inputs is derived as:

$$\begin{aligned} w^* = (\alpha_w - \gamma_{w,i} \cdot i - \gamma_{w,f} \cdot f \\ - \gamma_{w,p} \cdot p - \gamma_{w,m} \cdot m \\ - \gamma_{w,l} \cdot l - \gamma_{w,s} \cdot s)/(2\gamma_{w,w}). \end{aligned} \quad (3.13)$$

The relation of w^* versus i is linear at given levels of f, p, m, l, and s for w^* versus f, p, m, l, or s. Because the value of α_w is far larger than the sum of the other items in the dividend of equation (3.13), the value of w^* is dominated by α_w. Values for w^* for demand site A_1 with normal levels of other inputs are presented in Table 3.1. The table also presents the relative contribution to w^*

Table 3.1 Optimal water application at given levels of other inputs in A1

Crop category	*w1**	*w2**	*w** = *w1** + *w2**	ETM	*w**/ETM
Wheat	1,817	58	1,875	562	3.3
Corn	1,302	93	1,395	927	1.5
Annfor	1,350	64	1,414	817	1.7
Prairie	1,886	178	2,064	1,306	1.6
Grapes	2,234	–224	2,010	781	2.6
Peaches	2,725	–318	2,407	750	3.2
Potatoes	2,257	–180	2,077	804	2.6
Pumpkins	2,196	–50	2,146	654	3.3
Lemons	1,685	29	1,714	743	2.3
Othjan	1,843	–58	1,785	702	2.5
Onions	1,536	–43	1,493	533	2.8
Carrots	1,452	–86	1,366	365	3.7

Notes: *w1** relates to the linear items of equation 3.13 and *w2** to the nonlinear items of equation 3.13. Annfor indicates annual forage; ETM, potential crop evapotranspiration; and othjan, other crops planted in January.

by the linear items, α_w (w_1*), and by the nonlinear items (w_2*). Table 3.1 shows that nonlinear items are positive for the lower-value crops, such as wheat, corn, annual forage, and prairie crops, whereas they are negative for high-value crops, such as grapes and peaches. This indicates that the optimal water application level is mainly affected by the profitability of water. The substitution effect differs for high- and low-value crops, as shown for the positive and negative values of w_2*. For high-value crops, water and other inputs can substitute for one another because additional other inputs tend to reduce the need for water application (negative sign of w_2*); for low-value crops, however, the relationship between water and other inputs is complementary. Thus the potential yield of high-value crops is probably not constrained by inputs other than water under the current level of those inputs, but the potential yield of low-value crops is constrained by both water and other inputs. Table 3.1 also shows the value of w* relative to potential crop evapotranspiration (ETM). The last column of Table 3.1 shows the relative value of w* relative to ETM.

Using the alternative crop yield function, the equations of net profit from irrigation would need to be modified to:

$$VA^d = \sum_c A^{d,c} Y_a^{d,c} p^{cp} - \sum_k \sum_c A^{d,c} \cdot inp^{d,c,k} \cdot cinp^{d,c,k}, \tag{3.14}$$

where d represents a demand site, c represents a crop, k is used as an index for agricultural inputs, A is the harvested crop area, Y is the crop yield, p is the crop price,[2] *inp* stands for inputs of water, irrigation investment, fertilizer, pesticide, labor, machinery, and seed per hectare, and *cinp* represents the input costs.

Profit/Benefit Functions for Non-irrigation Sectors

Net Benefit Function for M&I Water Uses. The net benefit function for M&I water use is derived from an inverse demand function for water (see Appendix A for details). The benefit from industrial and municipal demand sites is calculated as water use benefit minus water supply cost:

[2]Crop prices are exogenous to the model because the Maipo Basin is too small to determine crop prices.

$$VM(wm)^d = w_0 p_0^d/(1 + \alpha)\,[(w^d/w_0^d)^a + 2\alpha + 1] - wm^d \cdot wp^d, \quad (3.15)$$

where *VM* is the benefit from M&I water use (US$), w_0 is the normal water withdrawals (cubic meters), p_0 is the willingness to pay for additional water at normal water use (US$), *e* is the price elasticity of demand (estimated as –0.45), and $\alpha = 1/e$.

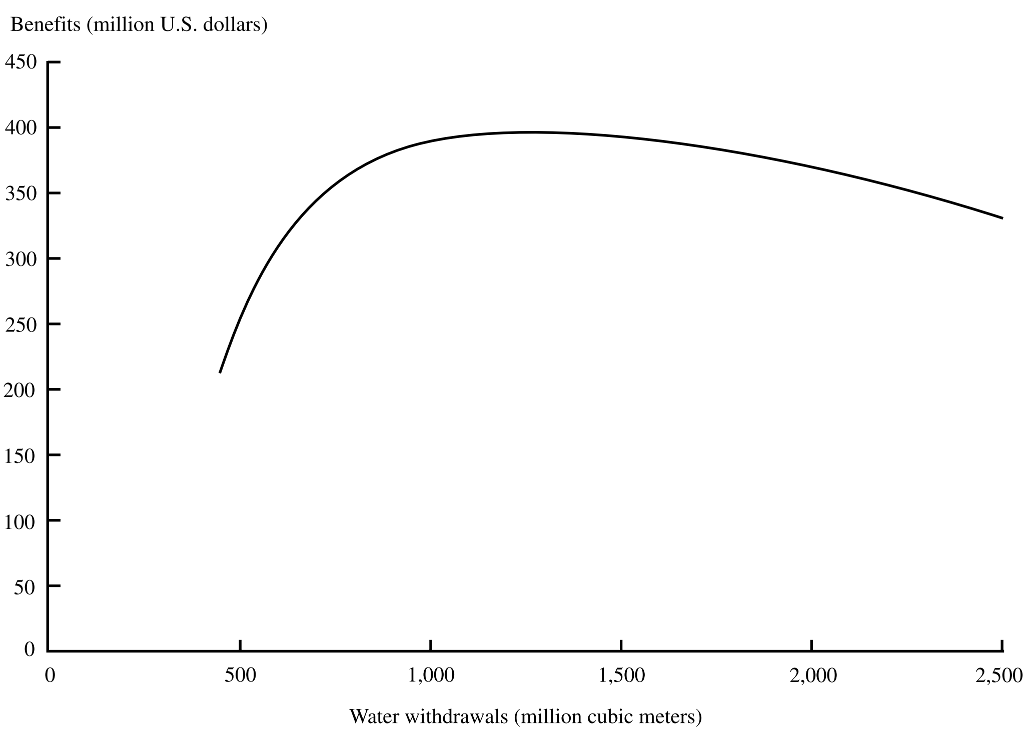
The function is based on a synthesis of partial secondary data, and its current form applies only to surface water. The willingness to pay for water at normal use is estimated at US$0.35 per cubic meter. The per unit value of water for M&I was estimated at 3.5 times the per unit value of water in agriculture, based on an iterative search process on value versus water demand, so that water withdrawals for irrigation and to M&I in the base year model solution match historical values. The small amount of local groundwater use (about 12 percent of annual M&I withdrawals or 95 million cubic meters) is treated as a fixed amount. Figure 3.11 presents the relationship between water withdrawals and benefits reflected in the M&I net benefit function.

Net Profit Function for Hydropower Generation. Benefits from power generation are relatively small in the Maipo Basin compared to off-stream water uses. The profit from power generation is equal to power production profits minus costs (equation A.16 in Appendix A).

Model Formulation for Water Trading

The integrated economic–hydrologic river basin model allows for a fairly realistic representation and analysis of water markets. Water trading is analyzed here as an important water allocation institution. The objective is not to reflect the current trading regime as such in detail, for example, the trading within the various sections of the Maipo and Mapocho, but rather to see what the benefits

Figure 3.11 Relationship between water withdrawals and municipal and industrial benefits



of water trading are compared with other water allocation institutions. Water in the modeling framework is traded, taking account of the water balance in the basin as well as the physical and technical constraints of the various demand sites, which reflect their relative positions regarding shadow prices. Water trades reflect the relative seasonal and spatial water scarcity in the basin, which is influenced by both basin inflows and the cropping pattern in agricultural demand sites (whereas the M&I water demands are more stable). Moreover, negative externalities, such as increased salinity in downstream reaches as a result of incremental irrigation water withdrawals upstream, are endogenous to the model framework.

To extend the model to water trading analysis, in a first step, a shadow price–water withdrawal relationship is determined for each demand site. For this, a general algebraic modeling system (GAMS) model is run separately for each spatial unit or demand site with varying water availabilities and thus withdrawals as inputs and shadow prices or marginal values as output derived from the crop-level water balance equation, with all other parameters at the normal level. Each irrigation demand site includes a crop-level water balance equation for each of up to 15 crops.

In GAMS, these marginal values can be read in directly from the model solution and are the optimal shadow values on each model constraint. (GAMS produces marginal values or shadow prices as outputs for all constraints in the model, if so specified in the GAMS program; the function is m).

The seasonal crop–water level balance, on which the relationship is based,

$$\frac{\sum_{pd\in DEM\_CP} twacp_{\mathrm{pd}}^{d,cp}}{\sum_{pd\in DEM\_CP} ep^{d}\cdot ACP^{d,cp}} = srw^{d,cp}, \qquad (3.16)$$

calculates the seasonal ratio of actual over potential total water demand (see also equation B.43 in Appendix B), where *srw* is the seasonal ratio of actual over potential water demand; *twacp* is the water directly available to each crop, including groundwater, surface water, effective rainfall, and reuse; *ep* is seasonal potential evapotranspiration; and *ACP* is the irrigated area for each crop at each demand site.

The components involved in the crop-level water balance are shown in Figure 3.3. This seasonal relationship in the model thus also connects to the monthly groundwater balance, salinity balances, the return flow balance, and river reach balances. A shadow price on this type of a constraint represents the marginal effect on net profit if any one of the crops in the model is brought into slight deficit in terms of the seasonal requirements. For very low-value cropping activities such as forage or prairie crops, we would expect this marginal effect to be very small, which is borne out in the model results. Other relationships related to the seasonal crop yield function that influence the water trading analysis are detailed in other sections of Chapter 3.

To obtain a single function by demand site, the shadow values for the various crops in each demand site were then averaged, with the net profits (derived from crop yields times crop price) of these crops used as weights. Alternatively, we could have chosen the irrigation demand site water balance to determine the marginal values for total water at each demand site. The results are basically the same (see Appendix C for a comparison).

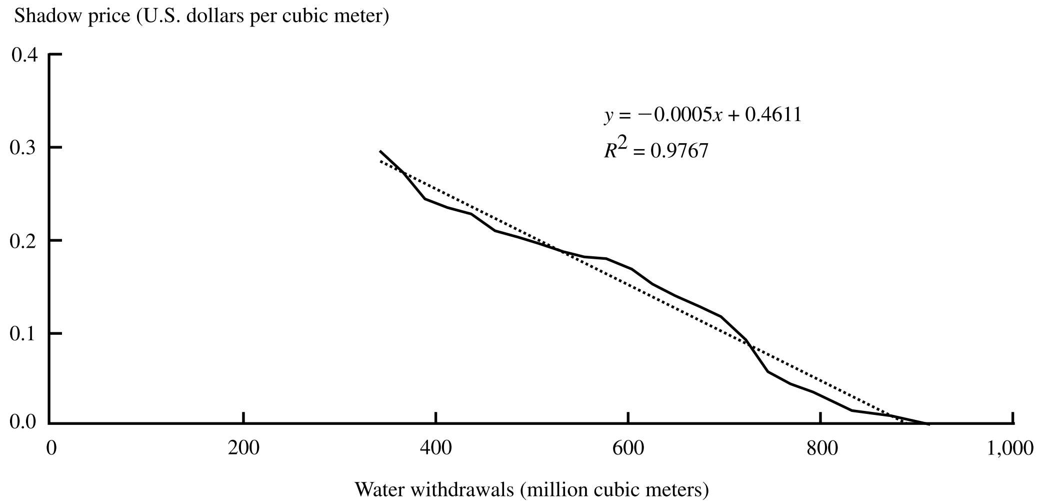
Based on these input and output values, a regression function was estimated for the shadow price–water withdrawal relationship for each demand site. The relationship takes the following form:

$$\begin{aligned}\mu^{dm} &= f_0^{dm} + f_1^{dm}\cdot w^{dm}\\ &\quad + f_2^{dm}\cdot \exp^{f_3{}^{dm}\cdot wdm},\end{aligned} \qquad (3.17)$$

in which f_0–f_3 are regression coefficients, w is the annual total water withdrawal, and μ is the shadow price for each demand site.

Figures 3.12 and 3.13 present the model results and estimated relationships between

Figure 3.12 Relationship between shadow prices and water withdrawals, demand site A1 (upstream)



water withdrawals and shadow prices for an upstream and downstream irrigation demand site, respectively. Differences in the functional form for these two demand sites depend on many factors, including crop pattern, climatic conditions, water quality, and efficiencies of water delivery and irrigation systems. Figure 3.14 presents the shadow price versus water withdrawal relationship for an M&I demand site. The values of all parameters estimated in Equation 3.17 for all demand sites are presented in Table 3.2.

It is assumed that no demand site can lose from trading, as benefits are calculated at the basin level, regardless of gains and losses among individual demand sites. To determine the lower bound for profits from water trade for individual demand sites, the model is solved for the case of water rights without trading.

Figure 3.13 Relationship between shadow prices and water withdrawals, demand site A5 (downstream)

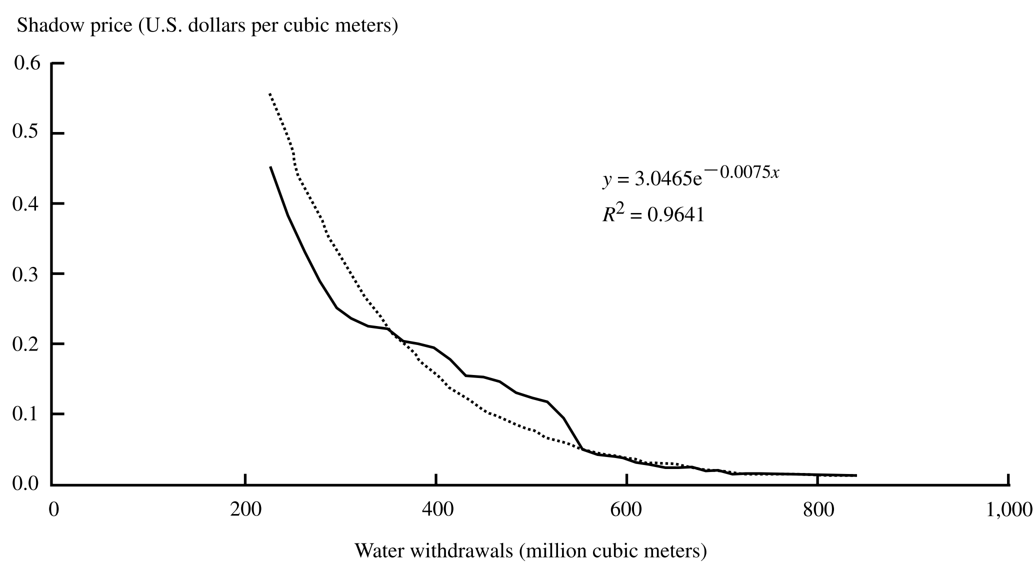
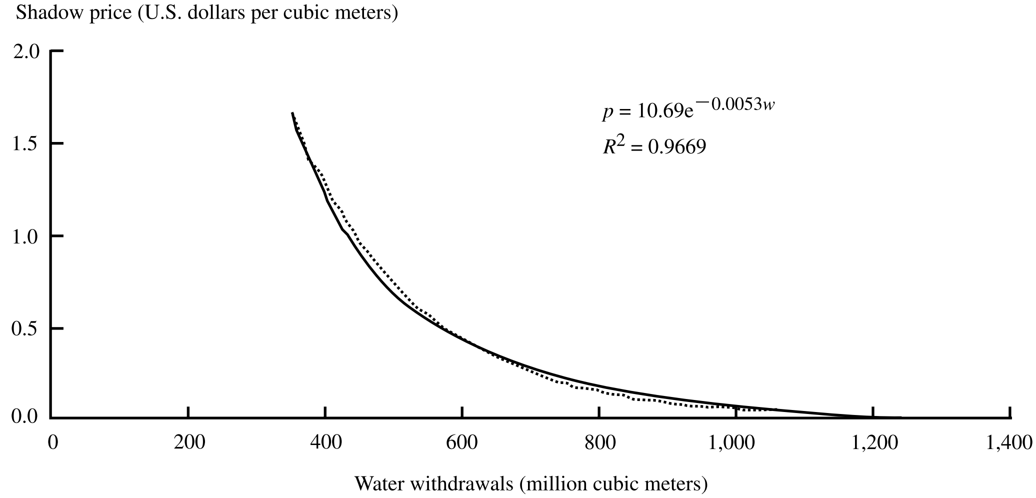


Figure 3.14 Relationship between shadow prices for water and water withdrawals, municipal and industrial demand site M1



Finally, the regression relationships of shadow price versus water withdrawals for all agricultural and M&I demand sites, individual water use rights, and other constraints related to water trading are added to the comprehensive basin model. For a complete market, shadow prices of various demand sites will converge toward a balanced market price, which is defined as the water trading price. The model solves for the water trading price, *wtp,* and the volume of water bought and sold by demand site.

The following additional assumptions have been specified for the water-trading analysis: Trade is allowed on a monthly basis and throughout the basin, but up to four months of the realized monthly water right can be traded, as monthly balances have been found to be too tight a constraint on water supply for crop growth. Transaction costs are incurred by both buyer and seller (US$0.04 per cubic meter); the water right is allocated proportionally to total inflows based on historical withdrawals for

Table 3.2 Coefficients of the shadow price–water regression function for different demand sites

Demand site	f_0	f_1	f_2	f_3
A1	0.4611	–0.0005	0	0
A2	0.4557	–0.0013	0	0
A3	0	0	3.2550	–0.0095
A4	0.4012	–0.0183	0	0
A5	0	0	3.0465	–0.0075
A6	0.4923	–0.0074	0	0
A7	0	0	2.6687	–0.2183
A8	0.4321	–0.0018	0	0
M1	0	0	10.69	–0.0053
M2	0	0	10.69	–0.0115

Note: A1–A8 are agricultural demand sites; M1 and M2, municipal demand sites (see Figure 3.1).

M&I areas and on the harvested (irrigated) area for agricultural demand sites. Thus, with reduced inflows, the realized volumes of the water rights change without changes in the rights structure. Moreover, the water right refers to surface water only.

Although, in principle, we would like to see that marginal value equalized across all of the constraints of the model both in the individual demand site models and in the full basin model using trading scenarios, we realize that the large number of constraints, and the degree of nonlinearity in the overall optimization problem might not allow this. These constraints include lower and upper bounds of crop acreage, upper bound of total crop area, and lower and upper bounds for crop yields. Because crop yield is determined by water use per hectare according to equation 3.1, if the yield is constrained for a particular crop, then water use per hectare is determined by the yield constraint, and if the crop area is also constrained, then total water use for the crop is constrained. If water use for specific crops is thus constrained, then the shadow prices of water are not able to equalize across crops. Given these constraints, shadow prices do not fully equalize by crop and irrigation site in the water-trading model, both under full optimization and under the alternative water-trading scenarios. This is only the case for low-value crops, such as annual forage and pasture. An alternative approach to imposing such constraints would be to employ positive mathematical programming methods (Howitt 1995), which in essence incorporate "penalty functions" that keep otherwise non-optimal cropping activities in the optimal basis of the solution. The marginal penalty on such a crop, at the optimal solution, would in essence make up for the difference that we see in the shadow values in the current formulation and allow the marginal value of all inputs to equalize more closely. Thus, unequal marginal values are a reflection of (hydrological engineering or institutional) hard constraints. Further research is required to identify those hard constraints and determine policies for engineering development and institutional reform to achieve optimal basin management outcomes.

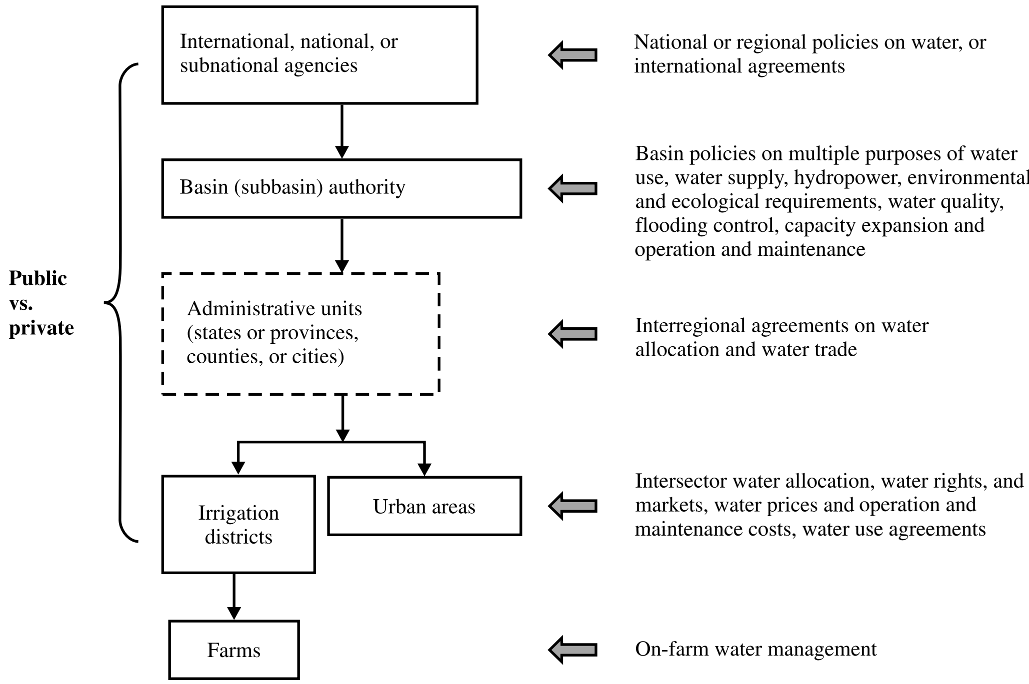
Institutional Framework

Models that support basin water management should be consistent with the institutional rules as well as the whole organizational setting of the basin. Brown et al. (1982) recognized four objectives of concern to water institutions: economic improvement, environmental preservation, maintenance of agricultural lifestyle, and equitable access to water. Young (1996) pointed out that if water management institutions are inadequate, farm-level resource use might be suboptimal when considered from a societal perspective. Gardner, Ostrom, and Walker (1990) encouraged the collective management of common pool resources such as water, which have many appropriators or users. Whereas each individual user may achieve only suboptimal outcomes, a collective institution is more likely to attain global optimality.

The challenge for basin modeling is to deal with institutions associated with stakeholders at multiple levels from national (and in some cases international) agencies to basin authorities, regional agencies, and finally cities and farms. Figure 3.15 presents a structure of organizations and policies or rules involved in basin water management, particularly for agriculture-dominated basins. The institutional rules associated with various levels of organizations can be categorized as (1) information rules, which specify information channels and conditions of access; (2) pay-off rules, which prescribe how benefits and costs of decision and actions are to be distributed among stakeholders; and (3) rules of decision and action, which specify the conditions under which decisions are made and actions are taken (Gregg 1990).

The model presented here provides a depiction of such an institutional framework through the representation of the organiza-

Figure 3.15 Institutional representation for river basin management



tion and interpretation of the institutional rules as modeling constraints. A critical assumption related to the institutional framework and incorporated into the model is that all decisions are based on the maximization of basinwide economic benefits. Because of this assumption, the model outcomes constrain individual profit and benefit functions to the overall benefit of the basin.

CHAPTER 4

Model Implementation and Solution

Integration of Model Components

All the components described in Chapter 3 are integrated into a consistent framework, with the objective of maximizing net economic profits in the river basin across all water uses: agricultural, domestic, and industrial sectors and hydropower generation (Appendix A, equation A.1).

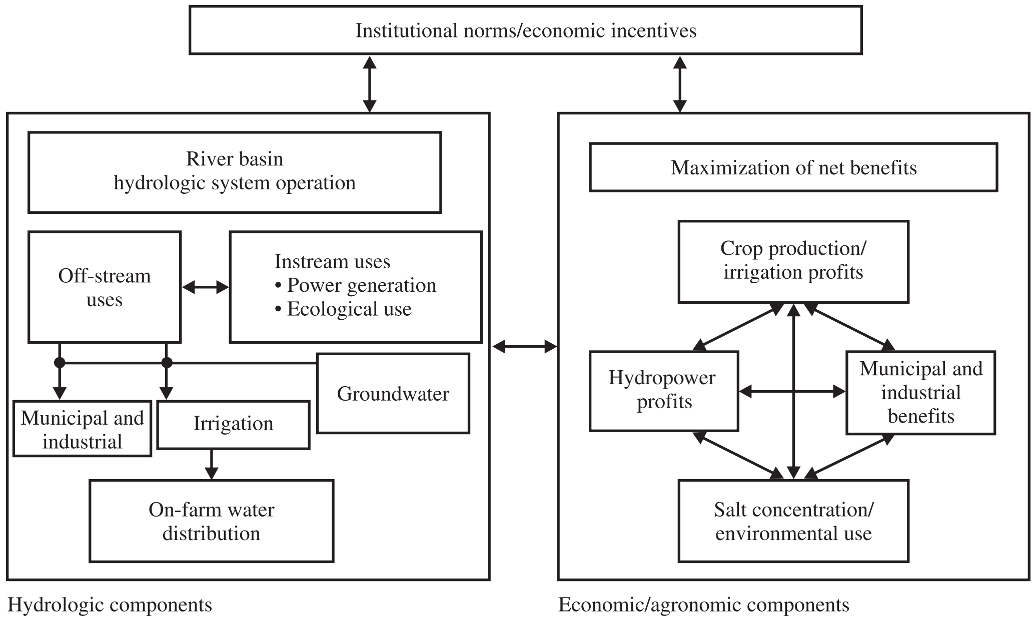
The interrelationships among the three major modeling components are graphically presented in Figure 4.1. In this holistic analytic framework, water demand is determined endogenously within the model based on empirical agronomic yield and crop production functions (yield vs. water-irrigation technology-salinity) and a municipal and industrial (M&I) net benefit function; whereas water supply is determined through the hydrologic water balance and infrastructure operations. Water demand and water supply are then integrated in an endogenous system, and the balance between supply and demand is derived based on the economic objective of maximizing net profits and benefits to water use subject to the physical, technical, and policy conditions given in the basin.

The decision process is illustrated in Figure 4.2. Decisions at the basin level include hydrologic system operation and water allocation among demand sites (cities and farms). At the irrigation system or farm level, water is allocated to crop fields based on local characteristics and profitability decisions. Finally, water sources are mixed for irrigation, the irrigation technology is determined, and irrigation is scheduled among growing stages. The consequences of decisions at all levels are evaluated in terms of both environmental effects and economic profits. The allocation decisions are driven by the maximization of economic benefits subject to agricultural and environmental polices and related institutions and economic incentives.

Matching Spatial and Temporal Scales in the Model

Matching Spatial Scales between the Economic and Hydrologic Components. A major task in the development of an integrated economic–hydrologic modeling framework is the determination of the adequate spatial resolution and aggregation of economic and hydrologic components that allows for a consistent integration of these relationships. An appropriate matching of scales would provide for an effective information transfer between the two components while economizing on the complexity of the holistic modeling framework so as to maintain an appropriate model size. The boundaries of the economic system of a specific resource problem are typically different from those of the hydrologic system. Whereas the economic component typically relates to political and administrative boundaries, the hydrologic scale usually relates to the river system or watershed. This results in the need to model the integrated system across

Figure 4.1 Basic structure of the optimization model



multiple scales. In addition, the area/volume over which the model results apply and over which results need to be validated can differ.

The integrated economic–hydrologic model presented here is implemented based on the node-link network described in Chapter 3. Spatial elements (source and demand nodes) are delineated so that the spatial variability of water resources and the allocation to various water demands can be adequately

Figure 4.2 Decision processes in the river basin model

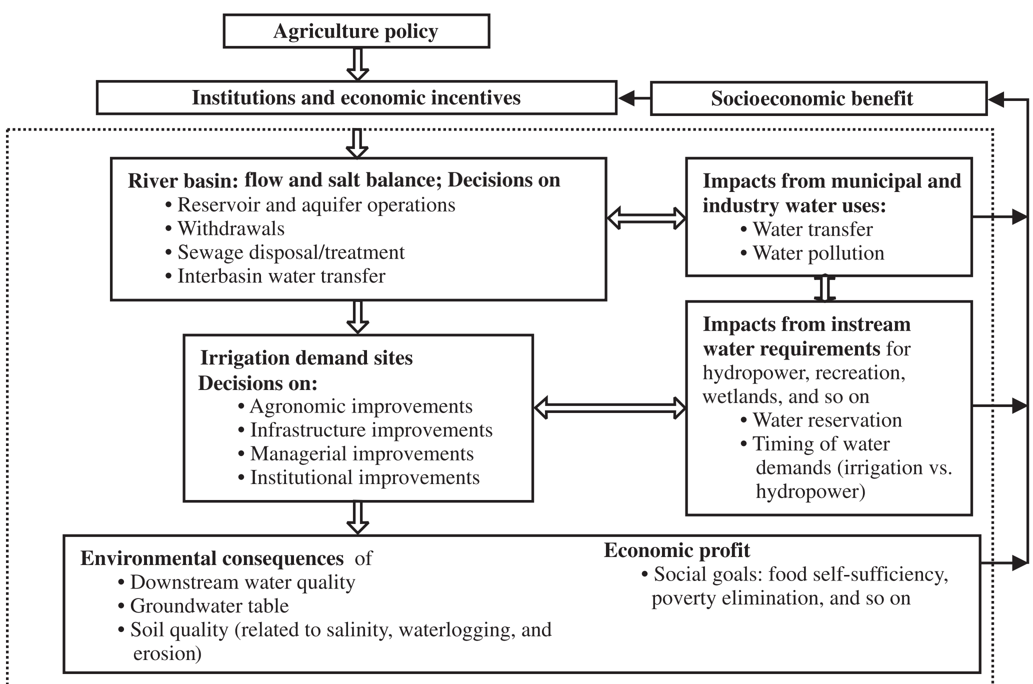
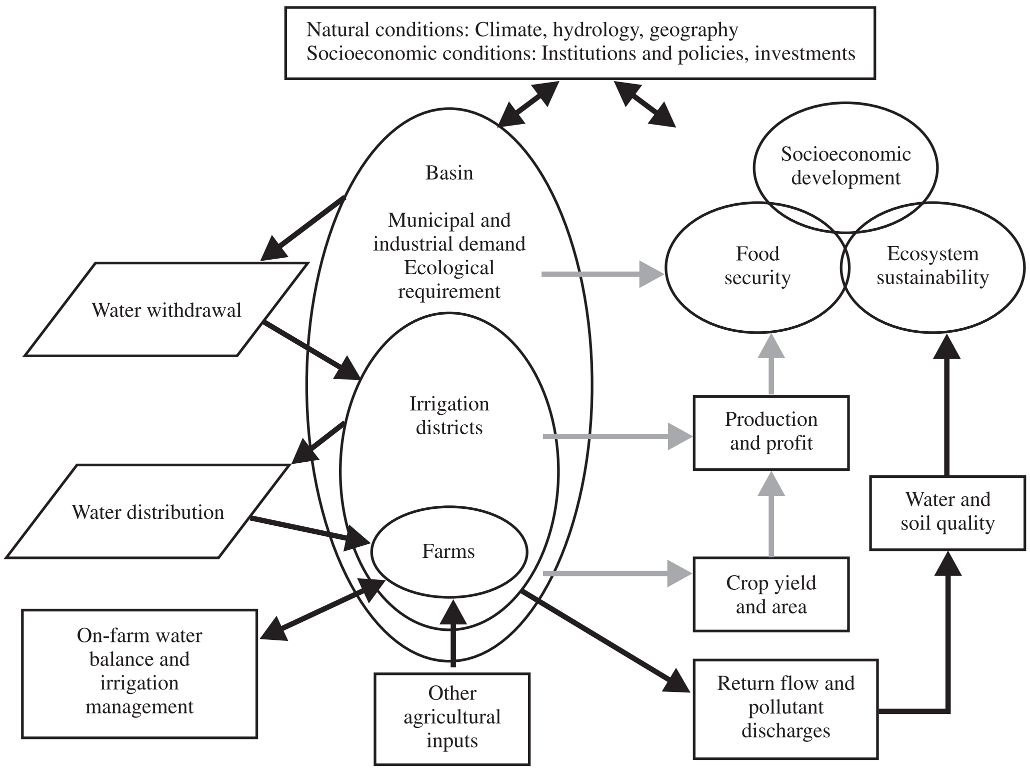


Figure 4.3 A diagram of the spatial scales and associated hydrologic and economic processes



reflected. Water allocation and balances are simulated at several spatial scales: crop fields, demand sites, source nodes (reservoirs, aquifers, river reaches), and for the entire basin. Profit from irrigation water use is calculated at the crop field level and is aggregated to demand sites and the basin level. Figure 4.3 shows a diagram of the spatial scales and associated hydrologic and economic processes. The various spatial scales allow the generation of reasonable results compared to actual observed data, including instream water flows, water withdrawals, consumptive use, and return flows, irrigated crop area, yield, and production, and returns to water use (Rosegrant et al. 2000).

Connecting Temporal Scales between the Economic and Hydrologic Components. Models can be classified as continuous or event-based (static responses to single events or events of very short duration), depending on the time scale of interest. Event-based models are used to simulate watershed responses to single storm events, for example. Continuous models simulate transit processes over a specified time interval (which may range from fractions of an hour to years) and can provide a time series of model outputs. Continuous models are typically used for integrated economic–hydrologic modeling, and both time intervals and time horizons applied need to be compatible with regard to the specific modeling purpose. Economic models generally use larger time intervals (seasonal or annual) and a longer time horizon (for example, for long-term forecasts) than hydrologic models. For hydrologic models, the time interval should be small enough to reflect real-world processes and capture the transition changes of physical systems that will affect economic costs/benefits; and it should be long enough to reflect the economic and environmental consequences resulting from water uses. However, the length is often limited by computational capacity and data availability.

In the modeling framework presented here, hydrologic processes are simulated on a monthly basis. Also, profit from industrial and domestic water uses and hydropower are computed using a monthly time step. However, irrigation profit is calculated based on a seasonal crop yield function with seasonal water application as an input variable (Appendix A, equation A.8). This results in a divergence in time steps between the hydrologic component, the monthly water application, and the economic component, the seasonal crop yield function. Whereas the seasonal yield function drives the seasonal water allocation among crops in irrigation demand sites, it is not able to allocate water within the crop season to the various crop growth stages. Moreover, different crop growth seasons require hydrologic system operation and water allocation to correspond to water requirements in crop growth stages of multiple crops. Because hydrologic processes are computed on a monthly basis, a monthly water–crop yield relationship corresponding to the hydrologic time step would be the ideal temporal scale to match the economic and hydrologic components. To bridge the gap between the hydrologic and agronomic/economic component in irrigation demand sites, a penalty term is introduced into the objective function that allocates water within seasons following the "crop yield response to water stress" relationship documented by the Food and Agriculture Organization of the United Nations (FAO) (Doorenbos and Kassam 1979). The definition of the penalty item is described in Appendix A, equation A.2. The penalty term, which is included in the objective function, minimizes the difference between the maximum and average monthly crop yield deficit caused by water stress. The penalty term is zero when the value of the yield deficit caused by water stress is equal across crop growth stages, that is, when water is supplied exactly according to the specific crop water demand and crop sensitivity to water stress in each growing stage; otherwise, crop profit will be penalized because crop yield will be adversely affected if water stress in one stage is significantly different from that in other stages. This process allows allocating water within crop seasons following plant water requirements.

Table 4.1 compares the performance of the objective function with and without the penalty term for wheat in one irrigation demand site. When the penalty term is not included, the intraseasonal crop yield deficit (*dft*) varies significantly. In some stages, the computed *dft* is negative because the monthly

Table 4.1 Comparison of the performance of objective formulations, water application in crop growth stages, example of wheat

Crop growth stages (millimeters)		August	September	October	November	December	January	Season total
	ETM	31.3	61.4	93.2	157.1	137.2	54.6	534.8
	ky	0.20	0.20	0.65	0.55	0.15	0.10	
Without penalty	ETA	101.3	145.5	146.8	54.4	36.4	14.1	498.5
	dft	–0.447	–0.274	–0.374	0.360	0.110	0.074	
With penalty	ETA	24.3	47.7	86.8	144.4	96.4	30.3	429.9
	dft	0.045	0.045	0.045	0.045	0.045	0.045	

Notes: ETM indicates the potential crop evapotranspiration and ETA, actual crop evapotranspiration (including effective rainfall and irrigation); *ky* is the crop yield response cefficient, and *dft* is the crop yield deficit.

actual crop evapotranspiration (ETA) (including effective rainfall and irrigation water applications) is larger than the potential crop evapotranspiration (ETM) (whereas the seasonal ETA remains below the seasonal ETM). Moreover, the seasonal ETA value without penalty is larger, which would lead to overestimated crop yields and profits from irrigation water use. The lack of matching temporal scales results in erroneous reservoir release, groundwater pumping, and water balance calculations. Adding the penalty item into the objective function smoothes the water allocation within the crop growth season as reflected in an evenly distributed *dft* across crop growth stages and adjusts the seasonal crop yields correspondingly.

Data Management

Data management refers to input data collection and processing and output display and manipulation. Input data requirements relate to the type of data and the level of aggregation required and desired. Multidisciplinary models, such as the integrated economic–hydrologic model developed here, require mixed types of data, including survey, statistical, and empirically estimated data, which differ in terms of their temporal and spatial scales. The types of input data include hydrologic data, infrastructure data, water demand data by sector, and economic data related to water usage.

The numerical scales of these data may differ, and their sensitivity to model output should be carefully checked. Uncertainties associated with these items as a result of natural phenomena (for example, with hydrologic data) and/or measurement errors add complexity for the judgment of the validity of model outputs. An integrated, multidisciplinary model must master the challenge of robustness regarding integration of various types of data, with various numerical scales and different spatial and temporal dimensions.

For the modeling framework presented here, input data related to measured historic records and empirical assessments were collected with local collaborators. Input parameters are listed in Appendix B. A special data set was prepared for the development of the crop yield function presented in equation 3.1 and the alternative crop yield function presented in equation 3.11. Data for equation 3.1 include a series of agronomic parameters as inputs to a simulation model adapted from Dinar and Letey (1996) (see Table B.1, Appendix B), whereas data for equation 3.11 are derived from a farm household survey, as described above.

The model output includes the values of major decision variables, as well as of important state and intermediate variables in the areas of hydrology, agricultural production, M&I water usage, and hydropower production. The major output items are listed in Boxes 4.1 and 4.2. Various environmental and economic indicators can be calculated based on these outputs. Details are presented in Chapter 5.

Solving the Model

The model is coded in the GAMS language (Brooke, Kendrick, and Meeraus 1996), a high-level modeling system for mathematical programming problems. Model size and extensive nonlinearities make the model highly complex. The model includes 7,619 equations, 15,129 variables, 54,240 nonzero Jacobian elements, and 17,686 nonconstant Jacobian elements. Solving the entire model using the MINOS5 and CONOPT2 NLP solvers of GAMS resulted in a large number of infeasibilities, even at loose feasibility tolerances, pivot tolerances (preventing singularity), and various scales and bounds on the variables.

Cai, McKinney, and Lasdon (2001) suggested a "piece-by-piece approach" to solve complex models such as this one. Most large optimization models are composed of "pieces," subsets of decision variables and constraints, whose union is the entire model. Each piece represents an additional aspect of the situation being modeled. This

Box 4.1 Major Outputs Related to Hydrology Conditions and Hydrologic System Operations

- Water withdrawals for each demand site
- Flow through river and tributary nodes
- Flow to pollution sinks and flow out of the basin (to the ocean or to another basin)
- Flow diverted out of the basin
- Flow reserved for instream/environmental purposes
- Reservoir inflow, release, and storage
- Energy generation from hydropower production
- Water allocation by sector: agricultural, industrial, and municipal
- Actual crop evapotranspiration (ETA) for each crop in each demand site
- Water allocated to crop stages (including diverted water and local water)
- Groundwater pumping to a crop field in each stage for each crop in each demand site
- Groundwater pumping to municipal sites in each month
- Groundwater table in each month
- Effective rainfall for each crop field in each demand site
- Deep percolation for each crop in each demand site
- Drainage reuse in each demand site
- Return flow from each crop field in each demand site
- Salt concentration in river reaches, reservoirs, and groundwater sources
- Salt concentration in drainage, return flow and deep percolation
- Salt concentration in mixed irrigation water

Box 4.2 Major Outputs Related to Agricultural Production/Water Economics

- Irrigation technology/Christiansen Uniformity Coefficient
- Irrigated area by crop in each demand site
- Crop production by demand site
- Crop yield and relative crop yield (actual yield/potential yield) by crop and demand site
- Irrigation efficiency (field application efficiency, system efficiency, and efficiency at the river basin scale)
- Water application per hectare by crop and demand site
- Total profit from all water uses
- Profit for each demand site
- Profit for each sector
- Profit for each hydropower station and total hydropower profit
- Profit per unit of water for each crop in each demand site and over the whole area
- Profit per hectare for each crop in a demand site and over the whole area
- Irrigation profit per unit of water supply in a demand site
- Water market (amount of water bought and sold and water trading prices)
- Agricultural inputs (water, fertilizer, pesticides, machinery, labor, irrigation investment, and seed for each crop in each demand site) and marginal return of each input

opens the possibility of solving the simplest piece first, adding the constraints and variables of another piece, and solving the subsequent submodel from a starting point provided by the first solution. This process is repeated until the complete model is solved. This "piece-by-piece" approach provides that each model is solved with a good starting point, which greatly increases the probability that a good nonlinear solver will find an optimal solution. This "piece-by-piece approach" is suitable to the structure of the holistic economic–hydrologic model developed for this study. This model can be disaggregated into the following submodels or components:

mod1: flow balance and crop production functions, with fixed water salinity and irrigation technology in the crop production functions
mod2: **mod1** plus salinity balance, with variable water salinity in the crop production functions but fixed irrigation technology
mod3: **mod2** plus variable irrigation technology in the crop production functions
mod4: **mod3** plus water rights constraints
mod5: **mod4** plus water-trading relationships

Flow balances are linear relationships and do not involve variables of later pieces. They can therefore be used as the constraints of the first submodel, **mod1,** which excludes nonlinear salinity mass equations and the more complex economic relationships, such as the irrigation technology-cost function, water rights, and water market–related relationships. These simplifications facilitate a solution of **mod1.** Salinity balances are added in **mod2.** The purpose of **mod2** is to find reasonable values for both salinity and flows. Irrigation technology is then determined endogenously in **mod3.** Water rights as institutional rules/constraints are added to **mod4.** Water market relationships, including the determination of the water-trading price and the volume of water traded, are added to the final **mod5,** which represents the complete model.

Table 4.2 presents statistics for model size and solver performance for each model solved in the piece-by-piece approach. The various measures of model size and nonlinearity, including the number of equations, variables, nonzero Jacobian elements, and nonconstant Jacobian elements, all increase from **mod1** to **mod5,** whereas the initial number of infeasibilities decreases sharply. This shows that the starting points for solving subsequent models are of improved quality.

Additionally, this approach makes it possible to analyze the role or influence of individual "pieces" or model components. As shown in Table 4.2, the model objective, the maximization of total net benefits to water use, differs for the various models.

Table 4.2 Model statistics at different steps

Model	Equations[a]	Variables[a]	Nonzero Jacobian elements[a]	Nonconstant Jacobian elements[a]	Initial infeasibilities[b]	Computation time[c] (seconds)	Optimal objective value (million US$)
Mod1	7,007	14,221	42,072	7,453	2,618	1,357	928
Mod2	7,305	14,999	52,602	17,081	286	623	922
Mod3	7,305	14,999	52,602	17,081	0	165	926
Mod4	7,545	15,119	53,250	17,081	291	524	653
Mod5	7,619	15,129	54,240	17,686	94	1,220	830

[a]Data were derived from model statistics in GAMS output files.
[b]The models were solved using CONOPT2 with infeasibilities at the initial point.
[c]Data on time resource usage were derived from GAMS output files using a 600 MHz Pentium personal computer.

The objective value in **mod2** is slightly lower than the value in **mod1** because the fixed irrigation water salinity in **mod1** might be below the value calculated endogenously from salt mass balances, and/or the fixed salinity mass balance and the upper limits on salinity in the irrigation water reduce water availability in irrigation so as to reduce basin water profits. The endogenous irrigation technology introduced in **mod3** leads to significant increases in water use benefits. In **mod4,** profits to water use are significantly reduced as the introduction of water rights constrains withdrawals to demand sites. Allowing for water trading among demand sites in **mod5** corrects many of the economic inefficiencies of the case with fixed water rights. With water trading permitted among demand sites, water moves from lower-valued crops into higher-valued, perennial crops, and particularly into higher-value urban water uses, at the same time benefiting farm incomes.

Summary

Holistic modeling can be a simple approach for building integrated water resources and economic models and an effective tool for combined environmental and economic analysis. However, both temporal and spatial scales of hydrologic and economic components need to be selected carefully so as to satisfy the tight linkage between the two components as well as the specific modeling purposes while avoiding oversized models. Using the prototype Maipo Basin model as an example, this chapter illustrates how spatial and temporal scales can be defined for hydrologic and economic components so as to allow for optimal solutions of such a complex model system. The penalty method is used to bridge the gap between the temporal scales of hydrologic modeling and economic modeling, and the piece-by-piece approach is presented as an effective strategy for solving the large and complex model.

Progress in computer and information technology will certainly further advance the development of holistic water resource–economics models (as an alternative to the compartment modeling approach). Twenty years ago it was very difficult, if not impossible, to solve a large and complex model like the one presented in this research report. Better computing facilities, including both hardware and software, will continue to reduce the limits imposed on model size and complexity and allow a greater resolution of both spatial and temporal scales. Emerging computer technologies including geographic information systems (GIS), remote sensing, and expert systems, and the advances in distributed hydrologic modeling will also support complex water resource–economic models. GIS and remote sensing can facilitate the assessment of economic and environmental consequences of alternative land use and management practices at various spatial scales and thus can support the data processing and analysis required for multidisciplinary modeling with a strong spatial dimension. These new technologies thus have great potential for building distributed models for both water resources and economics over a large spatial area. Detailed procedures for the calibration of the integrated economic–hydrologic model are described in Chapter 9.

CHAPTER 5

Basin-Optimizing Solution and Sensitivity Analyses

The Basin-optimizing solution (BOS) maximizes net benefits over the entire basin subject to existing physical and system control constraints, but without any institutional rules. Thus, the institution represented is that of an omniscient decisionmaker with perfect foresight optimizing the entire water-related basin economy. As a result, outputs from this scenario should be reasonable and indicative, but not necessarily what is actually observed. Moreover, sensitivity analysis based on this scenario should show expected changes for key economic and hydrologic parameters. BOS is used as a reference for comparison with alternative scenarios discussed in the following chapters.

Basin-Optimizing Solution

Assumptions for BOS include water fees for municipal and industrial (M&I) demand sites of US$0.1 per cubic meter and for irrigation of US$0.04 per cubic meter. Crop technology is fixed at Christiansen Uniformity Coefficient (CUC) equal to 85 for grapes and 70 for other crops, based on current irrigation practices in the basin. Moreover, it is assumed that at least 15 percent of the inflow is reserved for environmental (instream) uses. Average inflows are used for the baseline run (Table B.13, Appendix B). The source salinity is set at 0.3 grams per liter. No water rights are established; therefore, withdrawals to demand sites depend on their individual demands with the objective of maximizing basin benefits. Additional assumptions for the hydrologic, agronomic, and economic components are detailed in Appendix A, which lists the equations used in the model.

The model incorporates 15 crops aggregated from a larger set of crops, based on phenological and other characteristics. Table 5.1 shows the harvested area derived from BOS and Table 5.2 presents the comparison with the actual situation in the basin in the mid-1990s. The total harvested area estimated by the model is 146,000 hectares, compared with an area under production in 1994–96 of 127,000 hectares. Crops that demand large amounts of water or have lower economic values account for relatively less area in the model result compared with the actual data. Table 5.3 presents the relative crop yields for the irrigated crops included in the model under BOS. Yields of lower-valued crops are relatively lower compared with those of high-value crops, which are close to maximum basin yields. Table 5.4 compares the model outcomes for crop production under BOS with actual data during 1994–96. As can be seen, overall production under BOS is larger than actual values. Moreover, the solution favors those crops with higher profit per unit of water supplied, such as peaches and grapes.

The BOS scenario also incorporates the following three assumptions: (1) a multi-year, normal climatic and hydrologic levels (see Tables B.12 to B.14 in Appendix B for water flow and

Table 5.1 Harvested area under the Basin-optimizing solution (hectares)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrot	Peas	Prairie	Total
A1	5,607	4,196	2,529	9,264	6,463	4,725	2,322	2,638	1,466	1,466	1,515	1,924	1,748	2,209	260	48,329
A2	1,925	1,574	936	3,798	2,527	1,672	812	1,012	533	533	575	754	566	461	117	17,795
A3	3,899	5,219	1,925	1,064	1,401	1,547	1,188	1,741	1,137	1,137	886	885	776	823	2,501	26,128
A4	135	248	76	52	141	58	124	52	58	58	23	24	59	48	3	1,157
A5	7,446	3,344	2,521	1,916	2,574	1,879	1,825	1,999	1,579	1,579	1,063	1,030	1,120	1,214	2,553	33,642
A6	302	384	170	753	494	337	160	201	99	99	111	150	112	90	9	3,471
A7	482	19	325	2	2	26	37	2	85	85	5	28	24	26	78	1,227
A8	2,440	53	481	2,562	2,346	787	545	463	986	986	309	231	604	1,430	36	14,258
Basinwide harvested area	22,235	15,037	8,963	19,412	15,947	11,031	7,013	8,108	5,942	5,942	4,486	5,024	5,008	6,302	5,556	146,007

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.2 Harvested area from Basin-optimizing solution as a ratio of actual harvested area

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie	Total
A1	0.82	0.60	0.60	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.60	1.14
A2	0.77	0.60	0.60	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.60	1.13
A3	1.05	1.50	0.60	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.60	1.14
A4	0.60	1.21	0.60	1.49	1.50	1.49	1.49	1.49	1.53	1.53	1.53	1.50	1.51	1.50	0.60	1.13
A5	1.50	0.78	0.60	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.60	1.14
A6	0.60	0.72	0.60	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.51	1.50	0.60	1.13
A7	1.50	1.46	0.85	1.50	1.50	1.50	1.48	1.00	1.49	1.49	1.25	1.47	1.50	1.44	0.60	1.15
A8	0.82	0.60	0.60	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.60	1.25
Basinwide ratio	1.01	0.83	0.61	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	0.60	1.15

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.3 Crop yield under Basin-optimizing solution scenario as a ratio of maximum crop yield

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	0.92	0.91	0.75	1.00	1.00	0.98	0.99	1.00	0.98	1.00	1.00	1.00	1.00	1.00	0.74
A2	0.93	0.91	0.76	1.00	0.99	0.98	0.98	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.73
A3	0.93	0.92	0.77	1.00	1.00	0.98	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.73
A4	0.92	0.92	0.76	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.72
A5	0.93	0.91	0.76	1.00	1.00	0.98	0.98	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.73
A6	0.93	0.92	0.76	1.00	1.00	0.99	0.99	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.74
A7	0.92	0.91	0.76	1.00	1.00	0.99	1.00	1.00	0.99	1.00	1.00	1.00	1.00	1.00	0.73
A8	0.92	0.90	0.75	1.00	0.99	0.98	0.98	1.00	0.98	1.00	1.00	0.99	1.00	1.00	0.72

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.4 Crop production under the Basin-optimizing solution scenario (BOS) and comparison of basinwide production under BOS with actual crop production (1,000 metric tons)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	31.0	38.3	28.6	176.0	129.3	208.9	68.9	79.1	21.7	21.9	15.2	53.9	43.7	15.5	4.2
A2	10.7	14.3	10.7	72.2	50.1	73.7	23.9	30.4	7.9	8.0	5.7	21.1	14.1	3.2	1.9
A3	21.8	48.2	22.3	20.2	27.9	68.5	35.2	52.2	16.9	17.1	8.9	24.8	19.4	5.8	40.0
A4	0.7	2.3	0.9	1.0	2.8	2.6	3.7	1.6	0.9	0.9	0.2	0.7	1.5	0.3	0.0
A5	41.5	30.4	28.9	36.4	51.2	82.9	53.9	60.0	23.4	23.6	10.6	28.8	28.0	8.5	40.8
A6	1.7	3.5	1.9	14.3	9.9	14.9	4.8	6.0	1.5	1.5	1.1	4.2	2.8	0.6	0.1
A7	2.7	0.2	3.7	0.0	0.0	1.1	1.1	0.1	1.3	1.3	0.1	0.8	0.6	0.2	1.3
A8	13.5	0.5	5.4	48.7	46.6	34.6	16.1	13.9	14.6	14.8	3.1	6.4	15.1	10.0	0.6
Basinwide production under BOS	123.6	137.6	102.5	368.8	317.9	487.3	207.6	243.2	87.9	89.0	44.9	140.6	125.2	44.1	88.9
Actual basinwide production	105.2	165.2	192.1	220.1	193.3	302.2	126.6	144.6	51.5	51.5	25.2	80.8	68.2	24.4	129.9
Ratio of BOS to actual production	1.2	0.8	0.5	1.7	1.6	1.6	1.6	1.7	1.7	1.7	1.8	1.7	1.8	1.8	0.7

Source: Actual data provided by Donoso 1997.

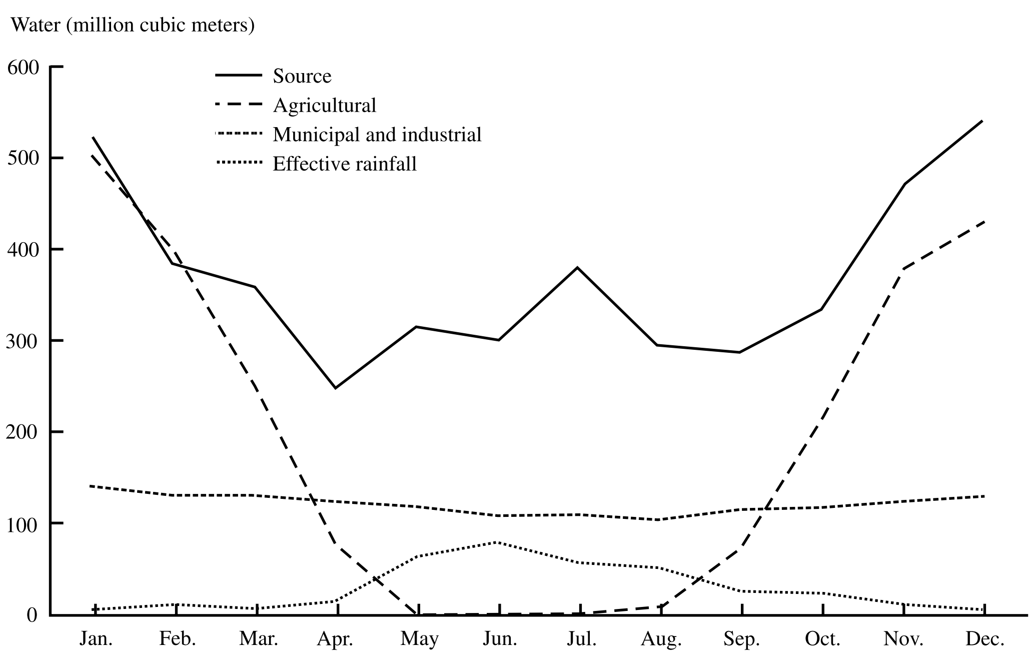
Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

groundwater data); (2) lower and upper bounds for crop acreage and yield based on historical records and empirical estimates (for example, crop harvested area ranges from 0.6 to 1.5 of observed values, and yield cannot fall below 50 percent of observed values); and (3) unlimited water withdrawals to demand sites (that is, no water use rights are implemented, and withdrawals to a demand site depend on the water use profitability in that demand site).

Under BOS, total effective rainfall is estimated at 116 million cubic meters. Total water withdrawals are 3,817 million cubic meters, or 86 percent of total basin inflows of 4,445 million cubic meters. Withdrawals are lowest during the months of June and July, as only perennial crops are present during this time. Figure 5.1 shows water withdrawals, surface water inflows, and effective rainfall under BOS. The apparent excessive use of surface water during the months of January–March and November–December can be explained with the high level of return flows that are being reused during these months. Total return flows amount to 872 million cubic meters or 20 percent of total inflows. Actual crop evapotranspiration is estimated at 954 million cubic meters, 99.7 percent of the total potential crop evapotranspiration of 956 million cubic meters. This value compares well with values estimated in Donoso (1997) of 972 million cubic meters. According to model results, total agricultural water withdrawals amount to 2,360 million cubic meters, close to the levels of 2,107 million cubic meters estimated in Donoso (1997). The difference can be explained, in part, by different estimates for irrigation efficiency levels. The average irrigation efficiency at the project or system level estimated by local experts is about 0.45, whereas the modeling results yield an overall efficiency level of 0.41.

Water withdrawals in the M&I demand sites reach the benefit-maximizing demand level at 1,457 million cubic meters, which is significantly higher than the 776.8 million cubic meters estimated in Donoso (1997). This shows a substantial potential for increasing M&I water supply in the basin. On the other hand, more recent estimates of

Figure 5.1 Water withdrawals, source, and effective rainfall under Basin-optimizing solution scenario



industrial withdrawals indicate that this potential is already being exploited.

More detailed results about irrigation water use and crop production are presented in Tables 5.5–5.12. Table 5.5 presents examples of ratios of crop water application to maximum crop evapotranspiration (ETM). Crop water use includes water delivered to crop fields and effective rainfall (*PE*). Values of 0 indicate that a crop is not presented in a specific month, and a value of 1 indicates that crop water use equals ETM. This occurs during some winter months. For most crops and irrigation months, crop water use is above ETM levels (up to 2.6 times for onions, for example), because of low irrigation efficiency levels and salt-leaching requirements. The relatively even distribution of the ratios among crop growing months shows that water is allocated according to the demand of different growth stages.

The ratios of crop water use to ETM are directly related to field application efficiencies presented in Table 5.6. As can be seen in Table 5.6, lower-value crops that generate lower profits per unit of water (see Table 5.8) have, on average, higher levels of irrigation efficiency, a seemingly counterintuitive result. But this result actually follows directly from the profit-maximizing behavior of the farmer. Farmers do apply more water relative to ETM for higher-value crops (and more water per hectare, in general, as well; see Table 5.7). Because the value per unit of output is higher for high-value crops, as shown in Tables 5.8 and 5.9, farmers irrigate much closer to the physical maximum crop yield for these crops. In contrast, the water application relative to ETM is much lower for lower-value crops because it is not profitable to further push out the physical crop yield function. At lower water applications relative to ETM, irrigation efficiency for lower-value crops is higher.

Tables 5.8 and 5.9 show large differences in the economic value among the various irrigated crops in the basin. In fact, profit per hectare for annual prairies is negative at the water price of US$0.04 per cubic meter because of a combination of large water consumption and low profit per hectare. The model outcome for annual prairie areas is 60 percent of actual area (Table 5.2), which corresponds to the predetermined lower bound of the model, imposed to reflect the traditional cropping pattern.

Return flows are explicitly calculated in the model, based on estimated delivery loss, field drainage, and groundwater water discharge. Table 5.10 presents data for irrigation return flows. As can be seen, return flows are confined to the irrigation season of August to April. The salt concentration is slightly higher in return flows from downstream irrigation areas, and especially in those demand sites that are downstream of large irrigation demand sites. For example, demand site A2 is just downstream of A1, the largest irrigation demand site in the basin. Return flows from A1 increase the salinity level in the flows received by A2, and the salinity concentration in return flows from A2 is higher still (Tables 5.10 and 5.11). Table 5.11 also shows that the salinity concentration in mixed irrigation sources differs slightly by crop because of varying crop salinity tolerance and availability of sources, including delivered surface water, groundwater, reused drainage, and effective rainfall, which have different salinity levels.

Table 5.12 shows the salt concentration in deep percolation, which is much higher than the concentration in the irrigation water mix. The high salinity level of deep percolation water is often responsible for high salinity levels in the return flow. The salinity level of deep percolation depends on the irrigation efficiency (Table 5.6) as well as on the salt concentration in mixed irrigation water (Table 5.11). As the tables show, higher field application efficiency levels are related to higher salt concentration (grams per liter) in deep percolation.

Sensitivity Analyses

Four sensitivity analyses are presented in the following to test the robustness of the model

Table 5.5 Ratio of crop water applied to maximum evapotranspiration at each crop growth stage, demand site A1

Crop category	January	February	March	April	May	June	July	August	September	October	November	December
Wheat	1.6	0.0	0.0	0.0	0.0	0.0	0.0	1.3	1.4	1.6	1.7	1.7
Corn	1.6	1.6	1.6	1.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.3
Annfor	0.9	0.7	0.0	0.0	0.0	0.0	0.0	0.0	0.7	0.9	1.0	1.0
Grapes	2.0	2.0	2.0	1.0	1.0	1.0	1.0	1.0	1.2	1.8	2.0	2.0
Peaches	2.4	2.3	2.3	1.0	1.0	1.0	1.0	1.0	1.5	2.0	2.3	2.4
Potatoes	1.7	1.7	1.7	0.0	0.0	0.0	0.0	0.0	0.0	1.4	1.7	1.7
Pumpkins	2.3	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.8	2.2	2.3
Lemons	2.5	2.4	2.5	2.2	1.0	1.0	1.0	1.0	1.6	2.1	2.4	2.5
Othjan	2.2	2.2	2.2	2.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Othjul	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.0	2.0	2.2	2.4	2.5
Avocados	2.5	2.5	2.5	2.3	1.0	1.0	1.0	1.0	1.9	2.2	2.5	2.5
Onions	2.6	2.6	2.7	2.5	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Carrots	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.3	2.6	2.8	0.0
Peas	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0	2.1	2.5	2.6	0.0
Prairie	1.4	1.5	1.3	1.4	1.0	1.0	1.0	1.0	1.2	1.3	1.3	1.4

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.6 Irrigation (field application) efficiency, by crop and demand site (ratio)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie	All crops(1)	All crops(2)
A1	0.56	0.60	0.62	0.48	0.41	0.57	0.43	0.39	0.44	0.40	0.38	0.36	0.33	0.36	0.65	0.54	0.41
A2	0.55	0.59	0.59	0.46	0.39	0.55	0.41	0.39	0.43	0.38	0.34	0.33	0.23	0.33	0.64	0.51	0.39
A3	0.54	0.57	0.59	0.47	0.39	0.55	0.41	0.38	0.43	0.38	0.36	0.34	0.31	0.34	0.64	0.52	0.41
A4	0.56	0.60	0.60	0.50	0.43	0.57	0.43	0.39	0.44	0.39	0.41	0.38	0.35	0.37	0.66	0.57	0.44
A5	0.56	0.59	0.58	0.47	0.40	0.56	0.42	0.39	0.44	0.40	0.36	0.34	0.32	0.28	0.65	0.51	0.40
A6	0.56	0.59	0.56	0.49	0.42	0.57	0.43	0.39	0.44	0.39	0.40	0.38	0.34	0.37	0.66	0.55	0.42
A7	0.58	0.62	0.61	0.50	0.43	0.58	0.44	0.39	0.45	0.40	0.41	0.39	0.36	0.38	0.65	0.53	0.51
A8	0.57	0.61	0.62	0.48	0.41	0.57	0.43	0.40	0.45	0.39	0.36	0.37	0.32	0.35	0.65	0.50	0.38

Notes: All crops(1) indicates average irrigation efficiency over all crop fields; all crops(2), average irrigation efficiency over all crop fields, considering delivery loss; annfor, annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.7 Water withdrawals, by crop and demand site (cubic meters per hectare)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	10,524	12,215	8,420	18,497	21,050	16,623	17,912	18,473	17,249	14,504	24,872	15,466	9,752	9,123	23,155
A2	10,663	12,257	8,735	19,130	21,391	16,689	18,086	18,355	17,308	14,997	27,712	16,724	14,100	9,858	23,692
A3	10,359	12,195	8,516	17,911	20,421	16,350	17,375	17,386	16,534	13,723	24,821	15,341	9,692	8,915	22,293
A4	10,379	12,187	8,287	17,776	19,743	16,534	17,551	18,121	16,819	14,148	23,113	14,509	9,034	8,588	22,214
A5	10,782	12,157	8,695	18,704	21,060	16,652	17,717	18,172	16,806	14,169	26,130	15,916	10,416	12,128	23,181
A6	10,673	12,599	8,548	18,054	20,331	16,834	17,817	18,214	17,060	13,992	23,814	14,894	9,272	8,788	22,494
A7	10,496	11,910	8,256	17,262	19,111	15,768	16,900	17,683	16,133	13,768	22,311	13,965	8,785	8,375	21,463
A8	11,004	12,343	8,784	19,543	21,823	17,298	18,384	18,958	17,475	15,052	27,488	15,822	10,936	9,999	24,249
Basinwide average	10,647	12,209	8,566	18,727	21,131	16,652	17,813	18,169	17,017	14,381	25,672	15,718	10,504	9,914	22,776

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.8 Profit per unit of water withdrawal, by crop and demand site (U.S. dollars per cubic meter)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	0.065	0.060	0.074	0.258	0.208	0.122	0.129	0.230	0.093	0.264	0.165	0.092	0.163	0.210	–0.011
A2	0.064	0.059	0.070	0.244	0.198	0.119	0.123	0.229	0.091	0.252	0.141	0.080	0.095	0.188	–0.012
A3	0.066	0.061	0.074	0.259	0.208	0.121	0.130	0.240	0.098	0.275	0.160	0.090	0.159	0.209	–0.009
A4	0.066	0.062	0.076	0.269	0.224	0.123	0.134	0.234	0.097	0.272	0.180	0.100	0.179	0.225	–0.009
A5	0.063	0.060	0.071	0.253	0.204	0.120	0.129	0.234	0.097	0.271	0.153	0.087	0.148	0.144	–0.011
A6	0.063	0.058	0.073	0.264	0.216	0.120	0.131	0.233	0.095	0.275	0.174	0.097	0.173	0.218	–0.010
A7	0.064	0.063	0.077	0.278	0.233	0.132	0.142	0.241	0.103	0.281	0.189	0.106	0.186	0.232	–0.007
A8	0.059	0.057	0.068	0.239	0.195	0.113	0.121	0.222	0.090	0.253	0.143	0.084	0.139	0.185	–0.013
Basinwide	0.061	0.065	0.072	0.234	0.201	0.121	0.130	0.204	0.093	0.243	0.140	0.083	0.144	0.177	–0.015

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.9 Profit, by crop and demand site (U.S. dollars per hectare)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	507.6	550.5	461.9	3,551.1	3,265.0	1,512.1	1,723.0	3,171.1	1,193.4	2,857.2	3,057.1	1,055.4	1,183.9	1,426.1	–313.6
A2	512.2	545.2	461.7	3,525.8	3,195.8	1,496.7	1,678.6	3,175.8	1,193.6	2,854.1	2,943.5	1,005.0	1,010.0	1,396.7	–349.5
A3	529.3	568.9	482.9	3,574.6	3,269.4	1,528.0	1,733.9	3,214.6	1,242.7	2,905.1	3,059.2	1,060.4	1,186.3	1,434.4	–256.2
A4	512.0	563.4	471.3	3,580.0	3,317.3	1,528.7	1,767.4	3,185.2	1,219.5	2,888.1	3,127.5	1,093.6	1,212.6	1,447.5	–251.0
A5	505.6	549.1	462.9	3,542.9	3,229.3	1,501.0	1,709.1	3,183.1	1,217.9	2,877.2	3,006.8	1,037.3	1,157.4	1,305.9	–315.4
A6	506.0	552.7	465.6	3,568.9	3,293.8	1,516.8	1,746.1	3,181.4	1,217.5	2,886.4	3,099.5	1,078.2	1,203.1	1,439.5	–269.6
A7	502.7	561.4	476.0	3,600.5	3,342.6	1,560.0	1,795.9	3,202.6	1,243.5	2,903.3	3,159.5	1,115.4	1,222.6	1,456.0	–200.9
A8	486.1	526.9	445.1	3,509.3	3,191.0	1,466.2	1,671.8	3,151.7	1,183.8	2,851.9	2,952.5	999.5	1,136.6	1,391.0	–386.6
Basinwide	508.7	556.2	466.4	3,541.9	3,239.1	1,507.2	1,713.8	3,183.2	1,209.1	2,872.0	3,025.4	1,043.6	1,153.9	1,394.4	–288.1

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.10 Return flows from agriculture, by period and demand site

Demand site	Return flows (million cubic meters)													Salt concentration (grams per liter)
	January	February	March	April	May	June	July	August	September	October	November	December	Annual	
A1	19.6	15.9	11.9	3.2	0.0	0.0	0.0	0.2	2.9	9.5	14.9	16.9	95.0	1.3
A2	8.1	6.5	4.9	1.4	0.0	0.0	0.0	0.1	1.3	4.0	5.8	6.8	38.9	1.7
A3	11.3	9.8	7.8	3.2	0.0	0.0	0.0	0.2	1.6	5.6	7.9	9.0	56.4	1.5
A4	0.4	0.3	0.2	0.1	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.3	1.9	1.1
A5	13.2	10.5	8.4	3.7	0.1	0.0	0.0	0.4	3.7	8.0	11.3	12.1	71.4	1.5
A6	1.5	1.2	0.9	0.2	0.0	0.0	0.0	0.0	0.1	0.6	1.0	1.2	6.7	1.2
A7	0.3	0.2	0.1	0.1	0.0	0.0	0.0	0.0	0.1	0.2	0.3	0.3	1.6	1.2
A8	5.4	4.1	3.1	0.7	0.1	0.0	0.0	0.1	1.5	4.0	5.6	5.3	29.9	1.5

Table 5.11 Salt concentration in mixed irrigation sources (grams per liter)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	0.42	0.40	0.40	0.42	0.42	0.42	0.43	0.39	0.41	0.41	0.40	0.41	0.39	0.40	0.41
A2	0.55	0.52	0.53	0.55	0.56	0.56	0.56	0.52	0.54	0.54	0.53	0.54	0.53	0.53	0.54
A3	0.49	0.45	0.47	0.49	0.50	0.50	0.50	0.46	0.48	0.48	0.47	0.48	0.46	0.47	0.48
A4	0.35	0.34	0.32	0.34	0.35	0.35	0.35	0.32	0.34	0.33	0.32	0.34	0.31	0.32	0.34
A5	0.51	0.50	0.49	0.51	0.51	0.51	0.51	0.47	0.49	0.49	0.48	0.49	0.47	0.49	0.49
A6	0.39	0.36	0.37	0.38	0.39	0.39	0.39	0.36	0.38	0.37	0.36	0.38	0.35	0.36	0.38
A7	0.33	0.31	0.32	0.33	0.33	0.33	0.34	0.31	0.33	0.32	0.31	0.32	0.31	0.32	0.32
A8	0.51	0.50	0.50	0.51	0.51	0.52	0.52	0.48	0.50	0.50	0.49	0.50	0.48	0.49	0.50

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 5.12 Salt concentration in deep percolation, by crop and demand site (grams per liter)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	1.0	1.1	2.0	0.9	0.7	1.0	0.8	0.7	0.8	0.7	0.7	0.7	0.7	0.7	1.7
A2	1.3	1.4	2.3	1.1	1.0	1.3	1.0	0.9	1.0	0.9	0.9	0.9	0.8	0.9	1.9
A3	1.1	1.2	2.7	1.0	0.9	1.1	0.9	0.8	0.9	0.8	0.8	0.8	0.8	0.8	1.8
A4	0.8	0.9	2.4	0.7	0.6	0.9	0.6	0.6	0.7	0.6	0.6	0.6	0.6	0.6	1.6
A5	1.2	1.3	2.1	1.0	0.9	1.2	0.9	0.9	0.9	0.9	0.8	0.8	0.8	0.7	1.8
A6	0.9	1.0	2.6	0.8	0.7	0.9	0.7	0.7	0.7	0.7	0.7	0.6	0.6	0.6	1.6
A7	0.8	0.9	2.3	0.7	0.6	0.8	0.6	0.6	0.6	0.6	0.6	0.6	0.5	0.6	1.6
A8	1.2	1.3	2.5	1.0	0.9	1.2	0.9	0.9	1.0	0.9	0.8	0.8	0.8	0.8	1.8

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

results: changes in hydrologic levels, crop price, source salinity levels, and water price (Table 5.13). Water withdrawals for M&I demand sites barely change in these alternative scenarios. This is because, at normal inflows, M&I demand sites can withdraw up to their benefit-maximizing level within the varying range of those parameters. However, M&I withdrawals and benefits do vary in the dry-year case and with changing water prices.

With a reduction of normal inflows by half, water withdrawals and benefits for both agricultural and M&I demand sites decline sharply. Agricultural profits decrease by 37 percent, and M&I benefits decline by 9 percent compared to normal inflows. Moreover, water withdrawals plunge by 42 percent for irrigation and by 13 percent in M&I demand sites. Thus, in the case of drought, the agriculture sector is much more affected.

Proportional changes over all crop prices in the range of ±25 percent have only small effects on irrigation water withdrawals. However, farmer incomes from irrigation are significantly affected. With a reduction of crop prices by 25 percent, water withdrawals for agricultural uses decline by 5 percent, whereas profits from irrigation drop by 60 percent. On the other hand, an increase in crop prices by 25 percent results in a slight increase in agricultural water withdrawals (2 percent) and a large increase in farmer profits (61 percent).

A reduction by half in the source salinity reduces water withdrawals in agriculture by 4 percent as less water is required for salt leaching. As a result, profits from irrigation increase by 3 percent. A doubling of the source salinity, on the other hand, leads to an increase in irrigation water withdrawals for salt leaching by 5 percent. Increased salt leaching, however, reduces profits from irrigation by 14 percent. Moreover, changes in the salinity level influence crop patterns, with a decline in the harvested area of crops with lower salt tolerance. With doubled source salinity, the area planted to maize declines to 8 percent from 13 percent under BOS at 0.3 grams per liter, whereas the area planted with wheat, a more salt-tolerant crop, increases to 18 percent from 12 percent under BOS, as shown in Figure 5.2.

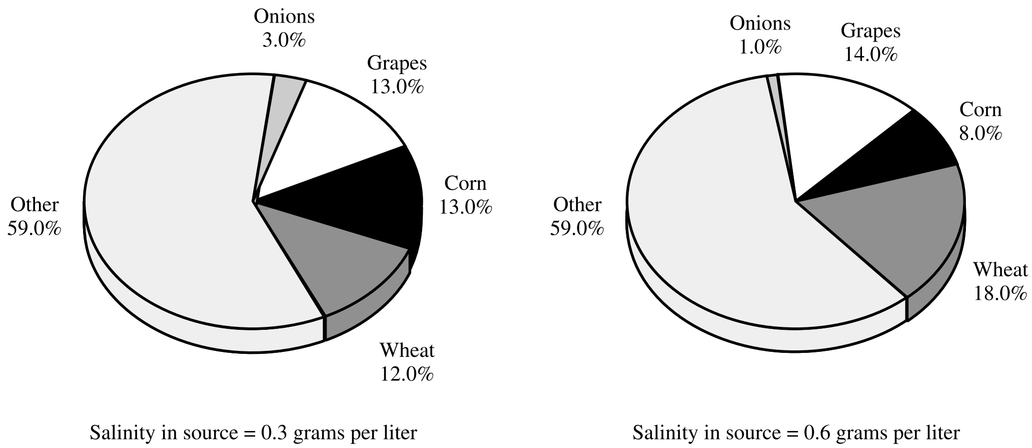
A sensitivity analysis was also carried out for irrigation charges (US$0.04 per cubic meter) and M&I tariffs (US$0.10 per cubic meter). These prices were doubled and halved, respectively. The results are very robust with regard to withdrawals and profits for both agriculture and urban areas. With a doubling of the water prices, agricultural withdrawals drop by 10 percent, and profits

Table 5.13 Sensitivity analysis, various parameters (percentage)

Parameter	Parameter levels	Irrigation withdrawal	M&I withdrawal	Irrigation profits	M&I benefits
Inflow	50	58.3	86.7	63.1	90.5
	150	101.2	100.0	100.1	100.0
Crop price	75	94.8	100.0	39.8	100.0
	125	101.6	100.0	161.0	100.0
	50	95.5	100.0	102.8	100.0
Salinity in source	150	101.6	100.0	96.4	100.0
	200	105.1	100.0	86.4	100.0
Water price	50	100.8	100.0	118.5	111.9
	200	89.9	100.0	65.0	76.2

Notes: With the exception of the inflow scenarios, sensitivity analyses were carried out based on normal flows. All percentages are relative to the Basin-optimizing solution scenario. M&I indicates municipal and industrial.

Figure 5.2 Crop pattern change as a result of changes in source salinity



from irrigation decline by 35 percent. For M&I demand sites, water withdrawals do not change, but benefits decline sharply by 24 percent. If the water charge for agriculture and M&I uses is halved, irrigation withdrawals increase by 1 percent, and profits from irrigation by 19 percent. M&I withdrawals do not change, but benefits increase by 12 percent.

Table 5.14 shows the effects of changes in water fees for agriculture on water withdrawals and incomes in the irrigation and M&I sectors for a drought-year case (50 percent of normal inflows). With an increase in the water charge for irrigation from zero to US$0.08 per cubic meter, water withdrawals for agriculture decline by 5 percent, from 1,387 million cubic meters to 1,326 million cubic meters. However, changes in the water fee barely affect the crop area. A doubling of the water charge, for example, from US$0.04 per cubic meter to US$0.08 per cubic meter, results in a small decline in the crop area from 115,176 hectares to 115,032 hectares (0.13 percent). Irrigated area is maintained because farmers shift on the margin to more water-efficient crops and reduce water use per hectare on other crops. Although both agricultural water withdrawals and irrigated crop area barely change with varying water charges, farmer incomes can drop by as much as 42 percent under such an "administrative price scenario"—from US$224 million to US$130 million—as a result of increased irrigation water prices. On the other hand, a reduction in the baseline water charge for irrigation by half, from US$0.04 per cubic meter to US$0.02 per cubic meter, would increase net farmer profits by 19 percent. M&I net

Table 5.14 Sensitivity analysis for agricultural water price at 50 percent of normal inflow

	Scenario			
Parameter	**I**	**II**	**III**	**IV**
Water price (US$ per cubic meter)	0	0.02	0.04	0.08
Irrigation withdrawals (million cubic meters)	1,387	1,380	1,351	1,326
Irrigated crop area (hectares)	115,200	115,191	115,176	115,032
Municipal and industrial water withdrawal (million cubic meters)	1,258	1,263	1,283	1,303
Irrigation profits (million US$)	224	196	165	130
Municipal and industrial profits (million US$)	550	552	558	570
Total profits (million US$)	774	748	722	700

benefits increase steadily with continuing water tariff increases in agriculture, from US$550 million to US$570 million, and M&I water withdrawals increase by 3.6 percent. With water prices already quite high, further price increases would be a blunt instrument for influencing water demand. Under these circumstances, water markets that allow farmers to retain the income from sales of water may be preferable. This issue is discussed in Chapter 6.

Summary

The BOS or Basin-optimizing scenario, in which water is allocated to the most profitable uses within existing physical, technical, and system control constraints, reflects the best solution from an economic efficiency perspective. Although such an optimal solution, where an omniscient decisionmaker has full knowledge of the temporally and spatially distributed scarcity values of water in the basin, cannot be achieved in reality, it can be used as an indication or a reference point that basin agents could strive toward. The basic message from this scenario is that the switch of crop acreage and water from lower-value crops to higher-value crops results in additional profits compared with the actual status. In the following chapters, the BOS scenario is used as a reference point for comparison with alternative scenarios.

CHAPTER 6

Water Trade Analysis

The primary alternative to administratively based allocation of water is incentive-based allocation, either through volumetric water prices or through markets in tradable water rights. The empirical evidence shows that farmers are price responsive in their use of irrigation water (Gardner 1983; Rosegrant, Gazmuri Schleyer, and Yadav 1995). The choice between administered prices and markets should be largely a function of which system has the lowest administrative and transaction costs. Markets in tradable water rights can reduce information costs, increase farmer acceptance and participation, empower water users, provide security and incentives for investment and the internalization of the external costs of water uses, and provide flexibility in response to water demands. As previously discussed, the Chilean Water Law of 1981 established the basic characteristics of property rights over water as a proportional share over a variable flow or quantity. Changes in allocation of water within and between sectors are realized through markets in tradable water rights (for details, see Hearne and Easter 1995; Gazmuri Schleyer and Rosegrant 1996).

Scenario Analysis of Water Rights and Markets

Three scenarios are compared to assess the effect of water trading: Basin-optimizing solution (BOS), which was described in the previous chapter; fixed water rights (FWR) without the possibility of trading, and water rights with trading (TRD). Under FWR, water use rights are allocated following historic water use. Each demand site can withdraw water up to the fixed water right. Under TRD, each demand site can trade water. The scenario is set up so that the total amount of water sold is equal to that of water bought for each time period (month); and within each time period, one demand site can only buy or sell water. These scenarios are implemented at 100 percent and 60 percent of normal inflows (Table 6.1). In addition, three transaction cost scenarios are analyzed for average inflows (Table 6.2). The description of results will concentrate on the drought scenario (Case B), as the benefits vary more clearly depending on the economic instrument employed. Figure 6.1 compares these scenarios in terms of municipal and industrial (M&I) benefits, agricultural benefits, and shadow prices.

Economic Gains and Losses

In the case of a drought year (60 percent of normal inflows), total water withdrawals are highest for BOS, as water demands are constrained only by physical and system control constraints, and each demand site can withdraw according to its monthly needs but subject to an optimum result for the basin as a whole. Water withdrawals decline substantially in the FWR case, when no trading is allowed and withdrawals are limited to the respective water right. Agricultural withdrawals are often actually below the actual water right because dry-season flows are inadequate to fulfill all crop water requirements. Another reason is that, in about half

Table 6.1 Scenario analysis under the Basin-optimizing solution, Fixed water rights, and Water rights with trading scenarios

Demand site	Withdrawals[a] (million cubic meters)			Actual water rights (million cubic meters)	Trade (million cubic meters)	Net profits (million US$)			Gains[b] (million US$)	Shadow price of water (US$ per cubic meter)		
	BOS	FWR	TRD	FWR/TRD	TRD	BOS	FWR	TRD	TRD	BOS	FWR	TRD
Case A: 100 percent of normal inflow												
A1	696	617	610	867	13	120	117	118	1	0.044	0.128	0.132
A2	266	243	234	341	8	46	45	45	1	0.044	0.111	0.123
A3	371	391	349	547	70	47	49	52	2	0.046	0.075	0.119
A4	16	15	14	21	3	2	2	3	0	0.045	0.083	0.111
A5	506	502	444	704	147	65	67	71	5	0.051	0.091	0.138
A6	54	46	45	64	1	9	8	8	0	0.045	0.134	0.147
A7	15	17	14	25	10	2	2	2	1	0.072	0.040	0.099
A8	206	154	153	216	1	37	31	31	0	0.044	0.189	0.177
M1	991	678	841	678	–163	417	293	353	60	0.019	0.975	0.415
M2	460	315	404	315	–90	193	135	166	32	0.019	1.014	0.383
Total	3,581	2,977	3,108	3,778	0	939	749	850	101			
Case B: 60 percent of normal inflow												
A1	514	479	432	522	47	95	89	99	10	0.097	0.134	0.232
A2	222	188	166	205	90	40	36	52	17	0.102	0.230	0.221
A3	305	303	279	329	23	41	41	43	3	0.078	0.168	0.194
A4	7	11	10	13	2	1	1	2	1	0.096	0.100	0.195
A5	395	391	350	423	112	56	55	70	16	0.110	0.111	0.192
A6	43	34	33	38	2	8	7	7	1	0.077	0.225	0.224
A7	11	11	11	15	2	1	1	2	1	0.127	0.059	0.146
A8	142	120	102	130	18	27	23	25	2	0.098	0.259	0.259
M1	974	518	713	408	–195	413	102	266	164	0.056	1.439	0.789
M2	453	240	342	189	–101	192	34	129	94	0.056	1.720	0.735
Total	3,067	2,296	2,437	2,272	0	874	389	696	307			

Notes: BOS indicates Basin-optimizing solution; FWR, Fixed water rights scenario; TRD, Water rights with trading scenario.
[a]Withdrawals are net of water traded.
[b]Gains are gains from trade.

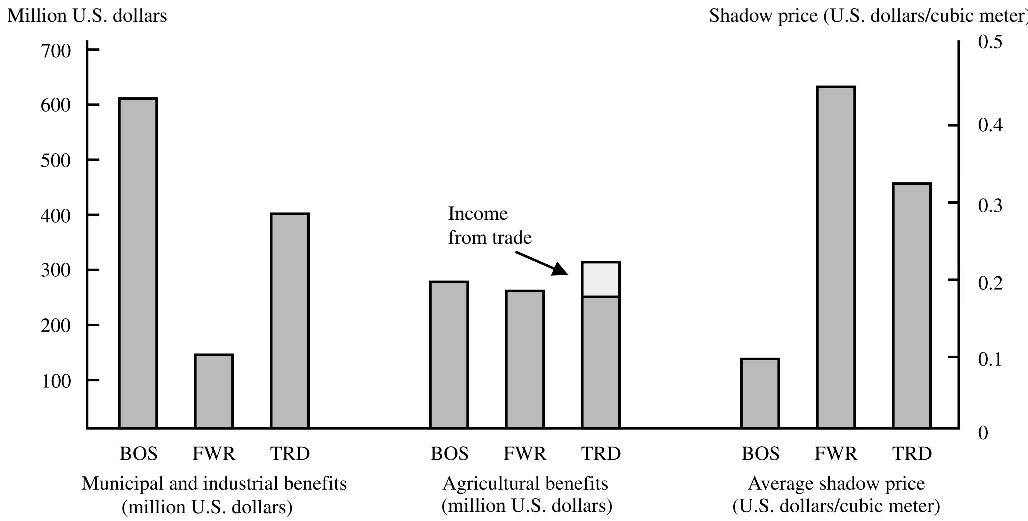
of the months, only perennial crops are grown, and thus, withdrawals are far below the allotted flow.

When water can be traded, irrigation withdrawals actually decline further, albeit not very much. Irrigation withdrawals decline because the irrigation districts sell part of their water rights to the M&I demand sites, thereby reaping substantial profits. In the dry-year case, a total water volume of

Table 6.2 Transaction cost scenarios (Case A)

Transaction costs (US$ per cubic meter)	Withdrawals (million cubic meters)	Water traded (million cubic meters)	Total net benefits (million US$)	Gains from trade (million US$)	Shadow price (US$ per cubic meter)
0.00	3,119	278	871	122	0.1808
0.04	3,108	264	850	101	0.1844
0.10	3,075	236	822	73	0.4127
0.20	3,051	138	755	6	1.2680

Figure 6.1 Scenario comparing: Basin-optimizing solution (BOS), Fixed water rights (FWR), and Water rights with trading (TRD) scenarios in terms of municipal and industrial benefits, agricultural benefits, and shadow prices



296 million cubic meters is traded, about 11 percent of total dry-year inflow. In the case of normal inflows, 264 million cubic meters of water is traded, about 6 percent of the inflow. The M&I areas are the main buyers in both cases, purchasing virtually all of the water offered by the irrigation districts. All irrigation districts are net sellers of water over the course of the year; only district A8 purchases 0.2 million cubic meters of water under the drought case to maintain its cropping pattern, which features the largest share of higher-value, perennial crops (grapes and peaches, among others). In the case of normal inflows, on the other hand, the marginal value of water is much lower, and two agricultural demand sites, A6 and A8, purchase water (0.2 million cubic meters and 10.8 million cubic meters, respectively) to supplement their crop production in some months; however, both districts are net sellers of water.

Because the FWR scenario does not allow the transfer of water to more beneficial uses, benefits from water are significantly reduced by locking the resource into relatively low-value uses during water shortages. As a result, total net benefits are less than one-half of the optimizing solution (US$389 million compared with US$874 million). By permitting trading, water moves from less productive agricultural uses into higher-value urban water uses while benefiting farm incomes. Total benefits in the M&I demand sites almost triple, compared to FWR, but gains are also significant for the irrigation districts, and each district can increase net profits, by between 6 and 62 percent, depending on their respective physical and other characteristics. Total net profits of the sector increase by about 20 percent, from US$253 million to US$301 million. In irrigation districts A1–A5 and A7, total net profits under the TRD scenario are even higher than under BOS. This is because of the higher value of the scarcer water and the resulting benefits from trade, which does not occur with the normal inflow levels under BOS.

Moreover, net profits from crop production decline only slightly with trading: from US$253 million to US$244 million. Total crop production also barely declines, from 1.866 million metric tons to 1.729 million metric tons. In addition, the proportion of higher-value perennial crops increases substantially from the FWR to the TRD scenarios, from 14 percent to 19 percent for grapes and from 13 percent to 16 percent for peaches, for example. These results not only show the advantages of the water market approach compared with the FWR case, but also compared with the administrative price scenario presented in the sensitivity analysis, under which water is also reallocated from agricultural to nonagricultural uses, but at a punitive cost to agricultural incomes.

In the shift from fixed proportional water rights to trade, total benefits to the basin increase from 45 percent of the omniscient decisionmaker under FWR to 80 percent (under TRD). However, total benefits under water trading are actually even closer to the pure optimum than shown here because no monitoring/transaction costs are charged for the "omniscient decisionmaker" whereas the cost would very likely be high.

Transaction Costs

For the water-trading scenario, it is currently assumed that both buyer and seller contribute equally to transaction costs (US$0.04 per cubic meter). Three transaction cost scenarios were run in addition to this base-trading scenario: zero transaction costs, US$0.1 per cubic meter, and US$0.2 per cubic meter. The results are shown in Table 6.2. As can be expected, water withdrawals decline with increasing transaction costs, and the volume of water traded plunges by more than half, from 278 million cubic meters for the case without transaction costs to 138 million cubic meters for the case with transaction costs of US$0.2 per cubic meter. This is in part because under this benefit structure, the transaction costs are quite high relative to the shadow prices for water, which range from US$0.18 to US$1.27 per cubic meter. Total net benefits decline substantially, from US$871 million to US$755 million in the scenarios with no and very high transaction costs, respectively. Moreover, gains from trade drop sharply, from US$122 million when transaction costs are nonexistent to only US$6 million in the case of high transaction costs. Thus, making trading more efficient (reducing transaction costs) has significant benefits, increasing both the amount of trading and the benefits from trade.

Effects of Water Trading on Crop Pattern and Irrigation Technology Choice

Modeling results show that water markets induce changes in crop patterns in the Maipo River Basin (Table 6.3). With water markets, the opportunity cost of water to the farmer-irrigator has increased because water can be sold to M&I or to other farmers who have higher returns to farming. As a result, farmers reduce the area planted to those crops that have relatively low returns to water use, such as wheat, maize, forage, and other crops, including pumpkins, lemons,

Table 6.3 Harvested irrigated area with normal inflows under Basin-optimizing solution, Fixed water rights, and Water rights with trading scenarios (hectares)

Crop	Basin-optimizing solution scenario	Fixed water rights scenario	Water rights with trading scenarios
Wheat	16,022	16,022	13,228
Maize	11,188	11,188	10,940
Annual forage	9,112	9,113	8,925
Grapes	15,381	14,575	19,412
Peaches	13,291	13,289	15,422
Other	50,704	50,703	41,241
Total	115,698	114,890	109,168

Table 6.4 Irrigation technology under Basin-optimizing solution, Fixed water rights, and Water rights with trading scenarios, dry and normal years

	Dry			Normal		
Crop category	**BOS**	**FWR**	**TRD**	**BOS**	**FWR**	**TRD**
Wheat	0.70	0.70	0.70	0.70	0.70	0.70
Corn	0.70	0.70	0.70	0.70	0.70	0.70
Annfor	0.70	0.70	0.70	0.70	0.70	0.70
Grapes	0.80	0.81	0.84	0.80	0.81	0.81
Peaches	0.89	0.91	0.94	0.73	0.86	0.92
Potatoes	0.78	0.76	0.75	0.70	0.76	0.79
Pumpkins	0.79	0.79	0.79	0.70	0.75	0.78
Lemons	0.73	0.78	0.84	0.70	0.75	0.78
Othjan	0.79	0.79	0.83	0.71	0.79	0.83
Othjul	0.78	0.84	0.91	0.70	0.74	0.75
Avocados	0.93	0.94	0.95	0.75	0.90	0.95
Onions	0.70	0.71	0.74	0.70	0.72	0.75
Carrots	0.78	0.88	0.94	0.70	0.74	0.75
Peas	0.76	0.84	0.91	0.70	0.74	0.75
Prairie	0.70	0.70	0.70	0.70	0.70	0.70

Notes: BOS indicates Basin-optimizing solution; FWR, Fixed water rights scenario; TRD, Water rights with trading scenario. Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

othjan, othjul, avocados, onions, carrots, and peas. Total area is reduced slightly as a somewhat greater volume of water is sold to nonagricultural uses than is saved through improved irrigation efficiency.

Water markets can also induce improvements in irrigation technology, especially for crops with higher economic value. A key result shown in Table 6.4 is that both water rights and water rights with trading can induce improvements in on-farm irrigation technology for higher-valued crops, in both dry and normal years. For lower-value crops, on the other hand, even with water markets and higher opportunity cost of water, it is not profitable to invest in improved technology. Water rights alone induce improvement in technology (and in efficiency, as discussed in Chapter 7). This is because for some demand sites, the water rights structure is more constraining than under BOS; lack of water in these sites, reflected in higher shadow prices, induces improved irrigation technologies with enhanced irrigation efficiencies. Field irrigation technology choices are further discussed in Chapter 8.

Summary

A fixed water rights scenario (FWR) and a water rights with trading scenario (TRD) are compared with the Basin-optimizing scenario (BOS). The model results show the benefits of water rights trading with water moving into M&I and higher-value agricultural uses. Under water trading, net profits in irrigated agriculture increase substantially compared with the case of proportional use rights. Moreover, agricultural production does not decline significantly. Net benefits for irrigation districts can be even higher than for the basin-optimizing case, as farmers reap substantial benefits from selling their unused water rights to M&I areas during the months with little or no crop production. Finally, making trading more efficient, that is, reducing transaction costs, has significant benefits, increasing both the amount of trading and the benefits from trade. It should be noted that some alternative institutions such as partial markets (for example, markets limited to agricultural demand sites) have not been studied in this project, but those are often implemented in the real world.

CHAPTER 7

Water Use Efficiency Analysis

Improvement in the physical efficiency of water use, that is, water distribution/conveyance efficiency and field application efficiency, is related to water conservation through increasing the fraction of water beneficially used over water applied; enhancing economic efficiency is a broader concept seeking the highest economic value of water use through both physical and managerial measures. Physical and economic efficiency measures are both useful indicators for water management at the irrigation system and river basin level. However, the relationship between physical efficiency and economic efficiency is not always clear, and the values of these measures may indicate different directions for water policy and investments in irrigation. Open research questions include, for example: How do alternative water allocation mechanisms affect physical and economic irrigation efficiency? What is the effect of a change in irrigation system efficiency on basin efficiency? What is the effect of a change in physical efficiency (at both the irrigation system and basin levels) on economic efficiency? Our model is used to examine these questions in this chapter followed by a discussion on policy implications.

Efficiency Indicators

In this study, indicators for technical or physical and economic efficiency are compared to analyze improvements in the allocation of water resources in a river basin context. Economic efficiency is geared toward optimal production or optimal economic output and can be achieved only when both technical efficiency and price efficiency are achieved (Antle and McGuckin 1993). Price efficiency is the condition for maximum profit, including allocation efficiency (the ratio of marginal products of inputs equals the ratio of the input prices) and scale efficiency (marginal cost is the same as the price of the output). Wichelns (1999) presents a detailed review of physical and economic efficiency.

Physical Irrigation Efficiency Indicators

Physical irrigation efficiency is represented as the fraction of water beneficially used over water withdrawn. Classical irrigation efficiency (IE_c) is defined as the ratio of water volume beneficially used by plants to the volume of water delivered through an irrigation system, adjusted for effective rainfall and changes in the water storage in the root zone (Burt et al. 1997). Irrigation efficiency at the project level is typically subdivided into distribution efficiency (water distribution in the main canal), conveyance efficiency (water distribution in secondary canals), and field application efficiency (water distribution in the crop fields).

Keller and Keller (1995) and Keller, Keller, and Seckler (1996) argue that although the classical or local irrigation efficiency concept is appropriate for irrigation system design and management, it could lead to erroneous conclusions and serious mismanagement of scarce water resources if it is used for water accounting at a larger scale. This is because the classical approach ignores the potential reuses of irrigation return flows. To overcome the limitations of the classical irrigation efficiency concept, they propose a new concept, called effective efficiency (IE_e), which takes into account the quantity of water delivered from and returned to a water supply system:

$$IE_e = \frac{\text{Crop evapotranspiration} - \text{Effective rainfall}}{\text{Volume of water delivered} - \text{Change of root zone water storage} - \text{Volume of water returned}} \quad (7.1)$$

In this study, we examine classical efficiency at the irrigation system level and effective efficiency at both the irrigation system and the river basin level.

Economic Efficiency Indicators

Economic efficiency of irrigation water use refers to the economic benefits and costs of water use in agricultural production. Thus, it includes the cost of water delivery, the opportunity cost of irrigation and drainage activities, and potential third-party effects or negative (and positive) externalities (Dinar 1993). Dinar (1993), Grimble (1999), and Wichelns (1999) show that economic efficiency indicators typically have broader policy implications than physical efficiency measures because they enable an analysis of private and social costs and values in addition to including physical components associated with irrigation decisions. In the agricultural economics literature, a series of ratios have been developed to express economic efficiency indicators. For example, Dinar (1993) uses the ratio of "net value of output to water supplied" to measure water use efficiency in an irrigation system in Southern California; Sutton and Jones (1994) define economic efficiency as net profit per unit of area at the crop field level. A similar set of measures is used in other fields of agriculture. For example, in livestock production and nutrition, weight of saleable beef per unit feed intake (indicator for technical efficiency) and net profit per unit of feed or ratio of total feed cost over net production (indicator for economic efficiency) are used to guide the selection of feed rations or to guide a breeding program to improve feed conversion efficiency. In this chapter we use total net benefit and net benefit per unit of water use as economic efficiency measures.

Physical and Economic Efficiency Indicators at the River Basin Scale

At different scales, ranging from the crop level, field, farm, and irrigation district level to the whole basin, both physical and economic efficiencies have different implications and should be represented in different forms. Physical irrigation efficiency at the basin scale can be represented as the ratio of beneficial irrigation water consumption to total irrigation water consumption in the basin. This concept takes into account the potential reuse of return flows. The final basin efficiency value depends on how much runoff and drainage can be recycled for use in subsequent multiple uses because not all the water that runs off or drains from a field will be recoverable. Some will evaporate, and some will end up in inaccessible parts of the aquifer or river network (Wallace and Batchelor 2001). Various indicators of basin irrigation efficiency are presented in Molden (1997) and Molden and Sakthivadivel (1999). Seckler (1996) suggests a reduction in losses of usable water to sinks and a reduction in water pollution as useful measures for improving physical water use efficiency at the river basin level.

Engineering projects such as reservoir storage and operations and conjunctive surface and groundwater use can help to increase the share of return flow that can be reused and thus increase the physical basin efficiency. In contemplating the improvement of water recycling and reuse, both time lags and the quality of return flows need to be considered. If technological and financial conditions permit, agricultural drainage can be treated to increase the fraction of return flows that can be reused.

Economic efficiency at the basin scale seeks to maximize the net benefits of water use over the whole basin, accounting for upstream and downstream uses, intrasectoral and intersectoral water distribution, water productivity at different locations, as well as for physical efficiency. Economic incentives such as water markets and prices can significantly influence economic efficiency at the basin scale (Cummings and Nercissiante 1989; Dinar 1993; and Grimble 1999). As irrigation can contribute to water quality degradation economic efficiency at the basin scale should consider the social cost of environmental degradation (Dinar 1993). The economic efficiency concept can be used to assess the relative status of all water-using sectors.

At the basin level, the relationship between physical efficiency and economic efficiency can be highly complex. In water-scarce river basins with low (irrigation) infrastructure development and marginal cost of additional supply infrastructure below the marginal benefit of additional water use, investment in physical efficiency can lead to significant increases in economic efficiency, for example. However, in some highly developed river basins, where little or no (re)usable water leaves the basin area (see Seckler 1996), the effect of increased physical irrigation efficiency on economic efficiency is less clear. Here, storage facilities typically control most of the renewable water available, irrigation systems are close to the physical limit, and basin efficiency is already high. In this case, the emphasis will likely be on increasing economic efficiencies through nonstructural means. If, in addition, the marginal cost of increasing the physical efficiency is larger than the additional water use benefit in a particular irrigation system setting, then improvements in physical efficiency are attractive from an economic perspective only if the water saved is transferred to higher-value uses, for example, through changes in the cropping pattern, through water marketing between systems, or through reallocation of water to higher-value uses such as domestic and industrial uses.

Mathematical Representation of Physical and Economic Efficiency

The local irrigation efficiency at a specific irrigation demand site or farm is calculated in the model assuming no change in the seasonal crop root zone water storage,

$$IE^{d} = \frac{\sum_{t}\sum_{c}(eta^{d,c,t} - er^{d,c,t}) \cdot A^{d,c}}{\sum_{t} WD^{d,t}}, \quad (7.2)$$

where c is crop type, d is demand site, t is monthly time period, eta is the actual crop evapotranspiration, er is the effective rainfall, A is the irrigated harvested area, and WD stands for water withdrawals, including surface and groundwater, both determined in the model. Considering return flows that can be reused downstream and ignoring soil moisture change over crop seasons, effective efficiency (equation 7.1) at irrigation demand sites, EIE^{d} is determined as:

$$EIE^{d} = \frac{\sum_{t}\sum_{c}(eta^{d,c,t} - er^{d,c,t}) \cdot A^{d,c}}{\sum_{t}(WD^{d,t} - RF^{d,t})}, \quad (7.3)$$

where RF is the return flow from demand sites to the water supply system, including surface drainage and groundwater discharge. Surface drainage includes part of the distribution loss, tail water from crop fields, and artificial drainage; and groundwater drainage depends on the effect of field percolation to the groundwater table (Loeltz and Leake 1983).

The basin irrigation efficiency is calculated as:

$$IEB = \frac{WCIRB}{WCIR} = \frac{\sum_d \sum_t \sum_c (eta^{d,c,t} - er^{d,c,t}) \cdot A^{d,c}}{\sum_t (inflow^{t} - outflow^{t}) - \sum_t WCMI^t - \sum_t L^t - \Delta S}, \tag{7.4}$$

where *WCIR* is the total irrigation water consumption in the basin, *WCIRB* is the beneficial irrigation water consumption, *inflow* is the basin inflow including surface drainage and groundwater recharge, *outflow* is the water leaving the basin, *WCMI* is the water consumption from municipal and industrial uses, *L* is the instream water seepage and evaporation loss, and ΔS is the change of surface and groundwater storage in one year.

For the case study basin, a monthly time step is used. It is assumed that return flows in one period (t) return to the river system in the same time period. This is justified by specific conditions in the Maipo Basin—that is, narrow valley with steep slopes and a large share of return flows.

We use several indicators for economic efficiency, including total net benefits across the basin, net benefit per unit of water consumed, irrigation profit, and irrigation profit per unit of water consumed. Total net benefits to water use (*TNB*) should include a contribution from instream environmental water uses and hydropower generation as well as off-stream water uses, such as irrigation and municipal and industrial water uses, over the corresponding water demand sites (d) and hydropower stations (st):

$$\begin{aligned} TNB = & \sum_{d \cdot Agr.} (\mathrm{PTIR}^d - WIR^d \cdot CWIR^d \\ & - DIR^d \cdot CDIR^d) \\ & + \sum_{d \in M\&I} (PTMI^d - WMI^d \\ & \cdot CWMI^d - DMI^d \cdot CDMI^d) \\ & + \sum_{st} (PTHP^{st} - WHP^{st} \cdot CWHP^{st}), \end{aligned} \tag{7.5}$$

where *PTIR, PTMI,* and *PTHP* are profits from irrigation, municipal and industrial (M&I), and hydropower, respectively; *WIR, WMI,* and *WHP* are withdrawals for these sectors; *CWIR, CWMI,* and *CWHP* denote the respective costs; *DIR* and *DMI* are the drainage flows; and *CDIR* and *CDMI* are costs for drainage treatment from the irrigation and M&I sectors, respectively. Although important in many river basins, including the Maipo Basin, environmental uses are not explicitly valued in the current modeling framework. Instead, a minimum flow requirement for environmental purposes has been incorporated as a constraint. In the case study of the Maipo River Basin, drainage costs are accounted for in the water costs, and there is no charge for water diversion for hydropower generation.

The analysis focuses on the irrigation sector, with water application for municipal and industrial uses fixed in the alternative scenarios. The benefit from hydropower is minor relative to the irrigation benefit in the case study area, and it is ignored in the result analysis. Two indicators are calculated for irrigation: net profit from irrigation by demand site (*NPTIR*) and net profit from irrigation per unit of water consumed (*NPUWI*). The first indicator is expressed as:

$$\begin{aligned} NPTIR^d = & \sum_c A^{d,c} Y_a^{d,c} p^c \\ & - \sum_c A^{d,c} \cdot (fc^{d,c} + tc^{d,c}) \\ & - WIR^d \cdot CWIR^d - DIR^d \cdot CDIR^d, \end{aligned} \tag{7.6}$$

where Y_a is the actual crop yield; p is the crop price; *fc* is the fixed crop cost including costs from other inputs such as labor, machinery, fertilizers, pesticides, and seed; and *tc* is the technology cost associated with irrigation distribution uniformity, including capital investment for irrigation systems, maintenance costs, and costs for field water management.

NPUWI is formulated as:

$$NPUWI = \frac{\sum_{d \in Agr.} NPTIR^d}{\sum_{d \in Agr.} WIR^d}, \tag{7.7}$$

and net profit from water use for all sectors per unit of water consumed, *NPUW,* is formulated as:

$$NPUW = \frac{TNB}{WC}, \qquad (7.8)$$

where *WC* denotes total water consumption.

Effect on Efficiency from Changes in Economic Incentives, Local Infrastructure Improvement, and Water Availability

Effect on Local-Level Efficiency from Changes in Economic Incentives

In this section, we compare three scenarios, Basin-optimizing solution (BOS), Fixed water rights (FWR), and Water rights with trading (TRD), which were discussed in Chapter 6, in terms of the effect of economic incentives on physical field application efficiency (FAE). Table 7.1 shows that FAE increases under FWR compared with BOS for some demand sites and crops—for example, wheat for A1 and A2—because water rights under FWR constrain crop development in these sites. In other irrigation districts, such as A3, FAE decreases for wheat under FWR compared with BOS, because under the Water rights scenario, water quantities are suboptimal, whereas under BOS, they are reallocated to other sites and crops.

Water rights are fixed under FWR, but rights can be traded under TRD. As a result, FAE increases for most crops in agricultural demand sites. There is no change for those crops that have already reached the maximum possible FAE (assumed to be 0.85 in the model). However, in some demand sites for high-value crops, irrigation efficiency even decreases (for example, in demand site A6 for grapes and peaches). This shows that water trading induces farmers to reallocate water among crops, that is, including increased water allocation to higher-value crops (which may reduce FAE) while reducing water use for lower-value crops. Under TRD, farmers can also buy additional water for the more sensitive growing periods of the high-value crops and thus use more water for those crops while selling water for higher benefit during other periods. In general, FAE increases from BOS to FWR and to TRD. This can be seen in Table 7.2, presenting the aggregate FAE values by demand site for the three scenarios under two climate conditions. As can be seen, under the "dry year" condition, the effects from the water rights and market incentives on FAE are more significant than under average climate conditions. Thus, economic incentives are more effective under larger water stress. Table 7.3 presents water application per hectare, another indicator of changes in FAE, with results similar to those of Table 7.1.

Table 7.4 presents the economic crop value per unit of water applied (water arriving at the crop field) under the three alternative scenarios. As the results show, first, there is less variation in economic values compared with changes in FAE values between the BOS and TRD scenarios. Second, changes in the economic value per unit of water application at the crop field between the scenarios are not always similar to those of FAE. For example, for wheat at demand site A1, the value of FAE increases between FWR and TRD, whereas the economic value per unit of water declines.

Effect on Basin-Level Efficiency from Changes in Economic Incentives

Four scenarios are analyzed to assess the effect of economic incentives on physical and economic efficiency at the basin level: BOS, FWR, TRD (the transaction cost is set at US$0.04 per cubic meter), and one additional scenario with fixed irrigation technology (FIT). Under the FIT scenario, the Christiansen Uniformity Coefficient (CUC) is fixed at the lower bound, and all other parameters and assumptions are defined per BOS.

Table 7.1 Change in field application efficiency for various crops (under 60 percent of normal inflow) under the Basin-optimizing solution, Fixed water rights, and Water rights with trading scenarios (ratio)

Scenario	Demand site	Wheat	Corn	Annual forage	Grapes	Peaches	Potatoes	Other
Basin-optimizing solution	A1	0.70	0.85	0.85	0.52	0.48	0.68	0.43
	A2	0.71	0.85	0.85	0.52	0.47	0.67	0.41
	A3	0.58	0.85	0.85	0.50	0.46	0.66	0.42
	A4	0.70	0.85	0.85	0.51	0.47	0.55	0.44
	A5	0.75	0.85	0.85	0.53	0.49	0.71	0.43
	A6	0.59	0.85	0.85	0.49	0.45	0.67	0.39
	A7	0.77	0.60	0.85	0.50	0.52	0.55	0.41
	A8	0.71	0.85	0.85	0.52	0.48	0.75	0.46
Fixed water rights	A1	0.74	0.85	0.85	0.54	0.50	0.75	0.43
	A2	0.85	0.85	0.85	0.64	0.59	0.85	0.42
	A3	0.51	0.85	0.85	0.50	0.50	0.76	0.42
	A4	0.42	0.49	0.36	0.50	0.43	0.53	0.40
	A5	0.74	0.85	0.85	0.53	0.48	0.71	0.44
	A6	0.63	0.85	0.85	0.67	0.63	0.85	0.39
	A7	0.79	0.49	0.85	0.50	0.43	0.53	0.39
	A8	0.85	0.75	0.85	0.69	0.63	0.85	0.44
Water rights with trading	A1	0.85	0.85	0.85	0.65	0.60	0.85	0.43
	A2	0.85	0.85	0.85	0.63	0.58	0.85	0.42
	A3	0.85	0.85	0.85	0.50	0.55	0.84	0.42
	A4	0.85	0.85	0.85	0.60	0.55	0.85	0.45
	A5	0.85	0.85	0.85	0.60	0.55	0.84	0.44
	A6	0.85	0.85	0.85	0.64	0.59	0.85	0.40
	A7	0.77	0.61	0.85	0.50	0.45	0.65	0.41
	A8	0.85	0.85	0.85	0.70	0.65	0.85	0.48

Table 7.2 Aggregated field application efficiency by demand sites, at 100 percent of normal inflow (normal year) and 60 percent of normal inflow (dry year) under the Basin-optimizing solution, Fixed water rights, and Water rights with trading scenarios (ratio)

	Normal year			Dry year		
Demand site	BOS	FWR	TRD	BOS	FWR	TRD
A1	0.56	0.63	0.63	0.62	0.64	0.72
A2	0.53	0.58	0.60	0.61	0.70	0.69
A3	0.54	0.55	0.59	0.57	0.57	0.60
A4	0.56	0.60	0.62	0.68	0.69	0.69
A5	0.52	0.56	0.59	0.58	0.58	0.60
A6	0.52	0.60	0.62	0.57	0.69	0.69
A7	0.66	0.61	0.64	0.68	0.68	0.68
A8	0.51	0.63	0.63	0.58	0.66	0.72

Notes: BOS indicates Basin-optimizing solution; FWR, Fixed water rights scenario; TRD, Water rights with trading scenario.

Table 7.3 Water withdrawals at 60 percent of normal inflow under the Basin-optimizing solution, Fixed water rights, and Water rights with trading scenarios (cubic meters per hectare)

Scenario	Demand site	Wheat	Corn	Annual forage	Grapes	Peaches	Potatoes	Other
Basin-optimizing solution	A1	7,923	7,793	8,477	17,249	17,826	13,363	14,532
	A2	7,658	7,674	8,391	16,982	17,692	13,150	16,122
	A3	9,512	7,451	7,958	16,907	17,512	13,135	14,249
	A4	7,723	7,730	8,277	17,174	17,766	17,297	13,617
	A5	7,394	7,694	8,415	16,351	17,048	12,529	14,173
	A6	10,010	7,839	8,359	18,167	18,841	13,717	16,274
	A7	7,137	12,258	8,238	17,309	15,454	16,475	13,702
	A8	8,295	8,028	8,874	17,660	18,262	12,391	13,762
Fixed water rights	A1	7,208	7,793	8,477	16,281	16,793	11,798	14,239
	A2	5,933	7,674	8,391	12,909	13,636	9,610	15,542
	A3	11,090	7,451	7,958	16,907	15,647	10,968	14,179
	A4	14,358	15,693	25,880	17,754	19,671	17,935	15,492
	A5	7,467	7,694	8,415	16,594	17,245	12,271	13,627
	A6	9,087	7,839	8,359	12,109	12,373	9,860	15,734
	A7	6,781	15,752	8,238	17,385	19,319	17,274	13,697
	A8	6,436	9,434	8,874	12,493	13,363	10,383	14,385
Water rights with trading	A1	5,917	7,793	8,477	12,820	13,440	9,914	13,851
	A2	5,933	7,674	8,391	13,203	13,852	9,610	15,066
	A3	5,630	7,451	7,958	16,907	14,190	9,562	14,213
	A4	5,826	7,730	8,277	14,110	14,819	9,961	13,431
	A5	6,135	7,694	8,415	14,127	14,868	9,924	14,101
	A6	5,947	7,839	8,359	12,943	13,624	9,860	15,480
	A7	7,073	11,930	8,238	17,287	18,312	13,720	14,176
	A8	6,436	8,028	8,874	12,192	12,835	10,383	11,771

Table 7.5a shows the results from these four scenarios for total and M&I water withdrawals, total net profits and net benefits from M&I water use, and total profit per unit of water at the basin level. As expected, the BOS or full optimization scenario generates the highest total benefits from water usage in the river basin. However, it should be noted that the costs of administration of the BOS scenario (which are likely to be very high but cannot be estimated), are not deducted from the net benefits. At the other end of the spectrum, the Fixed water rights regime results in the lowest overall profits. Compared with BOS, FWR has slightly lower irrigation water withdrawals (89 percent of those under BOS), and much lower M&I water withdrawals (52 percent of those under BOS); correspondingly, the M&I net benefit under the FWR scenario is only 23 percent of the BOS result, and profit per unit of water withdrawn is US$0.11 per cubic meter lower than under BOS (Table 7.5a). There are also significant changes in water withdrawals among irrigation demand sites. Under FWR, water withdrawals for upstream and midstream demand sites (for example, A1) decline, on average, by 19 percent compared with those under BOS; while water withdrawals for downstream demand sites decrease less or even slightly increase (for example, A5).

Allowing water trading corrects many of the distortions experienced under fixed water rights. When trading is permitted under the TRD scenario, water moves from lower-value crops into higher-value crops and particularly into higher-value urban water uses

Table 7.4 Economic crop value per unit of water use at 60 percent of normal inflows under the Basin-optimizing solution, Fixed water rights, and Water rights with trading scenarios (U.S. dollars per cubic meter)

Scenario	Demand site	Wheat	Corn	Annual forage	Grapes	Peaches	Potatoes	Other
Basin-optimizing solution	A1	0.133	0.128	0.128	0.331	0.300	0.201	0.250
	A2	0.133	0.127	0.127	0.328	0.293	0.200	0.230
	A3	0.124	0.129	0.131	0.330	0.298	0.201	0.250
	A4	0.133	0.127	0.129	0.329	0.297	0.171	0.240
	A5	0.131	0.126	0.127	0.336	0.299	0.202	0.240
	A6	0.120	0.121	0.127	0.312	0.278	0.190	0.230
	A7	0.131	0.114	0.130	0.330	0.321	0.179	0.250
	A8	0.125	0.123	0.121	0.320	0.289	0.199	0.230
Fixed water rights	A1	0.135	0.128	0.128	0.342	0.310	0.210	0.250
	A2	0.133	0.127	0.127	0.369	0.323	0.211	0.240
	A3	0.114	0.129	0.131	0.330	0.316	0.213	0.250
	A4	0.096	0.100	0.058	0.322	0.278	0.167	0.220
	A5	0.131	0.126	0.127	0.333	0.298	0.203	0.240
	A6	0.124	0.121	0.127	0.368	0.315	0.200	0.240
	A7	0.131	0.100	0.130	0.329	0.283	0.173	0.240
	A8	0.124	0.122	0.121	0.365	0.320	0.202	0.220
Water rights with trading	A1	0.134	0.128	0.128	0.377	0.333	0.214	0.260
	A2	0.133	0.127	0.127	0.367	0.322	0.211	0.250
	A3	0.137	0.129	0.131	0.330	0.329	0.215	0.260
	A4	0.134	0.127	0.129	0.363	0.322	0.209	0.250
	A5	0.130	0.126	0.127	0.360	0.316	0.208	0.250
	A6	0.130	0.121	0.127	0.364	0.314	0.200	0.250
	A7	0.131	0.116	0.130	0.330	0.294	0.200	0.230
	A8	0.124	0.123	0.121	0.366	0.320	0.202	0.250

while at the same time increasing farm incomes from water sales. Under the TRD scenario, total profits in M&I demand sites increase threefold compared with the FWR case, but gains are also significant for irrigation districts, with profits including those from water trading increasing by 13 percent, from US$287 million to US$325 million (Table 7.5b); profits from irrigated agricultural production alone decline to US$267 million under the TRD scenario. Water trading also increases the value of water in irrigated agriculture, with profit per unit of water in irrigation demand sites increasing, on average, from US$0.236 per cubic meter under the FWR scenario to US$0.310 per cubic meter under the TRD scenario; and overall, from US$0.184 per cubic meter to US$0.295 per cubic meter (Tables 7.5a,b). At the same time, irrigation water withdrawals decline across irrigation districts, on average, by 10 percent compared to the FWR scenario. This is a result of the change in the incentive structure for irrigation districts under the TRD scenario, which provides more flexibility to respond to market signals. As a result, both classical (local) irrigation efficiency and effective basin efficiency increase as it becomes more profitable for farmers to invest in improved irrigation technologies and to sell the surplus water to urban areas (Table 7.5b). Although the net benefits to M&I water uses under TRD are significantly larger than under FRW, they are still 35 percent below the basin-optimizing level because of the cost incurred from purchasing additional water, including transaction costs (Table 7.5a).

Table 7.5a Basin-level aggregation at 60 percent of normal inflows under the Basin-optimizing solution, Field irrigation technology, Fixed water rights, and Water rights with trading scenarios, selected results

Scenario	Total water withdrawal (million cubic meters)	Municipal and industrial water withdrawal (million cubic meters)	Total net profits (million US$)	Municipal and industrial net benefit (million US$)	Profit per unit water (US$ per cubic meter)
BOS	3,182	1,457	918	605	0.291
FIT	3,067	1,428	874	605	0.282
FWR	2,297	758	423	136	0.184
TRD	2,435	1,050	717	392	0.295

Notes: BOS indicates Basin-optimizing solution scenario; FIT, Field irrigation technology scenario; FWR, Fixed water rights scenario; and TRD, Water rights with trading scenario.

Table 7.5b Irrigation demand sites at 60 percent of normal inflows under the Basin-optimizing solution, Field irrigation technology, Fixed water rights, and Water rights with trading scenarios, selected results

Efficiency	Scenario	Demand site A1 (upstream)	Demand site A5 (downstream)	Basin-level irrigation
Classical irrigation efficiency (EI) (ratio)	BOS	0.424	0.443	0.431
	FIT	0.424	0.428	0.426
	FWR	0.478	0.417	0.457
	TRD	0.511	0.474	0.498
Effective efficiency (EIE) (ratio)	BOS	0.536	0.466	0.530
	FIT	0.527	0.429	0.506
	FWR	0.597	0.446	0.550
	TRD	0.623	0.488	0.583
Irrigation benefit per unit water (NBPUW) (US$ per cubic meter)	BOS	0.266	0.177	0.227
	FIT	0.246	0.160	0.214
	FWR	0.287	0.172	0.236
	TRD	0.338	0.225	0.310
Net irrigation benefit (NBIR) (million US$)	BOS	114.6	57.8	312.6
	FIT	97.8	57.8	269.2
	FWR	105.4	59.3	286.6
	TRD	116.7	69.7	324.8
Irrigation withdrawals (million cubic meters)	BOS	561.1	365.1	1,726.0
	FIT	513.7	395.3	1,639.5
	FWR	478.7	388.8	1,538.4
	TRD	432.0	342.8	1,384.4

Notes: BOS indicates Basin-optimizing solution scenario; FIT, Field irrigation technology scenario; FWR, Fixed water rights scenario; and TRD, Water rights with trading scenario.

Table 7.6 Comparison of wheat and grape production at the basin level under the Basin-optimizing solution and Fixed water rights scenarios, selected results

	Basin-optimizing solution scenario				Fixed water rights scenario			
Crop category	Area (hectares)	Relative yield	Water application (cubic meters per hectare)	Field application efficiency	Area (hectares)	Relative yield	Water application (cubic meters per hectare)	Field application efficiency
Wheat	18,839	0.83	8,251	0.67	16,022	0.82	8,086	0.69
Grapes	19,412	1.00	17,771	0.50	15,381	0.99	17,143	0.52

Table 7.6 presents results for wheat and grapes at the basin level for the BOS and FWR scenarios. Under the FWR scenario, irrigation water applied at the field level is lower than under the BOS scenario, but only by 2 and 4 percent, respectively. Under FWR, wheat area is 15 percent lower, and grape area is 21 percent lower. This result is because under Fixed water rights, not all crop water demands can be met during the low-flow season of February to March, which is crucial for the maintenance of grape and other perennial crops, whereas wheat is less affected because this dry period occurs only in the late stage of wheat growth. As a result, area planted to grapes declines more than area planted to wheat. Moreover, area planted to grapes declines most in the upstream/midstream reaches, which are the center of grape production and are more affected by water right constraints. This frees up water for downstream irrigation districts, helping those districts to maintain their grape areas. Thus, compared with the full optimization scenario, a Fixed water rights regime locks water into less productive uses both within and among irrigation districts.

Choice of irrigation technology also proves to be very important for farmer incomes under the model specifications. When irrigation technology is fixed under the FIT scenario, profits from irrigated agriculture decline by 14 percent compared to the Basin-optimizing level that allows for endogenous technology choice based on the economic profitability of the various crops in the model. Net benefits in M&I sites, on the other hand, remain unaffected. Irrigation withdrawals decline (but only by 5 percent compared with BOS), as both classical and effective irrigation efficiencies decline, on average, by 1.2 and 4.5 percent, respectively, because of the lack of responsiveness of technology to the variation in water values across irrigated crops; as a result, water productivity declines (Table 7.5b).

With the possibility of endogenous adjustment of the CUC value, BOS results in advanced irrigation technologies for all high-value crops, for example, grapes and fruit trees, whereas the technology level stays at the lower bound for low-value crops such as wheat, corn, and annual forage. Under the current cost–benefit situation in the basin, it is unattractive from an economic point of view to invest in improved irrigation technology for grains, which cover about 30 percent of the total irrigated area in the basin.

A comparison across scenarios shows that the water-trading scenario results in the highest physical efficiency level both for classical and effective efficiency at individual irrigation districts and for overall basin efficiency (Table 7.5b). The TRD scenario also results in the highest economic efficiency levels for agriculture alone, both at per-unit and total profit level. Total profits from water use, on the other hand, are largest under BOS. The increased profitability of irrigation under TRD derives from the possibility of irrigation districts to sell their unused water rights to M&I areas where their use has a larger value.

Moreover, as expected, effective efficiency is consistently higher than classical irrigation efficiency at the irrigation system level, and overall basin efficiency is higher than classical irrigation efficiency at individual demand sites for all scenarios (Table 7.5b). Thus, the potential for water savings from increases in water use efficiency in irrigation in a basin context is lower than what individual system efficiencies might indicate. This issue is further explored in the following section.

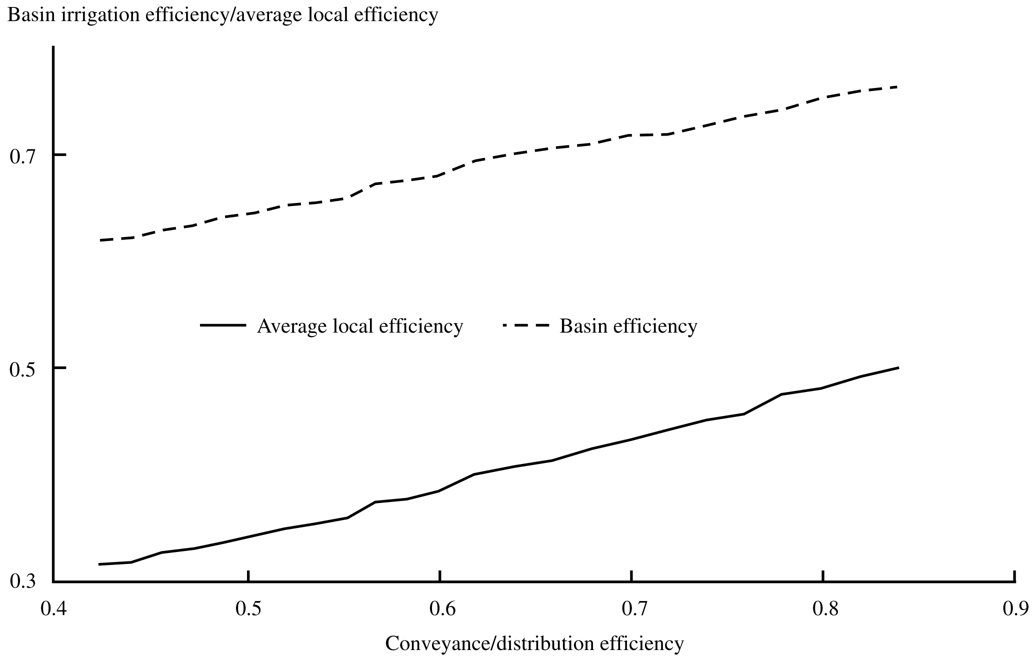
The results also show a tradeoff between optimal off-stream profits from water usage and resource conservation in the absence of an explicit valuation of instream flows. Overall water withdrawals are largest under the BOS scenario, followed by the FIT scenario, as water can move without restrictions to the most profitable uses. Under these scenarios, instream flows left in the Maipo River are near the minimum flow requirements included in the modeling framework as constraints. Under the FWR scenario, on the other hand, the fixed water rights limit the ability of water to move to the most productive uses. As a result, water in excess of (off-stream) water rights is left instream, particularly during the high-flow season, whereas (perennial) crop water demands cannot be fully met during the low-flow season because of the water rights constraints. Under the TRD scenario, flexibility in water allocation is restored, but the trading of water at a price equal to the opportunity cost of water in irrigated agriculture, together with the transaction costs of trading, reduces both irrigation withdrawals and water demand in the M&I sector. Outflows to the sea are 657 million cubic meters under the BOS scenario and 648 cubic meters under the FIT scenario but are much larger at 1,153 million cubic meters and 1,037 million cubic meters under the FWR and TRD scenarios, respectively. To the extent that instream flows in excess of minimum flow constraints have value for environmental uses, such as conservation of the river habitat, water quality improvement through waste dilution, and for the general esthetics at the outflow of the Maipo into the sea, the current incentive structure for water allocation would need to be adjusted to better reflect the optimal value of water for all water-using sectors.

Effect on Efficiency from Combined Improvements in Local Infrastructure and Changes in Economic Incentives

Measures to improve the distribution and conveyance efficiency, and thus to reduce water losses during distribution and conveyance, include improved canal lining and appropriate scheduling of water diversion in terms of both quantity and timing to avoid excess diversion. To explore the relationship between basin physical and economic efficiency under alternative irrigation water loss rates and water charges, a series of scenarios are defined for combined water distribution and conveyance efficiency levels ranging from 42 to 85 percent. In order to examine the conceptual and empirical difference between local and basin efficiency more clearly, in this set of scenarios, reduced rates of nonbeneficial evaporation and deep percolation losses during drainage and return flows to the river system are assumed. This increases the return flow fraction of water withdrawals and thus the overall basin efficiency levels and allows the examination of a wider range of local and basin efficiency levels than are presented in Table 7.5b. The effects of changes in the distribution/conveyance efficiency on basin economic and physical efficiency are analyzed for irrigation water charges of US$0.015 per cubic meter and US$0.060 per cubic meter, respectively.

The physical (effective) basin efficiency (defined in equation 7.1) and the average system-level or classic irrigation efficiency levels are plotted in Figure 7.1 for various conveyance/distribution efficiencies. The figure shows that both measures of physical

Figure 7.1 Basin irrigation efficiency and average local irrigation efficiency at various levels of water distribution efficiency



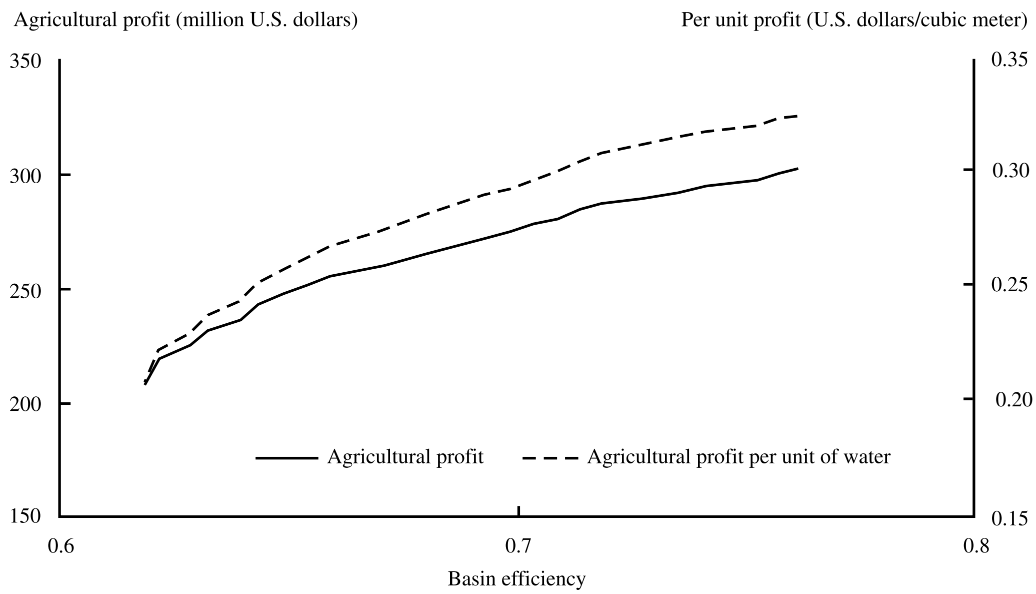
Note: The average local efficiency is based on the efficiency at each demand site.

efficiency increase over the range of increasing conveyance/distribution efficiency levels, by 24 percent for basin efficiency and by 58 percent for system-level efficiency. Because basin efficiency is already high, and part of the distribution loss is already reused within the basin, the total basin efficiency improves less under increasing distribution efficiency than the local irrigation efficiency.

Figures 7.2a and 7.2b present the relationship between economic and physical efficiency under various conveyance/distribution efficiencies at the basin and system level for a water charge of US$0.015 per cubic meter. Figure 7.2a plots the relationship between total agricultural profit and profit per unit of water withdrawn and basin irrigation efficiency. Both total profits from irrigated agriculture and profits per unit of water increase at a declining rate with increasing basin irrigation efficiency. However, because of a lack of data, the costs associated with improving physical efficiency levels, for example through the lining of irrigation canals, are not incorporated into the model. If these costs were included, the economic efficiency level would peak at the point where the marginal benefits of improved physical infrastructure equal the marginal costs of the improvement; thereafter, the economic efficiency level would decline. Typically, the cost for infrastructure improvement measures increases rapidly after a certain (high) level of physical irrigation efficiency has been reached; at that point, the cost of infrastructural improvement could become the major constraint for improving economic efficiency of water use through structural investments.

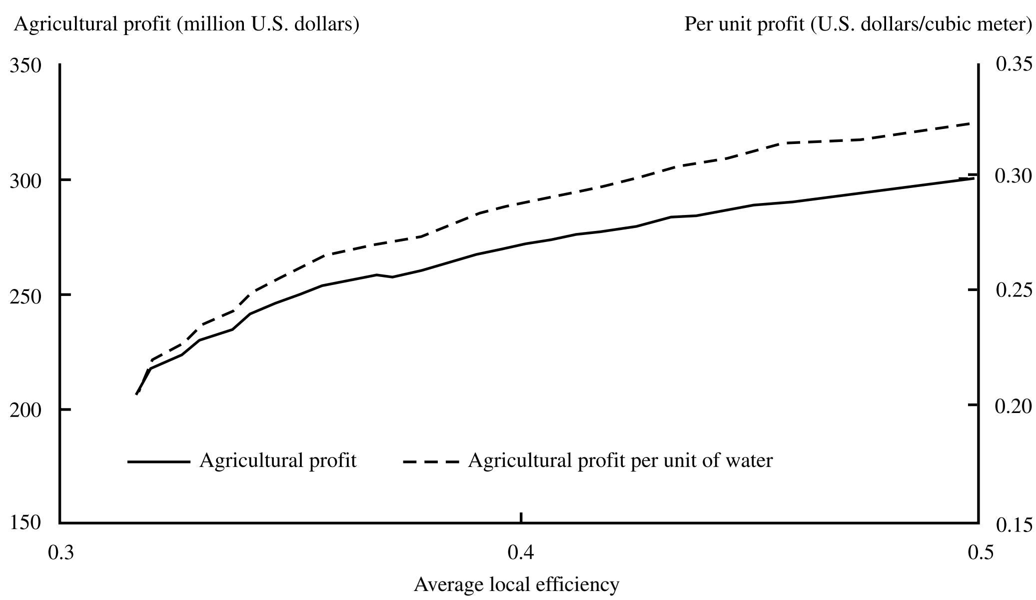
Figure 7.2b plots the relationship between total irrigation profits and per-unit profit and average local irrigation efficiency. Compared with the curves shown in Figure 7.2a, economic efficiency levels increase more slowly with respect to changing levels of system-level irrigation efficiency. This result confirms that increasing the local irrigation efficiency will not have as large an

Figure 7.2a Basin irrigation efficiency (physical) versus economic efficiency (total and per unit water use profit)



Note: Water charge is equal to US$0.015 per cubic meter.

Figure 7.2b Average local irrigation efficiency (physical) versus economic efficiency (total and per unit water use profit)



Note: Water charge is equal to US$0.015 per cubic meter.

effect as an equal percentage increase in basin efficiency because the computation of local efficiency treats return flows as nonbeneficial use. Nevertheless, the gains in agricultural profits from improved local efficiency are substantial through much of the range of local efficiency. When local efficiency approaches 0.50—that is, half of the water reaching the crop field is evapotranspirated beneficially—basin efficiency reaches a level of 0.75 (Figure 7.1), with the result that further improvements in local efficiency contribute little to the overall basin efficiency, and increases in agricultural profits are minimal. However, the increase in average local efficiency from 0.32 to 0.50 results in an increase in basin irrigation profits of US$93 million (from US$207 to US$300 million). Increased local efficiency increases the beneficial evapotranspiration in the crop field, reduces local water losses to deep percolation and nonbeneficial evapotranspiration, and decreases return flows to the river system. The contribution of improvements in local efficiency to overall basin profits depends on various factors. At low levels of local efficiency, improvements in system-level efficiency generate significant basinwide profits. However, when local efficiencies reach higher levels, the relative contribution to basinwide water use profits declines.

In order to study the effects of nonstructural measures on physical efficiency levels, a series of scenarios is run that explores the relationship between distribution/conveyance efficiency and basin efficiency under alternative irrigation water fees. As can be seen in Figure 7.3, the higher water price results in a slightly higher basin irrigation efficiency, as farmers reduce water use, shift from lower-valued to higher-valued crops, and shift to higher levels of irrigation technology for some crops.

The effect of the higher water fee on basin efficiency is more pronounced at higher distribution/conveyance efficiency levels. At low levels of conveyance and distribution efficiency, the large amount of irrigation water withdrawals needed at the off-take level do not induce significant shifts to more profitable crops; instead, withdrawals are reduced and shifted to M&I areas, or water is simply left instream.

Figure 7.4 shows the profit for irrigated agriculture at different conveyance/distribution efficiencies under alternative irrigation water fees. The higher water charge

Figure 7.3 Relationship between basin irrigation efficiency and system-level conveyance/distribution efficiency under alternative water prices

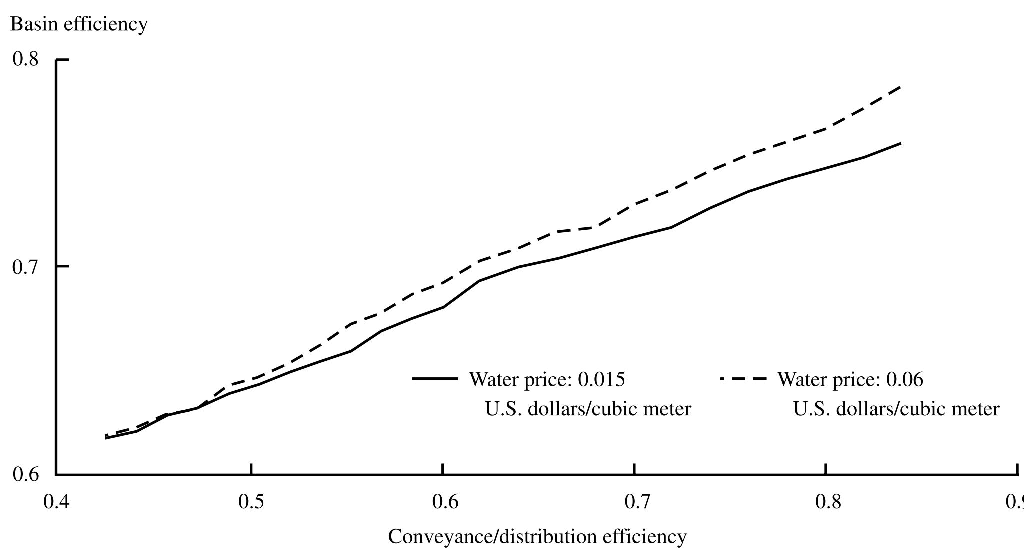
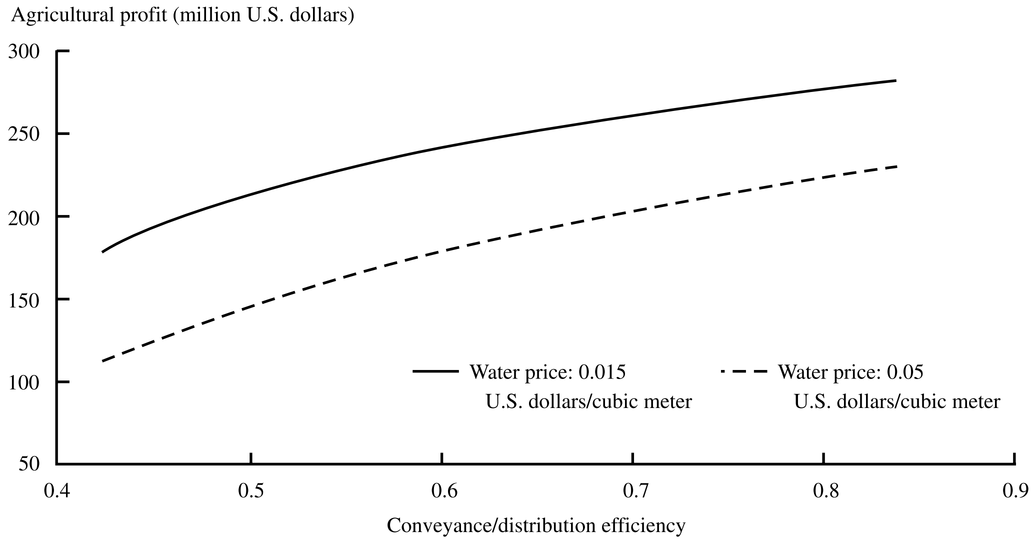


Figure 7.4 Relationship between irrigation profit (water charge subtracted) and conveyance/distribution efficiency under alternative water prices



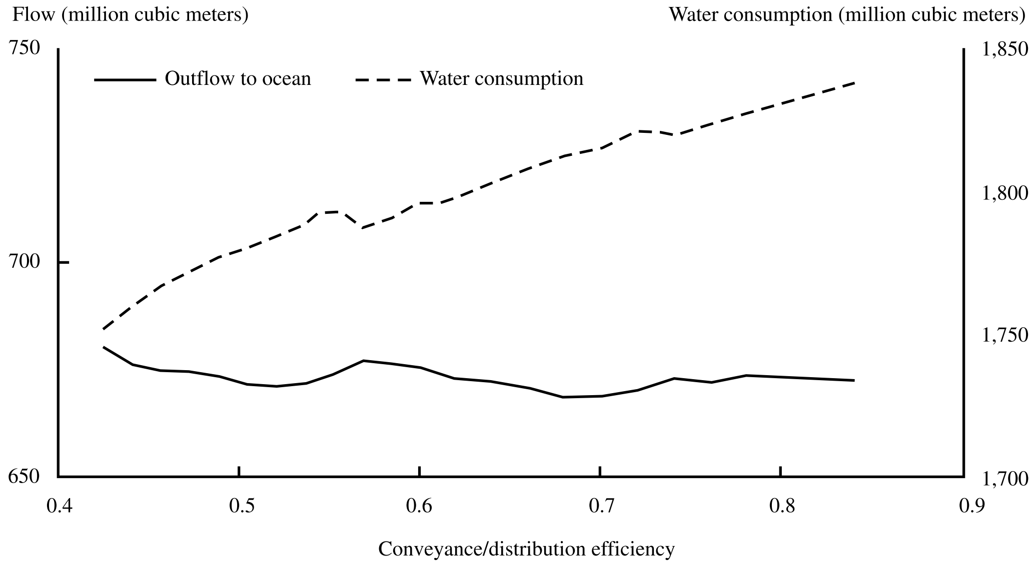
results in a decline in irrigation profits, as would be expected. Although farmers adjust to the change in incentive structure from alternative irrigation water fees by reducing water withdrawals through changes in irrigation technology and shifts of water uses to higher-value crops, the increase in water price results in an overall decline in irrigation profits. Agricultural incomes decline more rapidly at lower levels of distribution/conveyance efficiency as, below a certain efficiency level, the price incentive is less effective because farmers/agricultural demand sites cannot adjust their production structure in response to water charges at high levels of water losses.

Does improvement in irrigation efficiency always lead to a decline in water consumption at the basin level? This is an important question in many basins around the world, where water shortages and the maintenance of instream flows for environmental water uses are a serious concern. The results for the Maipo River Basin based on the modeling framework show that increases in irrigation efficiency in fact lead to increased water consumption. Figure 7.5 shows that water consumption increases and outflows to the sea decline slightly with increasing physical efficiency levels. Thus, "new" consumptive use can be gained through recovery of otherwise lost on-farm and conveyance losses. However, water withdrawals decline in the basin (Figure 7.6). When distribution/conveyance efficiency is improved, less water needs to be abstracted to satisfy existing water demands, as the share of beneficial water consumption increases, whereas nonbeneficial evaporation losses decline. The balance of the two factors, the decline of water withdrawals and the increase in water demand, results in the nonmonotonic trends shown in Figure 7.6. For a more robust analysis, the uncertainties associated with water availability and water cost, as well as the valuation of environmental uses, should be considered in future research.

Effect on Efficiency from Variations in Water Withdrawals or Water Availability

For a given water requirement, physical efficiency and economic efficiency levels depend on water withdrawals and availability. A series of scenarios are run to analyze how physical and economic efficiency indicators change under a range of water withdrawals

Figure 7.5 Relationship between water consumption and outflow to the sea and conveyance/distribution efficiency



Note: Water charge is equal to US$0.015 per cubic meter.

and fixed water demands (that is, the same irrigated area and cropping patterns, and the same climate condition) and fixed M&I water withdrawals. Under these scenarios, irrigation water availability ranges from 1,000 million cubic meters to 2,810 million cubic meters.

As can be seen in Figure 7.7, basin efficiency increases as water availability declines and water becomes scarcer. When irrigation availability and thus withdrawals are low, a higher share of the water applied will be beneficially used by the plant. This leads to higher basin efficiencies as well as

Figure 7.6 Water withdrawal versus conveyance/distribution efficiency under alternative water prices

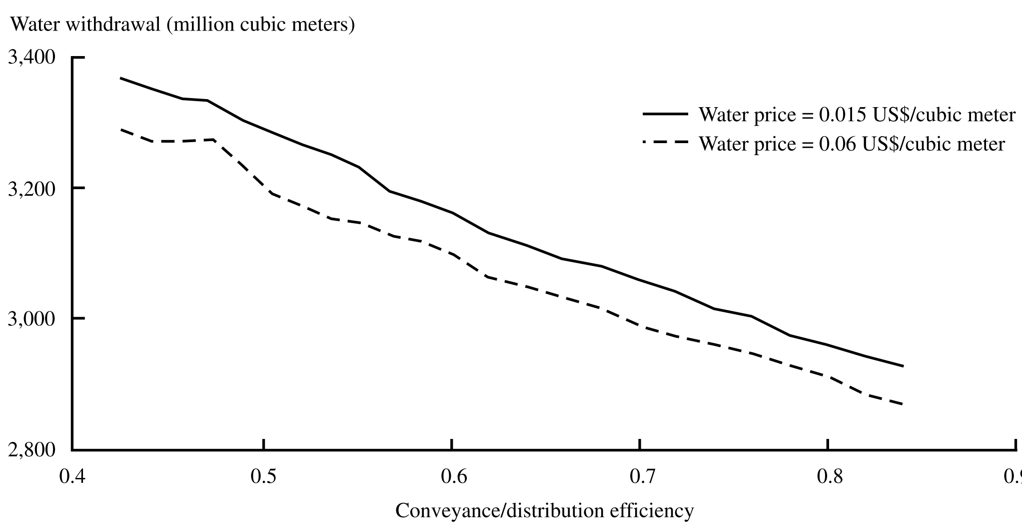
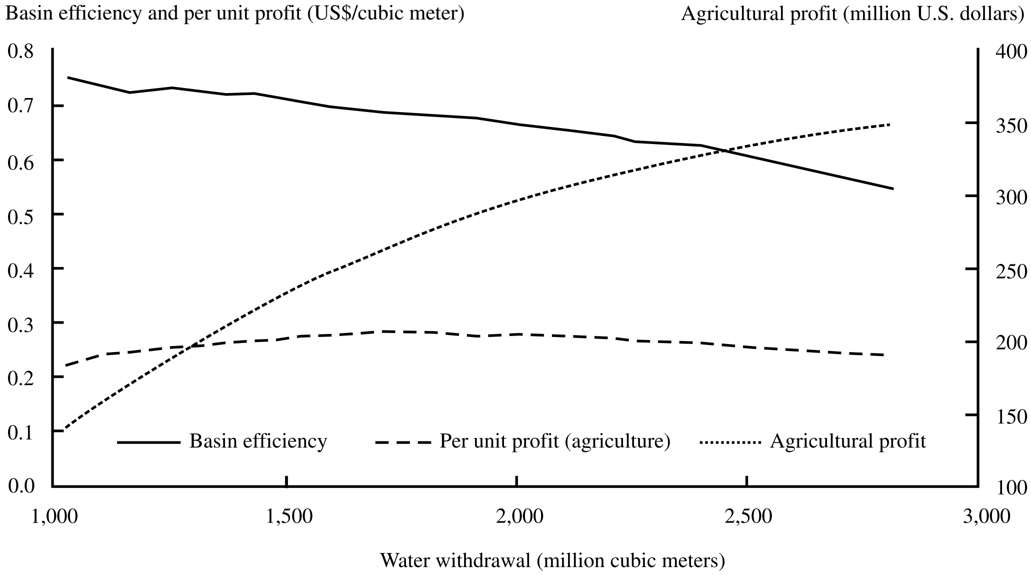


Figure 7.7 Physical and economic efficiency under various water availability levels under a given water demand



local efficiencies. At high levels of water withdrawals, on the other hand, the opposite applies.

In terms of economic efficiency indicators, the water withdrawal level can be divided into three subranges, 1,000–1,500 million cubic meters, 1,500–2,200 million cubic meters, and above 2,200 million cubic meters. At very low but increasing water availability compared with demand, both economic efficiency indicators for agricultural profit per cubic meter of water and total annual profit increase. This range can be indicative of river basins facing severe water constraints, which are characterized by high levels of basin irrigation efficiency and low levels of economic efficiency. In such basins, water availability is far below water requirements because of either limited natural sources or insufficient water supply infrastructure. At these low levels of water withdrawals compared with water demand, an increase in withdrawals will lead to significant increases in farmer incomes. The steep slope of the irrigation profit curve in this range shows that the marginal value of water is large, and additional water sources, such as water transfers from other basins, or infrastructure development to store water, can be attractive from an economic point of view.

For water withdrawals in excess of 2,200 million cubic meters, the maximum crop harvested area for high-value crops is reached, and the share of low-value (and very thirsty) crops increases, contributing to the declining profit per unit of water applied. This range is indicative of areas with relative water abundance, no or low charges for irrigation water, where externalities are not taken into account, or where water delivery is unreliable. Here, possibly excessive water withdrawals can be reduced to more optimal levels through incentive prices, which can result in both higher physical efficiency and higher economic efficiency, as shown in previous sections.

In the middle range of the water withdrawal level (1,500–2,200 million cubic meters), total profit from irrigation water use increases with increasing water withdrawals, but basin irrigation efficiency and profit per unit of water decline only slightly. In this range, appropriate physical and nonstructural improvements can enhance both physical and economic efficiency. This can also be seen in Figures 7.2 and 7.4, where water withdrawals (1,760 cubic meters) are within the range of 1,500–2,200 million cubic meters.

Summary

With growing water scarcity and increasing competition across water-using sectors, the need for water savings and more efficient water use has increased in importance in water resources management. Improvement in the physical efficiency of water use is related to water conservation through increasing the fraction of water beneficially used over water applied, and enhancing economic efficiency is a broader concept seeking the highest economic value of water use through both physical and managerial measures. Physical and economic efficiency measures are both useful indicators for water management at the irrigation system and river basin level. The relationship between physical efficiency and economic efficiency has been analyzed in this chapter through a series of modeling scenarios based on changes in physical and economic efficiencies for basinwide irrigation water management.

Economic incentives, for example, in the form of markets in water rights or irrigation service fees, have direct effects on both irrigation system and basin level efficiency indicators, and on both physical and economic efficiency levels. The effect of higher water fees on basin efficiency is more pronounced at higher distribution/conveyance efficiency levels. Agricultural incomes decline more rapidly at lower levels of distribution/conveyance efficiency as, below a certain efficiency level, the price incentive is less effective because farmers/agricultural demand sites cannot adjust their production structure in response to water charges at high levels of water losses.

Basin efficiency increases as water availability declines and water becomes scarcer. When irrigation availability and thus withdrawals are low, a higher share of the water applied will be beneficially used by the plant. This leads to higher basin efficiencies as well as local efficiencies. At high levels of water withdrawals, on the other hand, the opposite applies. At low levels of local efficiency, improvements in system-level efficiency generate significant basinwide profits. However, when local efficiencies reach higher levels, their relative contribution to basinwide water use profits declines.

Basins typically fall into one of three situations regarding water scarcity and basin efficiency: (1) At low water availability compared with demand, basin efficiencies tend to be high, the marginal value of water large, and additional water sources, such as water transfers from other basins, or infrastructure development to store water, can be attractive from an economic point of view. (2) At high water availability compared to demands, possibly excessive water withdrawals can be reduced to more optimal levels through incentive prices, which can result in both higher physical efficiency and higher economic efficiency. (3) At points between severe water scarcity and abundance, water use profits can be increased with increased withdrawals, while basin irrigation efficiency and profit per unit of water decline only slightly. In this range, a combination of appropriate physical and nonstructural improvements can enhance both physical and economic efficiency.

Finally, although improvement in irrigation efficiency does not always lead to increased water consumption at the basin level, water consumption actually increases for the case of the Maipo River Basin given the characteristics presented, in particular, the possibility of increasing crop areas and yield and thus economic efficiency.

CHAPTER 8

Irrigation Technology Choice under Uncertainty

Improving water use efficiency through modern irrigation technologies is considered an important activity toward saving water for non-irrigation off-stream and environmental in-stream uses. A large number of factors must be considered in making irrigation technology choices, including the location of the basin, its state of development, the water availability across the year, and the crop under consideration. Moreover, the irrigation technology considered needs to be compatible with other farm operations, including land preparation, cultivation, and harvesting, and the technology needs to be feasible from an economic, technical, and physical (topography and soil properties, for example) point of view (Walker and Skogerboe 1987). Other aspects that might play a role in technology choice include broad economic, institutional, and social perspectives related to new irrigation technology (Carruthers 1990) and external influences such as national policies regarding foreign exchange and strengthening specific sectors of the local economy.

Field irrigation technology (FIT) choices are an important means by which farmers can reduce the income risk from drought, but only within a specific investment limit. FIT choices have been studied extensively by both engineers and economists. As pointed out by Caswell and Zilberman (1985), engineering approaches usually estimate the frequency of use of each alternative irrigation technique based on the likelihood of the occurrence of circumstances favorable to a particular technology. This approach is useful for determining when and how to adopt new technologies (for example, Hart et al. 1980; Gates, Wets, and Grismer 1989; Hoffman, Howell, and Solomon 1990; Tecle and Yitayew 1990). Economic approaches use econometric tools and actual data on adoption patterns to explain and predict parameters and factors affecting the diffusion of modern irrigation technologies (Feder, Just, and Zilberman 1981; Caswell and Zilberman 1985; Negri and Brooks 1990; Green and Sunding 1997; Carey and Zilberman 2002). However, the effects of uncertainty on farmers' decisions regarding irrigation technology choice have been rarely addressed. In the engineering category, for example, Gates, Wets, and Grismer (1989) and Gates and Alshaikh (1993) presented simulation models to analyze the performance of new irrigation facilities, accounting for parameter uncertainty on both the supply and demand sides of the system as a result of temporal and spatial variability and inadequate data. However, these models mainly focus on engineering design and system operations and ignore the effect of crop profitability, farmers' income, and economic incentives for water allocation. In the economic category, Carey and Zilberman (2002) developed a stochastic dynamic model of irrigation technology adoption, taking into account the effects of random drought but mainly addressing the uncertainty associated with economic incentives such as water fees and water markets.

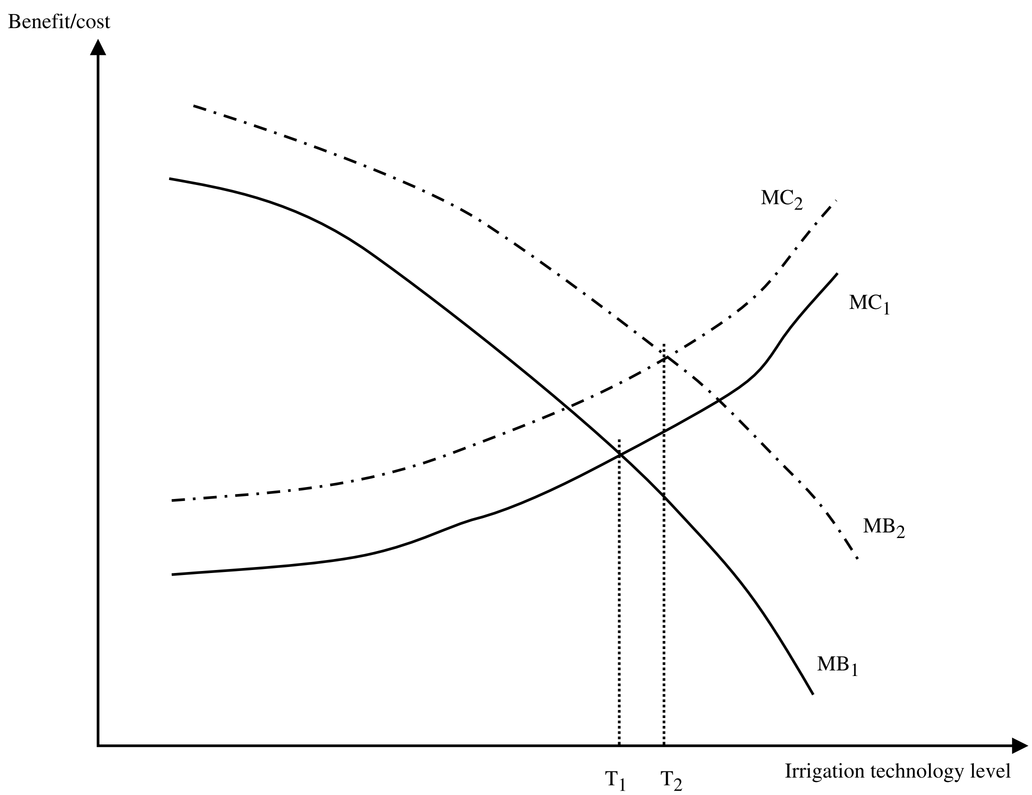
In this study, we apply the holistic economic–hydrologic model to study FIT choice. The advantage of this modeling framework lies in the specification of field irrigation technology represented by the Christiansen Uniformity Coefficient (CUC), which is treated as a decision variable together with water allocation and agricultural development. Thus, FIT choices are taken in conjunction with decisions on water allocation among crops and irrigation schedules for crops. Moreover, the river basin model can be extended to incorporate uncertainties in both irrigation water requirements and availability explicitly, which makes it possible to study FIT choices under hydrologic uncertainty.

Irrigation Technology Choice under Changing Water Prices and Salinity

Higher CUC tends to increase crop yield at given water and salinity levels (Figure 3.7). However, more advanced irrigation technology is associated with higher cost, which is explicitly represented in equation 3.10. Therefore, the model will choose the irrigation technology at the point where marginal profit is equal to the marginal cost of irrigation technology improvement. Figure 8.1 presents a simple conceptual explanation.

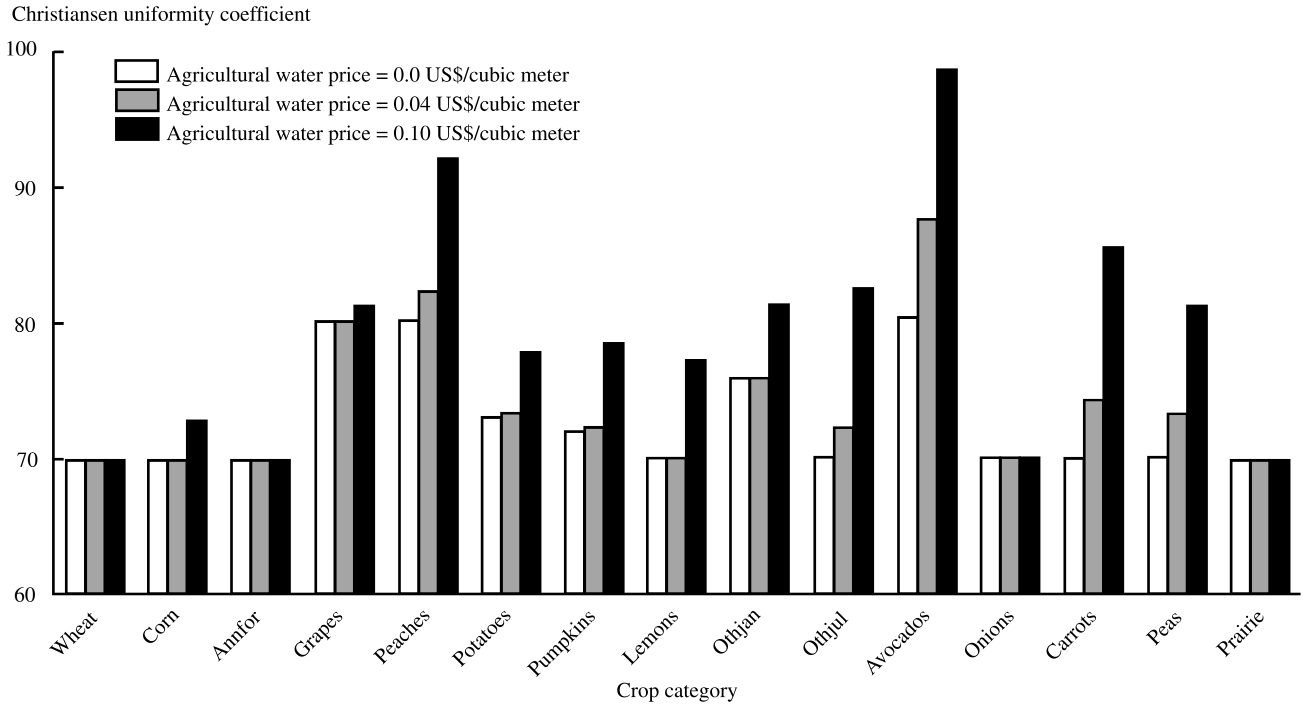
Figure 8.2 presents CUC values resulting from three different water fee scenarios with irrigation charges ranging from US$0.00 per cubic meter, to US$0.04 per cubic meter, and US$0.10 per cubic meter, respectively. With higher water fees, higher CUC values tend to be selected for crops. Moreover, for higher-value crops (see profits per unit of water for various crops, in Table 5.8), the CUC value increases more at higher water prices. This is expected because the marginal profit from enhanced irrigation technology is higher for these crops.

Figure 8.1 Marginal benefit/cost with changing irrigation technology for low-value (MB1 and MC1) and high-value (MB2 and MC2) crops



Note: This figure illustrates why more advanced irrigation technology is used for higher-value crops.

Figure 8.2 Christiansen Uniformity Coefficient values resulting from three water-price scenarios



Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

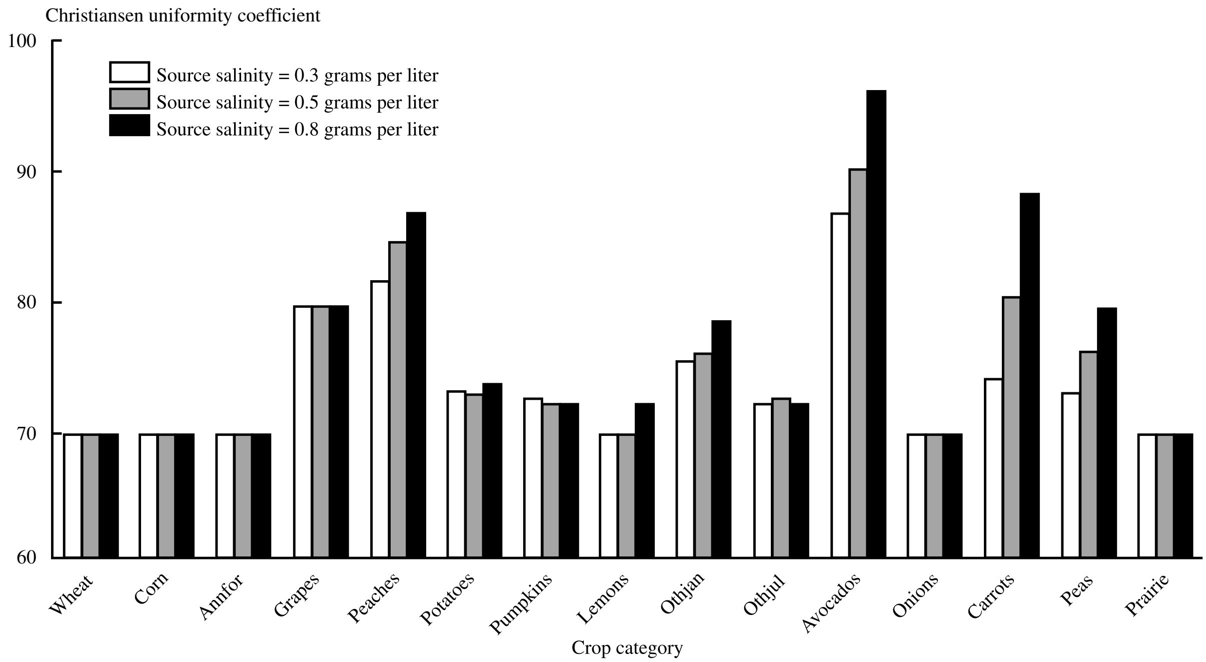
Changes in the source salinity affect irrigation technology choice as well. This is shown graphically in Figure 8.3. High levels of source salinity induce more advanced irrigation technology, which is consistent with the findings of Letey et al. (1989).

Irrigation Technology Choice under Hydrologic Uncertainty

Field irrigation technology (FIT) choice under hydrologic uncertainty is an important concern for farmers who seek to reduce income risk from drought and climate variability. Hydrologic uncertainties related to FIT choice include random distribution of crop evapotranspiration, precipitation, and irrigation water availability. Hydrologic uncertainties lead to seasonal variations in farmers' net profits, which is the gross profit from crop production minus various costs, including the annualized capital cost of the irrigation technology as well as operation and maintenance costs. Advanced FIT can help stabilize farmers' income by maintaining crop production when water supply is unreliable.

The gross irrigation water requirement is equal to crop evapotranspiration minus rainfall available for crop growth plus distribution and conveyance losses, tail water, and percolation. Satisfaction of the irrigation water requirement depends on the availability of water sources (groundwater, surface water storage, and runoff) and the performance of the irrigation system. In dry years, and particularly during droughts, a higher level of FIT can usually better accommodate larger irrigation requirements as a result of lower rainfall/runoff and decreased overall water availability. However, a high level of FIT that can be appropriate for dry years may not be necessary in normal years, and especially not in wet years, because of lower irrigation water requirements and greater water availability. Because more advanced FIT is typically associated with

Figure 8.3 Christiansen Uniformity Coefficient values resulting from three salinity scenarios



Note: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

higher capital costs, it may impose unnecessary costs in normal or wet years. The hydrologic level in future years is a random variable, and appropriate decisions on FIT choice need to take this uncertainty into account. The modeling framework presented here can integrate hydrologic uncertainties with irrigation water requirements and available sources and thus can help analyze the income risk for dry years and the risk of excess capital cost for normal or wet years.

In the following sections, we describe the relationship between FIT and hydrologic uncertainty, and the specification of hydrologic uncertainty in the model. We then show the effect of hydrologic uncertainty on FIT choice and risks associated with FIT choices.

Incorporation of Hydrologic Uncertainty

To incorporate uncertainty, the river basin model is extended to a scenario-based two-stage stochastic optimization model, incorporating uncertainties in rainfall, runoff, and crop evapotranspiration. Recent scenario-based stochastic optimization models applied in water resources include Watkins and McKinney (1997), Huang and Loucks (2000), and Watkins et al. (2000). In contrast to deterministic programming models (DPM) with perfect knowledge of the parameters, scenario-based stochastic programming models (SPM) support the “here and now” decision while providing a number of “wait and see” strategies dependent on which scenario unfolds. The fundamental idea behind the two-stage stochastic optimization model is the concept of recourse. Recourse is the ability to take corrective action after a random event has taken place (Birge and Louveaux 1997). For our problem, the first stage (now) is to determine the cropwise FIT adoption, with associated capital cost; the second stage (then) brings in a random event, for example, changes in rainfall, runoff, or temperature, resulting in changes in water allocation among crops and irrigation schedules to correct the earlier decision on FIT choice. The two stages are included in an endogenous model, with the recourse effect between the two stages embedded in the model.

A scenario-based approach is used to incorporate hydrologic scenarios into the model. A scenario in the model is specified to include a sequence of monthly water withdrawals that are allocated to irrigated areas or districts, associated with monthly crop evapotranspiration and effective rainfall for crop growth. Offtakes from river reaches are the major source of irrigation water supply, and the volume of the stream flow depends mainly on the amount of snowmelt upstream. Local rainfall in the basin occurs mainly during the winter months, and effective rainfall accounts for 30–40 percent of total crop evapotranspiration of the major irrigated crops in the basin. Because rainfall is concentrated during the winter season, and precipitation during the vegetation season is relatively stable, the variability of effective rainfall for crop growth is less pronounced than the variability of irrigation water supplies. Moreover, the variability in temperature and wind speed during the crop season is small, which corresponds with a lower significance of uncertainty related to crop water requirements (evapotranspiration) (see also the discussion related to Figure 8.6 below). In general, the specification of hydrologic scenarios used in this study should deal with uncertainties related to irrigation water availability, effective rainfall, and crop evapotranspiration simultaneously and take the cross effects of these three parameters into account. However, considering the conditions discussed above, for simplicity, but without loss of significance, scenarios for the modeling analysis presented in this chapter are identified according to the major source of uncertainty, that is, irrigation water availability. As can be seen, the covariance of effective rainfall and crop evapotranspiration with water withdrawals is embedded in the scenario specification, which is described in the following.

The cumulative distribution of annual inflow to the basin over a 48-year period (monthly inflow, Donoso 2001; personal communication) is shown in Figure 8.4. Five scenarios are defined, based on five annual inflows corresponding to cumulative probabilities of 10, 30, 50, 70, and 90 percent, as shown in Figure 8.5. The years selected are defined as Y_{10}, Y_{30}, Y_{50}, Y_{70}, and Y_{90}. Monthly withdrawals associated with each selected year are assigned to a scenario corresponding to the cumulative probability.

Figure 8.4 Distribution of total annual inflow in the Maipo River Basin

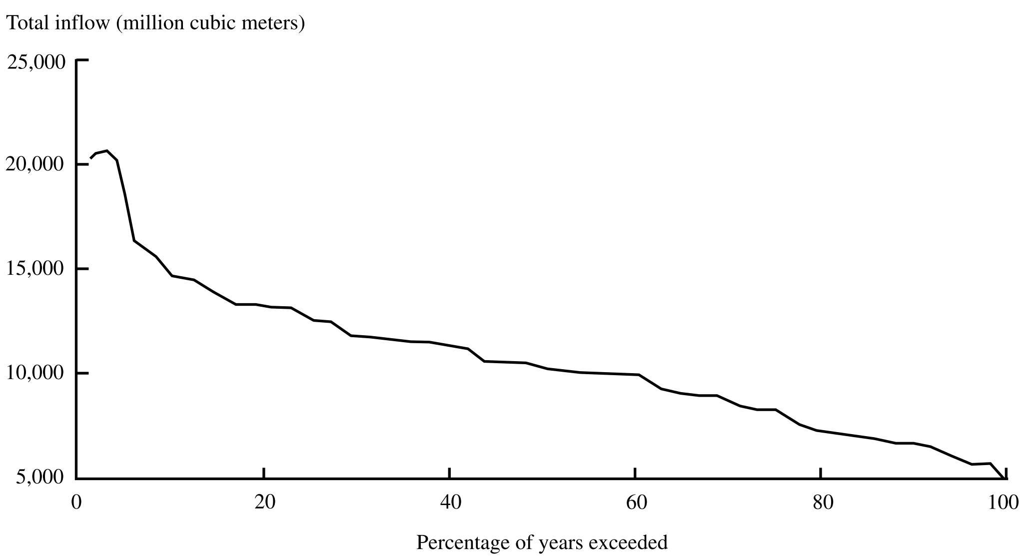
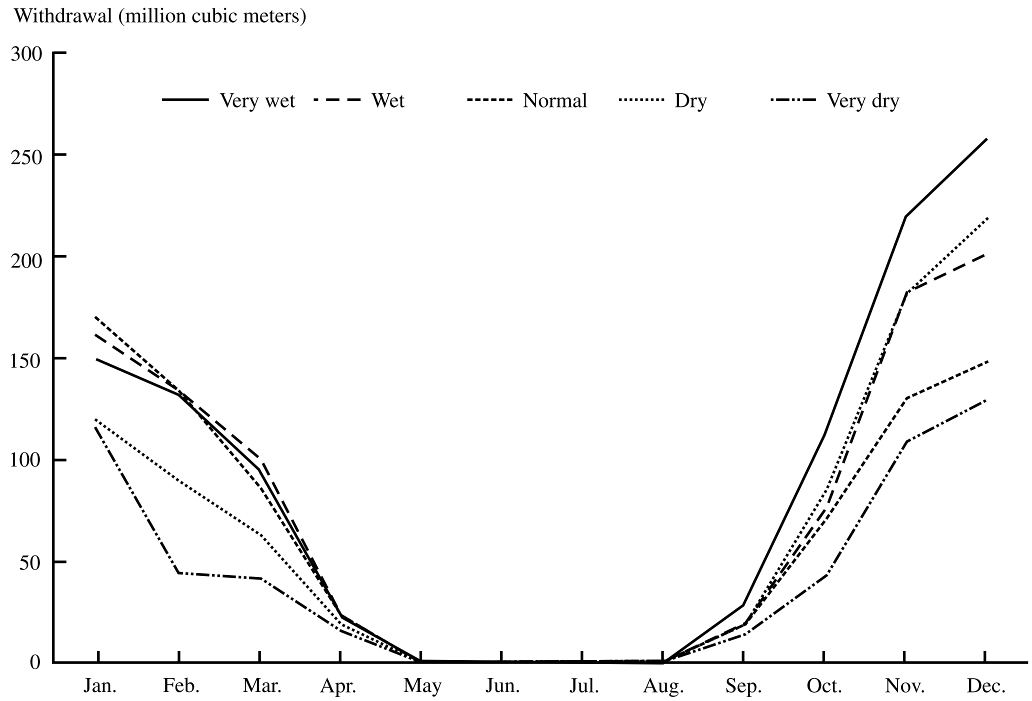


Figure 8.5 Water withdrawal to demand site A1 under five alternative hydrologic scenarios



Note: Five scenarios are defined, based on five annual inflows corresponding to cumulative probabilities of 10 percent (very dry), 30 percent (dry), 50 percent (normal), 70 percent (wet), and 90 percent (very wet).

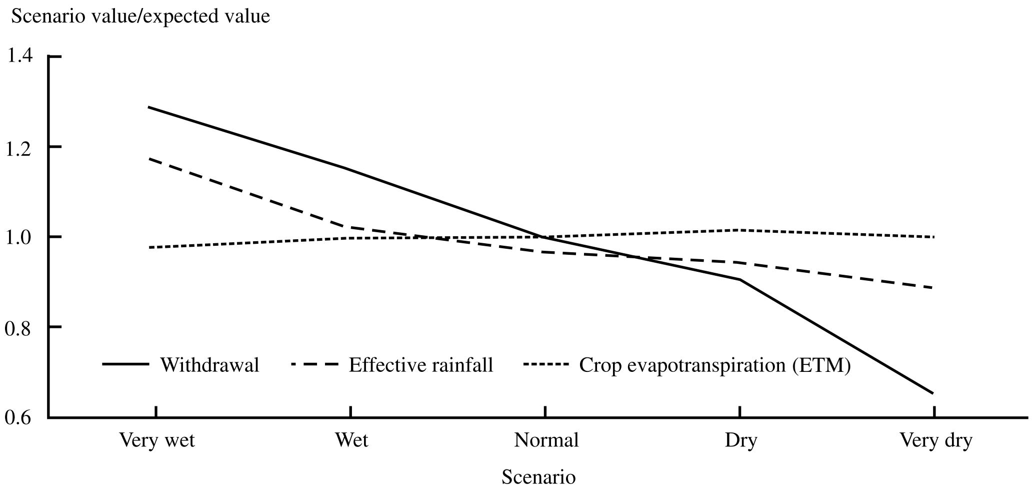
Moreover, monthly crop evapotranspiration and effective rainfall vectors are assigned to the corresponding scenarios. The scenarios specified in this way will mainly reflect the variance of water withdrawals (the major uncertainty with regard to irrigation under the assumptions made above), while, at the same time, the covariance of effective rainfall and crop evapotranspiration with water withdrawals will be embedded.

Once the scenarios of basin inflows are defined, water withdrawals under each scenario are determined by running the river basin model. Figure 8.5 shows the resulting monthly water withdrawals for irrigation area A1 under each of the five scenarios. Figure 8.6 presents a comparison of the variability of the three parameters (water withdrawals, effective rainfall, and crop evapotranspiration) by presenting relative values of annual irrigation withdrawals, seasonal effective rainfall, and seasonal crop evapotranspiration (the value under a scenario divided by the expected value) for wheat in A1. As can be seen, the variability of water withdrawals is more pronounced than for the other two items.

The two-stage stochastic optimization model incorporates the scenarios reflecting hydrologic uncertainties. The first-stage decision in the model relates to the FIT choice represented by CUC for each crop planted in the study district of A1. The second-stage decision involves water allocation to different crops in each month of the crop growth periods, subject to crop water requirements and water availability under the hydrologic scenarios defined above. The net profit consists of two parts: the capital cost associated with the chosen level of CUC and the expected value of irrigation profit from the various scenarios. This can be written as

$$npft = \sum_{c} -u^{c} \cdot a^{c} + \sum_{s} p_{s} \cdot pft_{s}, \qquad (8.1)$$

Figure 8.6 Water withdrawal, effective rainfall, and crop evapotranspiration relative to expected value under alternative scenarios for wheat in demand site A1



where u represents CUC, as previously defined, and a^c is the crop area allocated to crop c. The sum of all crop areas in each period is constrained by the total area available (ta),

$$\sum_c a^c \leq ta \quad \forall t, \quad c \in \Psi^t, \tag{8.2}$$

in which Ψ^t is the set of crops with growth stages in time period t. Moreover, the determination of crop area is subject to historic crop patterns and future agricultural planning, which is represented by crop-specific variable bounds for a^c,

$$\underline{a^c} \leq a^c \leq \overline{a^c}. \tag{8.3}$$

The p_s in equation 8.1 is the probability associated with scenario s; and pft is the profit resulting from scenario s:

$$pft_s = \sum_c ah_s^c \cdot (y_s^c \cdot pc^c - oc^c) - \sum_t wd_{w,t} \cdot pw_s, \tag{8.4}$$

in which ah_s^c is the harvested crop area under scenario s,

$$ah_s^c \leq a^c; \tag{8.5}$$

y is the crop yield (equation 3.1), pc is the crop price, oc is other cropping cost, wd is the water withdrawn, and pw is the water fee.

The two-stage stochastic optimization model can be extended to a robust optimization model (Mulvey, Vanderbei, and Zenios 1995; Watkins and McKinney 1997) by adding a risk-aversion item that penalizes the risk of crop production loss under "unfavorable (dry-year) scenarios":

$$obj = npft - \lambda \cdot \sum_{s \in \Omega} p_s \cdot (pft_s - \overline{pft})^2, \tag{8.6}$$

in which Ω is a subset of the dry scenarios under which crop production is subject to substantial risk of loss because of drought, $\overline{pft}$ is the expected value of the net profit, and λ is the weight assigned to the risk item and reflects the decision preference to risk aversion. With a risk weight (λ) equal to zero, the SPM puts the least emphasis on maintaining a stable solution; in these cases, the risk in the drought scenarios cannot be handled. A positive λ reduces the risk but results in sacrifices during the first stage. Other constraints related to the hydrologic scenarios are described in Appendix A.

The analysis of FIT choice under hydrologic uncertainty involves several assumptions. They include fixed salinity in irrigation water (0.3 grams per liter), variable water fee (*pw,* US$0.01 per cubic meter), CUC values constrained within a range of 60–90 for grapes and 50–90 for all other crops, constant other cropping cost (*oc*) over all hydrologic scenarios, and fixed crop prices (*pc*) for all crops.

FIT Choice under Hydrologic Uncertainty: Result Analysis

Comparison of the Stochastic and Deterministic Models

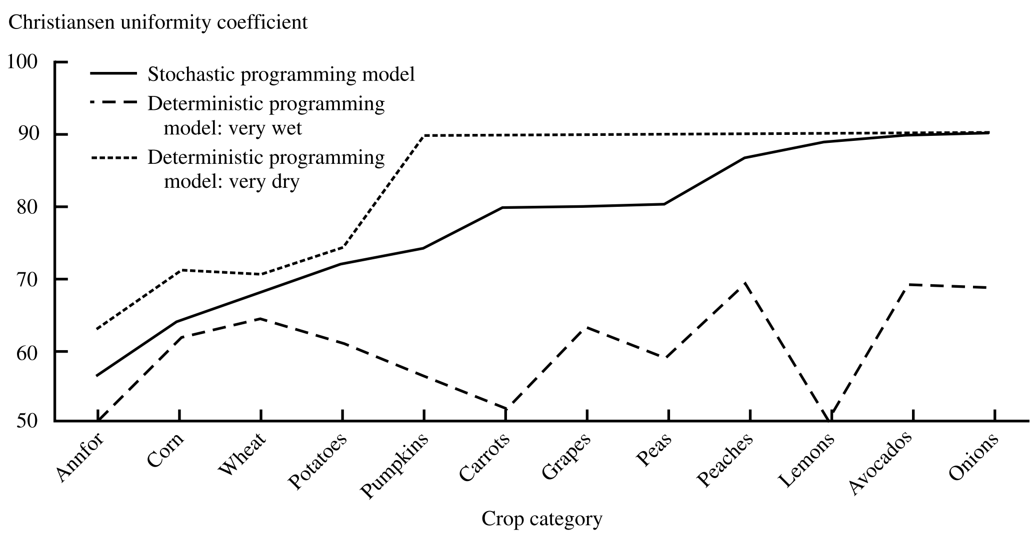
The alternative hydrologic scenarios result in different CUC levels. Figure 8.7 compares the CUC values for multiple crops from the SPM with values from the DPM under the "very wet" scenario and the "very dry" scenarios. As expected, the values of CUC resulting from the SPM are considerably higher than those from the DPM under the very wet scenario but lower than those under the very dry scenario. Results from these extreme scenarios vary significantly. The very wet scenario undervalues the irrigation technology, but the very dry scenario overvalues it when compared with the SPM results.

Hydrologic engineering design usually uses a probability of precipitation or runoff derived from frequency analysis to represent a "dependability level." Figure 8.4 presents the curve of probability levels and corresponding inflows that can be used to determine such levels for the Maipo River Basin. Among the five scenarios specified in this analysis, the "normal" scenario has a probability level of 50 percent. The FIT choices from DPM under this scenario are compared with those from SPM, with results shown in Figure 8.8. For some crop categories, such as wheat, maize, avocados, and lemons, the results from the normal scenario with a dependability level of 50 percent are close to those from SPM. However, for other crop categories, such as pumpkins, grapes, and onions, CUC values are substantially higher for SPM.

Behavior of SPM and DPM under Scenario Analysis Strategy

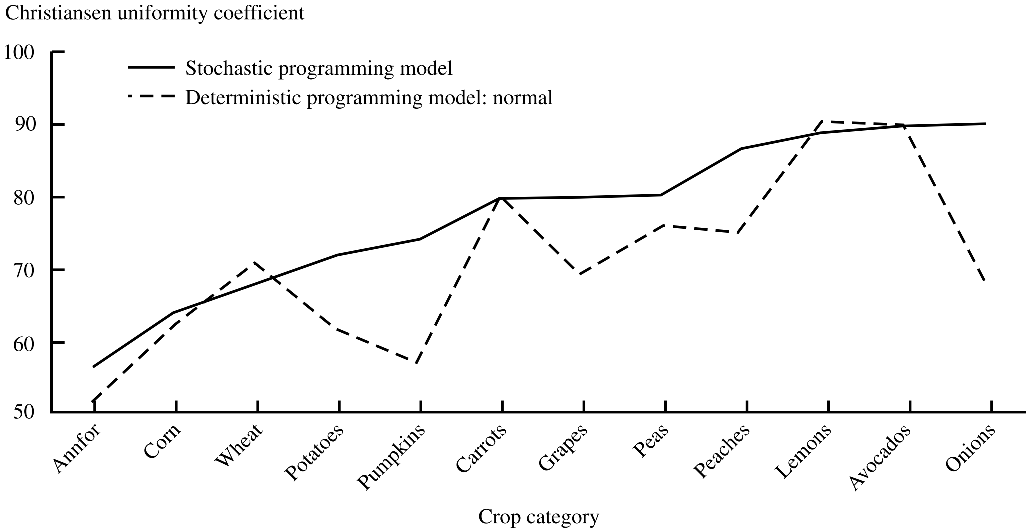
Scenario analysis strategy (SAS) is used to obtain a collection of first-stage decisions $\{x_\omega\}$ by solving Ω separate deterministic programs (one for each scenario) and then to combine these decisions as $x = \Sigma_{\omega \in \Omega} p_\omega x_\omega$

Figure 8.7 Christiansen Uniformity Coefficient of various crops from the stochastic programming model and the deterministic programming model under the very dry and very wet scenarios, respectively



Note: Annfor indicates annual forage.

Figure 8.8 Christiansen Uniformity Coefficient of various crops from the stochastic programming model and the deterministic programming model under the near-normal scenario



Note: Annfor indicates annual forage.

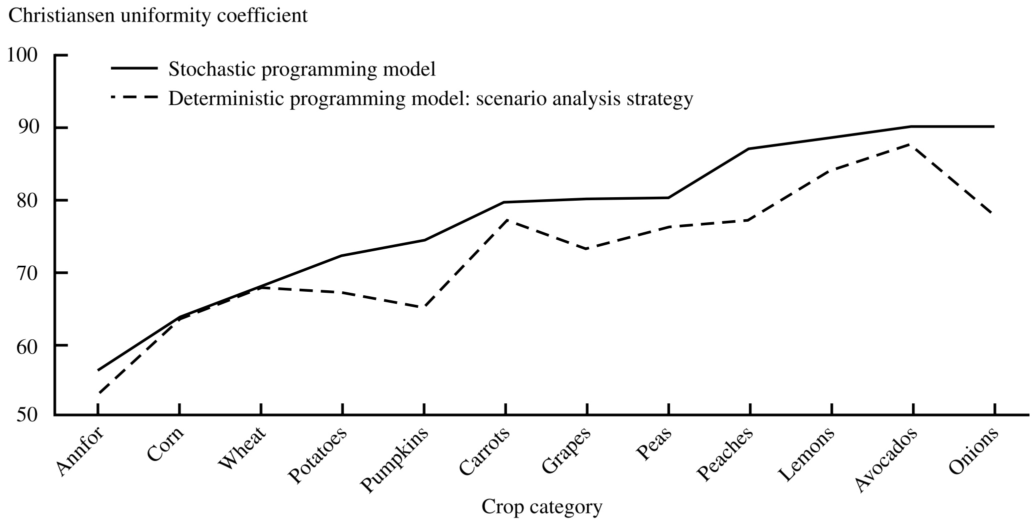
where p_ω is the probability for scenario $\omega \in \Omega$. SAS assumes perfect information regarding the future and thus results in "exact" decisionmaking. Figure 8.9 compares the CUC values resulting from SAS and SPM. For all crops, the CUC value from SPM is higher than the value from SAS, which shows that, at least for this specific case study, and with the assumption of perfect information regarding the future, SAS may underestimate the effect of irrigation uniformity. In other words, for this case study, without perfect information regarding the future, SPM will prefer a higher level of CUC compared with SAS.

As can be seen from Figures 8.8 and 8.9, the difference between CUC values under SPM and DPM are crop-specific. The CUC outcomes under SPM and DPM under the normal scenario and under SPM and SAS are similar for wheat, corn, and annual forage. This shows that decisions on FIT choice for these crops are less sensitive to hydrologic uncertainties. These crops together cover the largest irrigated harvested areas in demand site A1 (wheat, 16 percent; maize, 17 percent; and annual forage, 10 percent). In addition, larger amounts of water are applied to these crops. Under average hydrologic conditions, wheat accounts for 13 percent of total withdrawals, maize for 15 percent, and annual forage for 9 percent. Moreover, they are the least profitable crops. For example, the average economic value per cubic meter of water withdrawal in demand site A1 is US$0.17 (average over all crops and over all hydrologic scenarios), whereas the value is only US$0.08, US$0.06, and US$0.05 for wheat, corn, and annual forage, respectively. Because of these conditions, the decisions on CUC for wheat, corn, and annual forage might be explained as follows: in a dry year, water is allocated to crops with the highest economic returns. At the low water availability in dry years, high-value crops will be preferred, and thus no increase in CUC levels will be induced for the lower-value crops. In normal or wet years, CUC values at levels that permit meeting full water requirements and maximum yields are chosen, resulting in values only slightly lower compared with the dry year case.

Risk Analysis in FIT Choice

In Equation 8.6, assuming $\Omega = \{\text{very dry}\}$, we consider risk aversion only for the most

Figure 8.9 Christiansen Uniformity Coefficient of various crops from the stochastic programming model and the deterministic programming model under the Scenario analysis strategy



Note: Annfor indicates annual forage.

unfavorable (or dry) scenario. A series of λ values starting from zero are applied to the model to analyze CUC values, capital costs, and net profits under alternative λ values. The larger λ, the higher the preference placed on the profit under the very dry scenario, which will result in higher values of CUC and correspondingly higher capital cost. In Figure 8.10, the relationship between annualized capital cost per unit of crop area (C) versus the net profit under the very dry scenario (P^*) and the expected value of net profits (EP) are plotted, respectively. As can be seen, when C is less than US$105 per hectare, both EP and P^* increase with C; when C is within the range of US$105–130, EP is nearly flat and declines slightly with C, whereas P^* still increases with C; when C is larger than US$130 per hectare, the slopes of the two curves are gradually reversed, the curve of EP declines at an increasing rate, whereas the curve of P^* increases at a decreasing rate.

For further analysis, we define two indicators for risk analysis in FIT choice:

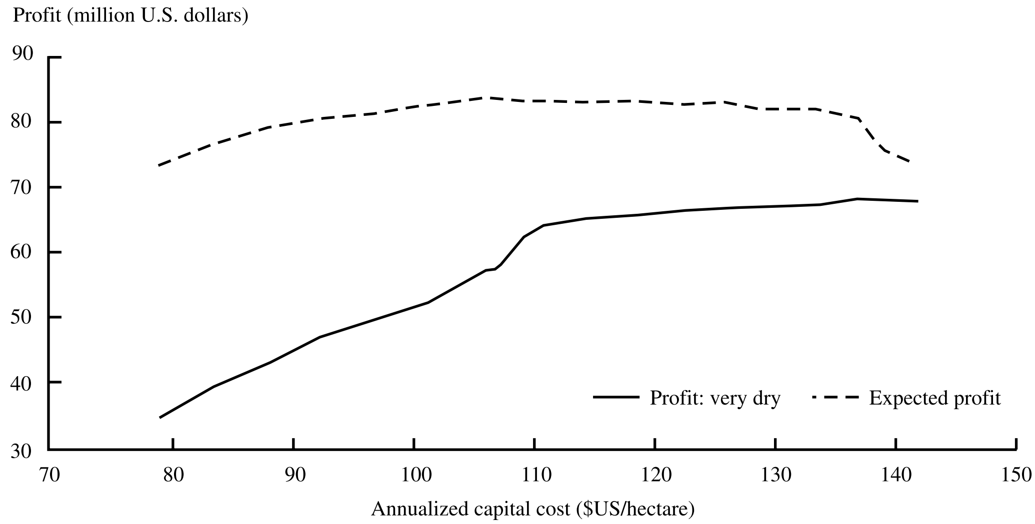
$$RI_1 = \frac{\partial EP}{\partial C}, \text{ and} \qquad (8.7)$$

$$RI_2 = \frac{\partial P^*}{\partial C}. \qquad (8.8)$$

RI_1 represents the marginal change of EP with annualized capital cost per hectare (C), and RI_2 represents the marginal change of P^* with C, as shown in Figure 8.11. By the first-order condition of the optimization problem, $\lambda = 0$, $RI_1 = 0$, and C = US$105 per hectare. When C < US$105 per hectare, $RI_1 < 0$; when US$105 per hectare < C < US$130 per hectare, $RI_1 < 0$ but close to 0; when C > US$130 per hectare, $RI_1 < 0$ at a level significantly below 0. $RI_2 > 0$ for the whole range shown in Figure 8.11 (US$60–140 per hectare), but it decreases with C. When C US$130 per hectare, RI_2 is close to 0.

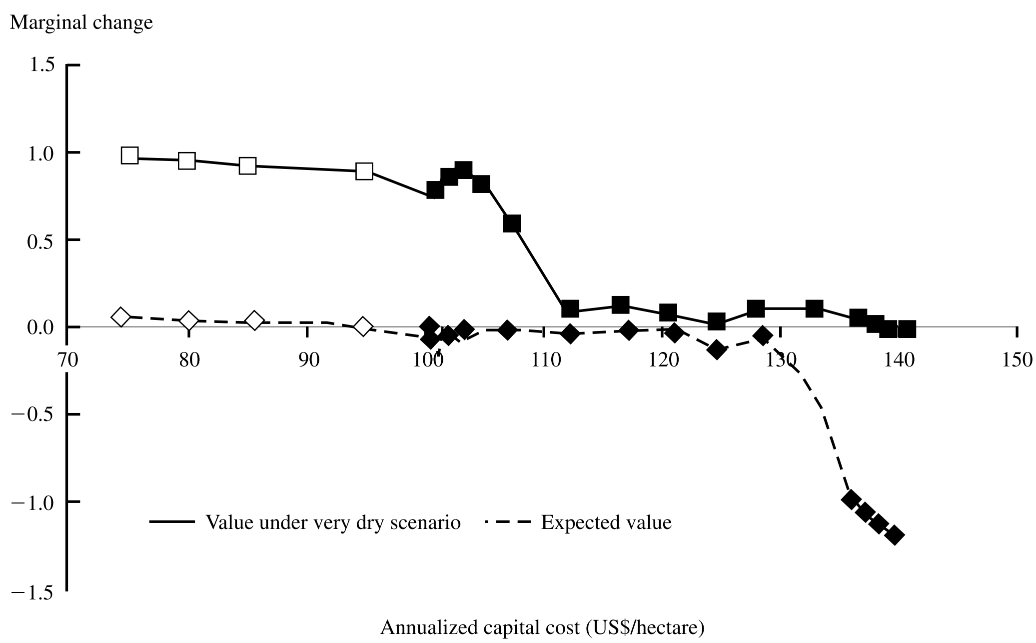
For the specific case before C reaches US$105 per hectare, increasing investment will lead to both higher expected profit and higher profit under drought conditions. That is to say, the capital cost per hectare for irrigation technology should be at least US$105 to take full advantage of the win-win condition for EP and P^* (RI_1, RI_2 < 0). At the value of C equal to US$105 per hectare, a turning point is reached, which is the starting

Figure 8.10 Net profit versus capital cost for irrigation technology and management: Expected value and value under the very dry scenario



point of a tradeoff zone. Until *C* reaches US$130 per hectare, *EP* slowly declines with increasing capital cost, and *P** continues to increase but at a decreasing rate. The level of *C* = US$130 per hectare represents the endpoint of the tradeoff zone. In the tradeoff zone, the gain in *P** is comparable to the loss in *EP*. In other words, the risk of production loss is basically contained without a significant negative effect on the ex-

Figure 8.11 Relationship between marginal change in net profit and capital cost: Expected value and value under the very dry scenario



Note: Unfilled data points show model results with an additional constraint on capital cost for irrigation technology and management improvements.

pected value in this range. As discussed above, appropriate FIT decisions should reach the starting point of the tradeoff zone (C = US$105 per hectare) and ideally stay within this zone. Beyond the endpoint of this zone (when C > US$130 per hectare), RI_1 will be largely below zero, and RI_2 will be close to 0 and will turn to below 0. That is to say, after a certain level of capital cost (US$130 per hectare for this case), the marginal return to the very dry scenario will be significantly less than the marginal cost of CUC. Therefore, decisions in the range beyond this point should be evaluated carefully regarding the tradeoff between the expected profit and the loss of profit under drought scenarios.

Summary

The holistic economic–hydrologic model presents an analytical framework to study irrigation technology choices endogenously with other decisions on water allocation and agricultural development. According to the outputs from this framework, water fees and water quality (in the form of salinity in the irrigation water) show strong effects on field irrigation technology for the study area. More importantly, the model was extended to incorporate hydrologic uncertainties related to both water requirements and water availability through a scenario-based approach, which provides a tool to analyze irrigation technology choice subject to hydrologic uncertainty.

Incorporating uncertainties into a consistent stochastic programming model (SPM) leads to different outcomes compared with a deterministic programming model (DPM) based on individual scenarios. Outcomes for CUC levels for extreme climate events based on a deterministic programming model will significantly undervalue or overvalue the level of CUC compared with SPM outcomes. Moreover, some low-value and high-water-demanding crops are less sensitive to hydrologic conditions in the case study site. The widely used dependability approach in engineering design, which is based on a single scenario specified from frequency analysis, might not be appropriate to analyze the tradeoff between farmers' profit from irrigation and cost for advanced irrigation technology adoption. The scenario analysis strategy (SAS) may also produce results diverging from those produced by SPM. In the specific case study presented in this report, we find that SAS underestimates the level of CUC. In other words, for this case study, without perfect information regarding the future, SPM will prefer a higher level of CUC compared with SAS. By these comparisons, we find that SPM can be a constructive approach that provides a mechanism with which model solutions can be adjusted to account for variations in water availability and water requirements.

Moreover, two indicators are proposed to determine appropriate investments for field irrigation technology in an irrigation district, with the objective to maximize expected profit and to minimize the income risk from drought. Based on these two indicators, we can identify the tradeoff zone, in which appropriate FIT decisions should be located. The investment for field irrigation technology should be within this tradeoff zone, which is defined as the range where expected profit is maximized while the risk of profit loss under drought conditions is minimized. The tradeoff zone can be identified through the modeling analysis.

Moreover, the model can be easily extended to broader policy analysis on irrigation technology choices, such as the effects of variability in crop prices and drainage disposal costs on FIT choices. The model is applied to an irrigation district in this report; however, it can also be applied to a single farm, given the probability distribution of water availability for the farm.

CHAPTER 9

Analysis of Water versus Other Inputs in an Integrated Economic–Hydrologic Modeling Framework

Increasing concerns about water availability, water quality, ecosystem sustainability, and food security have increased the importance of quantitative assessments of the substitution between water and other agricultural inputs at the margin for agricultural and environmental policy analysis. Plant growth is limited to the level afforded by the particular crop input, which is most constrained or least available. Substitution among inputs does not necessarily lead to higher yield, but it can change the demand for different resources. Different levels of water application can alter the nonlimiting levels of other inputs, particularly mobile plant nutrients. Such substitutions at the intensive margin can reduce the environmental cost of producing agricultural products or the cost of joint agricultural and environmental outcomes. Edwards, Howitt, and Flaim (1996) show that farmers respond to increases in electricity cost by substituting between water and other inputs, by changing the crop allocation on irrigated land, and by changing the total irrigated area, for example.

Quantitative substitution assessments are usually conducted through production functions, which present the technological relationships that determine the maximum quantities of agricultural outputs that can be produced from given combinations of inputs (Heady and Dillon 1961). Fernandez-Cornejo (1992) provides a procedure for assessing short- and long-run demand and substitution of agricultural inputs, based on the estimation of a theoretically consistent restricted profit function and using a series of decomposition equations. Howitt and Msangi (2002) present a multi-input–multi-output production framework within which the potential for substitution can be explicitly modeled. The framework is used as a basic policy tool, with incentives or penalties leading to input substitution under a given agricultural technology.

This chapter explores the potential substitutions between water and other agricultural inputs within the integrated economic–hydrologic modeling framework developed in the previous chapters. Compared with the multi-input–multi-output production framework, the modeling framework used here represents essential hydrologic and environmental relations determining both water supply and demand endogenously based on hydrologic, economic, and institutional relations. This allows a more comprehensive substitution analysis between water and other inputs.

The crop yield function shown in equation 3.11 with irrigation investment, application of fertilizer, pesticides, machinery, labor, and water as variables is used for the substitution analysis in the holistic economic–hydrologic framework. To make the analysis more realistic, a baseline calibrated against real-world conditions is used. The model is calibrated following the concept of “positive mathematical programming” (PMP), which has been applied by Howitt

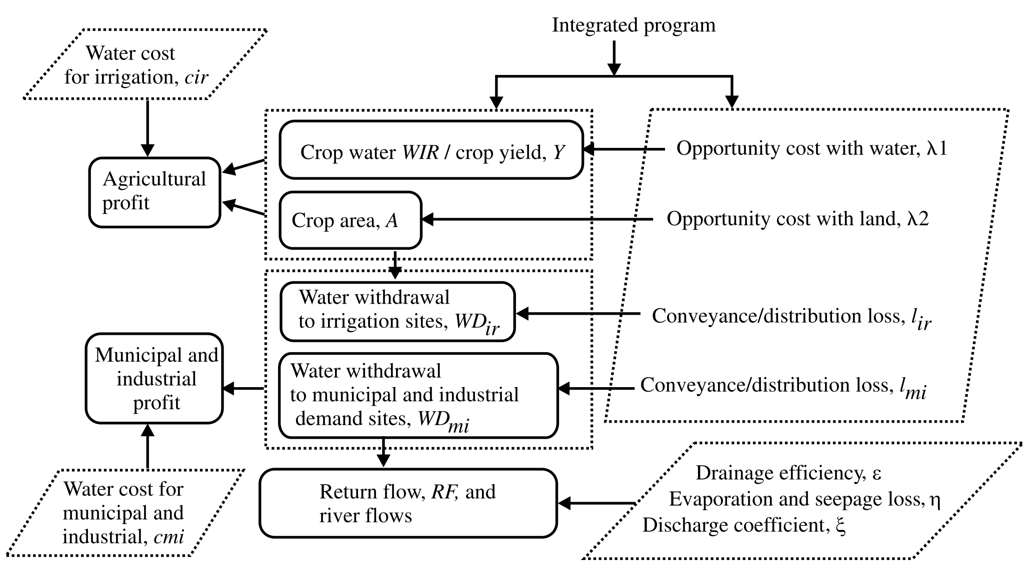
(1995) and has since been widely used in agricultural and applied economics. In the following, the calibration procedure is introduced, substitution scenarios are presented, and results are discussed.

Calibration of a Holistic Economic–Hydrologic Model

Mathematical programming models can be calibrated against real-world conditions (a base year or average over several years). A normative programming model usually shows a wide divergence between model outcomes in the base period and actual observations. Actually, mathematical programming models can rarely capture all real-world constraints explicitly. Therefore, results are considered indicative, and the focus is on the differences among alternative scenarios. Bounds on variables are often used to avoid outcomes that diverge too much from realistic values; however, tight bounds can be inappropriate for policy analysis (Howitt 1995).

Calibrating a holistic water resource and economics model that includes hydrologic, agronomic, and economic components is a challenging task. Figure 9.1 presents a diagram of data that need to be calibrated and the parameters that are adjusted during the calibration process. This figure also shows the connections between different items involved in the calibration procedure. The calibration matches computed with observed or recorded values under given climate regime and agricultural inputs. For the model used here, these items include (1) flow through river reaches; (2) water withdrawals to both agricultural demand sites and municipal and industrial sites, if they are observable; (3) crop harvested area and yield; and (4) farmer incomes and profit from industrial and municipal water uses. Model calibration and verification have been widely studied in the economic and water resources fields, respectively; however, few calibration studies attempt to jointly calibrate hydrologic and economic components. Howitt (1995) presents PMP as a procedure using both programming constraints and positive inferences from base-level observations. This approach has been applied for calibrating agricultural production models. Considering a holistic water resource-economics model as an extended economic model with physically based water resource components as constraints, the PMP approach can be

Figure 9.1 Model calibration: Parameters and procedures



extended to calibrate the Maipo River Basin model. The difficulty here consists in the large number of parameters involved in the calibration process and that the numerous searches for appropriate values for most of these parameters are dependent; that is, they should be determined simultaneously in an integrated framework.

The model is calibrated to a baseline with normal weather conditions and current level of technology and management. In the following we describe the calibration procedure with two questions in mind for each step: What will be calibrated? Which items will be adjusted to match the model outputs with the observed values?

Calibration Algorithms

Net Crop Profit

For a crop in an irrigation demand site, net crop profit (NP) is calculated as:

$$NP_{ir,c} = A_{ir,c} \cdot (PC_c \cdot Y_{ir,c} - \sum_{i \in I} IC^i_{ir,c} \cdot INPT^i_{ir,c}), \tag{9.1}$$

where *ir* is the index for irrigation demand site; *c* is the index for crops; *i* is the index for inputs including water, irrigation investment, fertilizer, pesticides, labor, machinery, and seed; *A* is the crop area; *Y* is the crop yield; *PC* is the crop price; *IC* is the input cost; and *INPT* is the input per unit of area. Because all items on the right-hand side of equation 9.1 are the "actual values" of the baseline case, net crop profit will be equal to the actual value. The following assumptions are made in the calibration procedure: (1) observed crop prices and input costs, except for water charges from the field survey, are used as "actual numbers"; (2) input quantities other than water application from the field survey are used as "actual values"; and water application and costs, which are usually subject to major uncertainties, are calibrated. Based on the crop yield function in equation 3.11, with crop yield as actual yield and inputs except for water as actual inputs, the actual water application can be solved directly from the equation. We define the actual water application for crop *i* in irrigation demand site *ir* as $WIR0_{ir,c}$. Given actual crop profit, actual crop area and yield, and all "actual inputs" and input costs except for water can be solved from equation 9.1.

Crop Yield and Area

Given the assumption that all inputs except water application are fixed as observed values, crop yield then depends on the amount of water applied; that is, if water application for irrigation *WIR* matches the actual *WIR*0, then crop yield will match its actual value. The determination of crop area depends on the economic return per unit of crop area as well as on land availability. To calibrate crop yield and area, we reformulate the net crop profit equation 9.1 to:

$$\begin{aligned} NP_{ir,c} = A_{ir,c} \cdot (PC_c \cdot Y_{ir,c} & - \sum_{i \in I} IC^i_{ir,c} \cdot INPT^i_{ir,c}) \\ & - \lambda 1_{ir,c} \cdot | A_{ir,c} - A0_{ir,c} | \\ & - \lambda 2_{ir,c} \cdot | WIR_{ir,c} - WIR0_{ir,c} |, \end{aligned} \tag{9.2}$$

in which *A*0 is the actual crop area and λ1 and λ2 represent the opportunity cost for land and water values that differ from the baseline values, respectively. If $A > A0$, λ1 represents the cost for increasing the crop area by one unit for a specific crop; otherwise it represents the cost for reducing the area by 1 unit for a specific crop. By adjusting the values of λ1 and λ2, the optimization model can solve for a matching of model area and yield with actual baseline values.

Water Withdrawal to an Irrigation Demand Site

If actual water withdrawals to irrigation demand sites are available, the computed water withdrawals can be calibrated to actual values. Water withdrawal to an irrigation demand site (WD_{ir}) is equal to the sum of the water applications over all crops plus conveyance and distribution losses. If we define a conveyance and distribution loss factor as l, which varies over periods (t) and over irrigation demand sites (ir), then we have:

$$WD_{ir,t} \cdot (1 - l_{ir,t}) = \sum_c WIR_{ir,c,t} \quad \forall ir,t, \text{ and} \tag{9.3a}$$

$$WD_{ir,t} = \sum_c WIR_{ir,c,t} / (1 - l_{ir,t}) \quad \forall ir,t. \tag{9.3b}$$

Thus, the calibration of water withdrawal depends on crop water application, which has been discussed above, and on the water loss factor l.

Water Withdrawal to a Municipal and Industrial Demand Site (*mi*)

Water withdrawal to municipal and industrial demand sites is driven by the net economic return of municipal and industrial water use, which is constrained by water availability. The calibration of municipal and industrial water uses and net profits (see equation 3.15 and Appendix A) has been described in Chapter 3. It is driven by the willingness to pay for additional water at normal use (p_0) and by the price elasticity of demand (e). Once the water application has been calibrated, water withdrawal to municipal and industrial sites depends on the water conveyance and distribution coefficient:

$$WD_{mi,t} = WMI_{mi,t} / (1 - l_{mi,t}) \quad \forall mi,t. \tag{9.4}$$

Flow through River Reaches

Given inflows, water withdrawals, and estimated instream losses, return flows need to be calibrated to match observed outflow data. For this study, return flow (RF) from an irrigation demand site to a river reach (n) is calculated as:

$$RF_{(ir,n),t} = \sum_{(ir,n)} \left[\sum_c DP_{ir,c,t} \cdot \varepsilon(ir) \cdot (1 - \eta(ir)) + DS_{(ir,n),t} \right] \quad \forall d,t, \tag{9.5}$$

where return flow is the sum of surface drainage, part of the field percolation from all fields, plus subsurface drainage from a groundwater source associated with an irrigation demand site (ir), ε is the drainage efficiency, defined as the ratio of drainage to field percolation; η specifies the evaporation and seepage loss during the path of surface drainage returning to the river system, and DS is the discharge from groundwater to the surface system. A linear relationship is assumed between the discharge DS and the water table head h of an aquifer (Smedema and Rycroft 1990):

$$DS(ir) = [\xi \cdot GA(ir)] \cdot h(ir), \tag{9.6}$$

where GA is the average area of the groundwater tank (approximately the sum of the irrigated area in an irrigation system). The aquifer is assumed to be a single "tank" associated with a specific irrigation demand site. Tank inflow includes natural recharge, surface water leakage, and deep percolation from irrigation fields; outflow includes pumping, groundwater extraction to root zones, and discharge to surface water systems. The calibration of return flows is done through the determination of appropriate values for the drainage efficiency, ε, the evaporation and seepage loss of surface drainage, and the discharge coefficient ξ. In this case study, ε is about 0.6, η is about 0.2, and ξ is about 0.1 million cubic meters per unit of area per unit of head change.

In some river systems, the river reaches are connected with reservoirs. In that case, monthly reservoir releases are fixed as the average releases under a normal hydrologic level, which are subjected to the designed reservoir operation curves. For alternative scenario analysis on reservoir operations, a bound based on the designed operation curve is set for the reservoir release.

As a summary, the calibration of a holistic water resource and economics model involves the adjustment of a large number of parameters with uncertain values so that model outputs match actual data. In this case study, water withdrawals to demand sites are observed, and computed water withdrawals are calibrated. Then flow through river reaches is calibrated separately. Crop yield, area, and irrigation withdrawals are related and have to be calibrated simultaneously.

Calibration Results

Table 9.1 shows the opportunity cost of water, λ1; Table 9.2 presents the opportunity cost of crop area, λ2; and Table 9.3 shows the calibrated water loss coefficients by demand site and month. To show the sensitivity of the calibrated model to alternative water charges, the model is run over a range of water fees (US$0.04–0.44 per cubic meter). Figure 9.2 presents the effect of alternative water prices on water withdrawals, instream flows, and agricultural profits for the calibrated model. At higher water fees, both irrigation withdrawals and agricultural profits decline, whereas instream flows increase.

Substitution Analysis of Crop Inputs

Figure 9.3a shows an example of the yield function for annual forage at increasing water application (including irrigation and effective rainfall) under three levels of irrigation investment and fixed levels of other inputs; Figure 9.3b presents the same relationship under three levels of labor inputs and given levels of other inputs. These figures present examples of substitution relationships between water application and irrigation investment and between water application and labor input cost.

To further explore such relations, a substitution coefficient is defined. For example, between water application (w) and irrigation investment (i), given the level of fertilizer (f^*), pesticides (p^*), labor (l^*), machinery (m^*), and seeds (s^*), and assuming:

$$y_1(w_1, i_1, f^*, p^*, s^*, l^*, m^*) = y_2(w_2, i_2, f^*, p^*, s^*, l^*, m^*) \quad \forall w_1 \geq w_2 \text{ and } i_1 \leq i_2. \tag{9.7}$$

The substitution coefficient ($\eta_{w,i}$) is calculated as:

$$\eta_{w,i} = \frac{w_2 - w_1}{i_1 - i_2}. \tag{9.8}$$

Substitution coefficients between water and other inputs can be calculated in the same form. Figure 9.4 presents values of $\eta_{w,i}$ versus water application (w) and irrigation investment (i). As can be seen, $\eta_{w,i}$ increases with w and decreases with i. This is expected because at high levels of water application, there is a large potential to save water through irrigation investment, whereas at high levels of irrigation investment, the marginal returns of water savings from irrigation investment will be low. Figure 9.5 presents values of $\eta_{w,l}$ versus water application (w) and labor cost (l). Results for the substitution coefficient with labor inputs are similar to those with irrigation investments. In particular, at high levels of labor input, there is a low potential to further increase labor to save water.

Modeling Scenarios for Substitution Analysis

Two sets of modeling scenarios are defined based on the calibrated Baseline scenario (BAS). The first set of scenarios explores the substitution effects among water and other inputs, each of which is allowed to change within a prescribed range; and the second set of scenarios explores the substitution between water and one of the other inputs, with that input changing within a prescribed range and the others fixed at BAS levels. Under BAS, inputs other than water are fixed. Table 9.4 presents agricultural inputs and net profit, total values, and values per unit of crop area under BAS.

Simultaneous Substitution among Water and All Other Inputs. The following two scenarios are defined to examine the substitution effects among water and other inputs:

- Full optimization scenario for substitution analysis (FOPS), starting from BAS and allowing for water and other inputs to change within prescribed ranges (0.5–2.0 times BAS values).

Table 9.1 Opportunity cost of water, by crop and demand site (λ2, U.S. dollars per cubic meter)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	0.0010	0.0010	0.0000	0.0011	0.0011	0.0009	0.0009	0.0009	0.0009	0.0009	0.0011	0.0009	0.0011	0.0011	0.0011
A2	0.0011	0.0010	0.0000	0.0011	0.0011	0.0009	0.0009	0.0009	0.0009	0.0009	0.0011	0.0009	0.0011	0.0011	0.0010
A3	0.0011	0.0011	0.0000	0.0011	0.0011	0.0009	0.0009	0.0009	0.0009	0.0009	0.0011	0.0009	0.0011	0.0011	0.0011
A4	0.0011	0.0011	0.0000	0.0011	0.0011	0.0009	0.0009	0.0009	0.0009	0.0009	0.0011	0.0009	0.0011	0.0011	0.0014
A5	0.0011	0.0011	0.0000	0.0011	0.0011	0.0009	0.0009	0.0009	0.0009	0.0009	0.0011	0.0009	0.0011	0.0011	0.0011
A6	0.0011	0.0010	0.0001	0.0011	0.0011	0.0009	0.0009	0.0009	0.0009	0.0009	0.0011	0.0009	0.0011	0.0011	0.0011
A7	0.0011	0.0011	0.0000	0.0011	0.0011	0.0009	0.0009	0.0009	0.0009	0.0009	0.0011	0.0009	0.0011	0.0011	0.0011
A8	0.0012	0.0010	0.0000	0.0011	0.0011	0.0009	0.0009	0.0009	0.0009	0.0009	0.0011	0.0009	0.0011	0.0011	0.0011

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 9.2 Opportunity cost of crop land, by crop and demand site (λ1, 1,000 U.S. dollars per hectare)

Demand site	Wheat	Corn	Annfor	Grapes	Peaches	Potatoes	Pumpkins	Lemons	Othjan	Othjul	Avocados	Onions	Carrots	Peas	Prairie
A1	0.0000	0.0000	0.0000	0.0003	0.0004	0.0002	0.0003	0.0009	0.0011	0.0011	0.0012	0.0010	0.0008	0.0004	0.0003
A2	0.0001	0.0001	0.0001	0.0006	0.0010	0.0006	0.0010	0.0024	0.0031	0.0030	0.0031	0.0024	0.0025	0.0019	0.0007
A3	0.0001	0.0001	0.0001	0.0022	0.0018	0.0006	0.0007	0.0014	0.0014	0.0014	0.0020	0.0021	0.0018	0.0011	0.0000
A4	0.0012	0.0009	0.0008	0.0455	0.0181	0.0168	0.0063	0.0479	0.0286	0.0279	0.0791	0.0776	0.0245	0.0188	0.1128
A5	0.0001	0.0000	0.0001	0.0012	0.0010	0.0005	0.0004	0.0012	0.0010	0.0010	0.0017	0.0018	0.0013	0.0008	0.0000
A6	0.0005	0.0004	0.0005	0.0032	0.0052	0.0029	0.0049	0.0123	0.0166	0.0163	0.0162	0.0123	0.0129	0.0099	0.0092
A7	0.0009	0.0143	0.0005	1.5780	1.6967	0.0377	0.0212	7.6561	0.0188	0.0188	5.6862	0.0661	0.0603	0.0369	0.0011
A8	0.0001	0.0022	0.0002	0.0009	0.0011	0.0012	0.0014	0.0053	0.0017	0.0016	0.0058	0.0080	0.0024	0.0006	0.0024

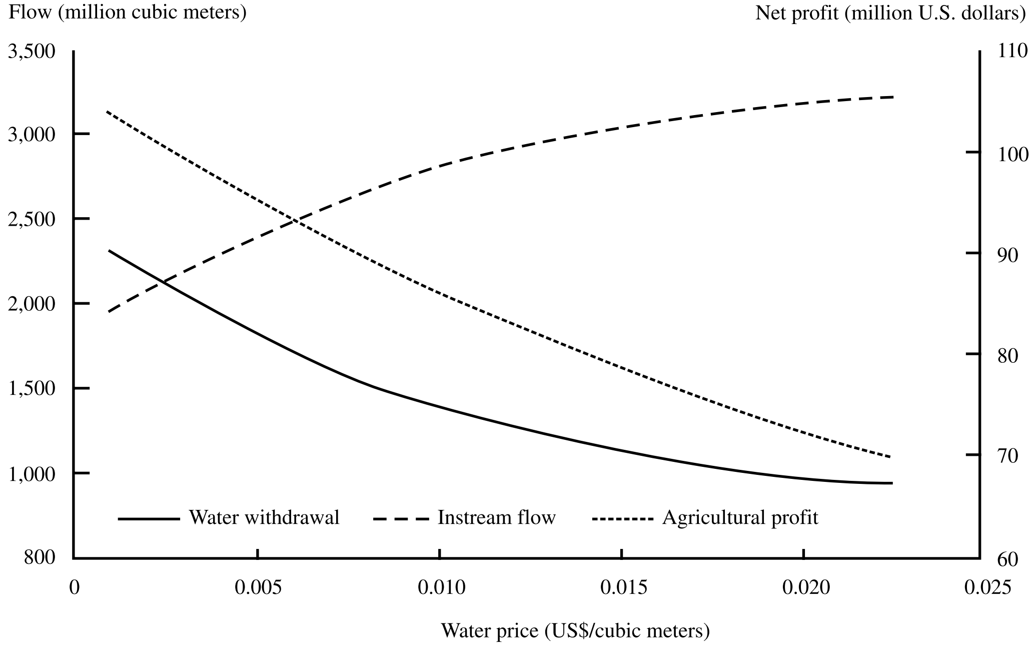
Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table 9.3 Calibrated water loss coefficients, by demand site and period

Demand site	January	February	March	April	May	June	July	August	September	October	November	December
A1	0.332	0.299	0.320	0.284	0.200	0.200	0.200	0.089	0.228	0.295	0.300	0.412
A2	0.292	0.364	0.320	0.289	0.200	0.200	0.200	0.083	0.237	0.288	0.291	0.310
A3	0.237	0.240	0.258	0.190	0.200	0.200	0.200	0.056	0.189	0.230	0.283	0.430
A4	0.263	0.410	0.300	0.271	0.200	0.200	0.200	0.112	0.206	0.242	0.248	0.252
A5	0.248	0.306	0.020	0.252	0.200	0.200	0.200	0.075	0.239	0.317	0.394	0.245
A6	0.290	0.436	0.321	0.502	0.200	0.200	0.200	0.096	0.196	0.271	0.268	0.279
A7	0.220	0.220	0.253	0.119	0.200	0.200	0.200	0.111	0.196	0.213	0.359	0.247
A8	0.298	0.387	0.383	0.213	0.200	0.200	0.200	0.000	0.420	0.359	0.296	0.316

Note: Coefficients are calculated in equation 9.3.

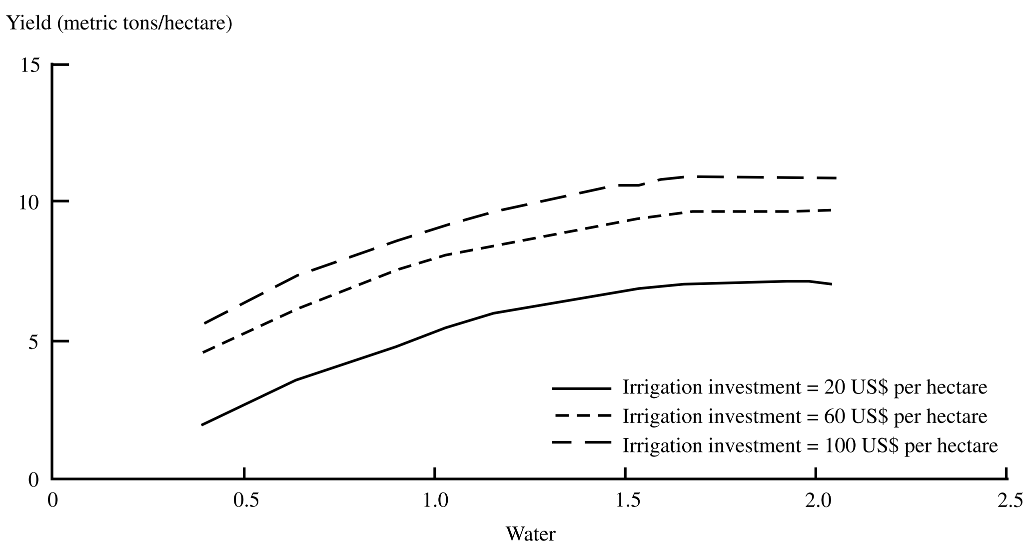
Figure 9.2 The impact of changing water prices on water withdrawals, instream flows, and agricultural profits



Note: Results are from the model with the alternative crop-yield function (equation 3.11).

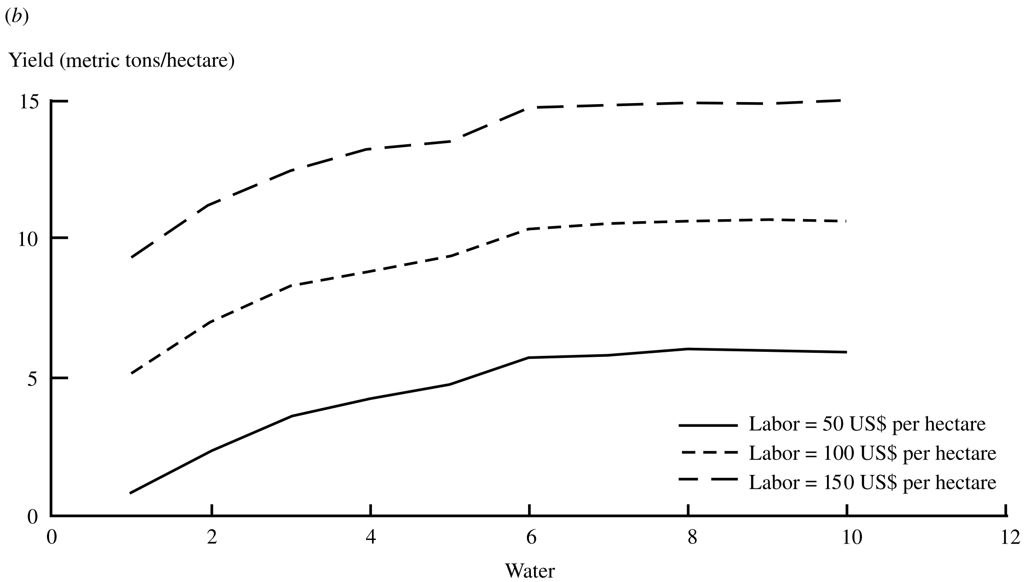
Figure 9.3a Relationship between water application and crop yield under three levels of irrigation investment, example of annual forage

(*a*)



Notes: Fertilizer = US$190 per hectare, pesticide = US$49 per hectare, machinery = US$171 per hectare, labor = US$125 per hectare, and seed = US$113 per hectare.

Figure 9.3b Relationship between water application and crop yield under three levels of labor cost, the example of annual forage



Notes: Irrigation = US$86 per hectare, fertilizer = US$190 per hectare, pesticide = US$49 per hectare, machinery = US$171 per hectare, and seed = US$113 per hectare.

- Substitution among water and other inputs (SUB) keeping net profits close to BAS levels. This scenario is the same as FOPS, allowing water and other inputs to change within prescribed ranges, but water charges are increased to reduce water use. The scenario is implemented through increasing water prices gradually up to the point where total net profits are close to BAS levels.

Figure 9.4 Relationship between water application and water-irrigation investment substitution coefficient ($\eta_{w,i}$) under different levels of irrigation investment

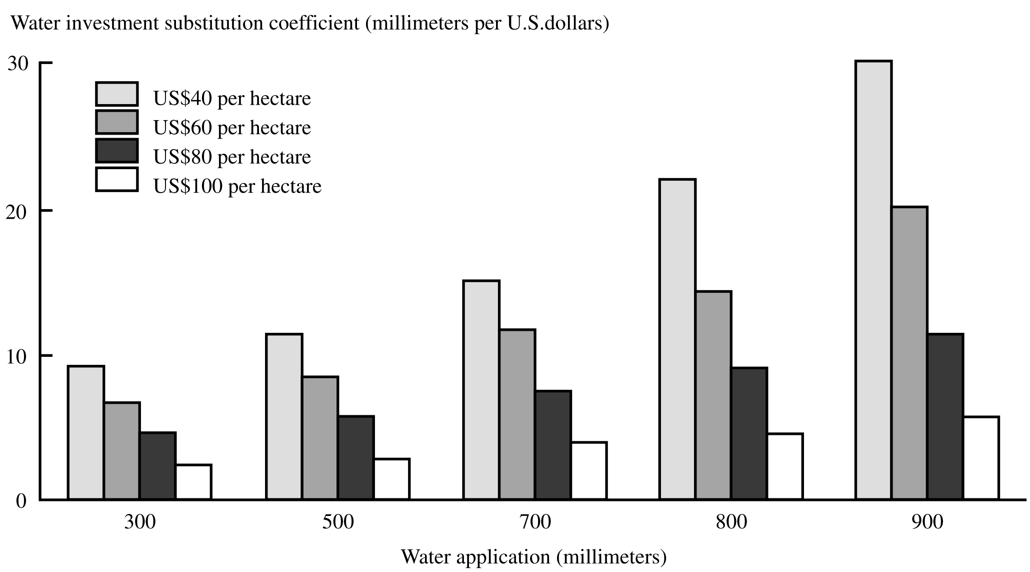


Figure 9.5 Relationship between water application and water-labor cost substitution coefficient ($\eta_{w,l}$) under different levels of labor cost

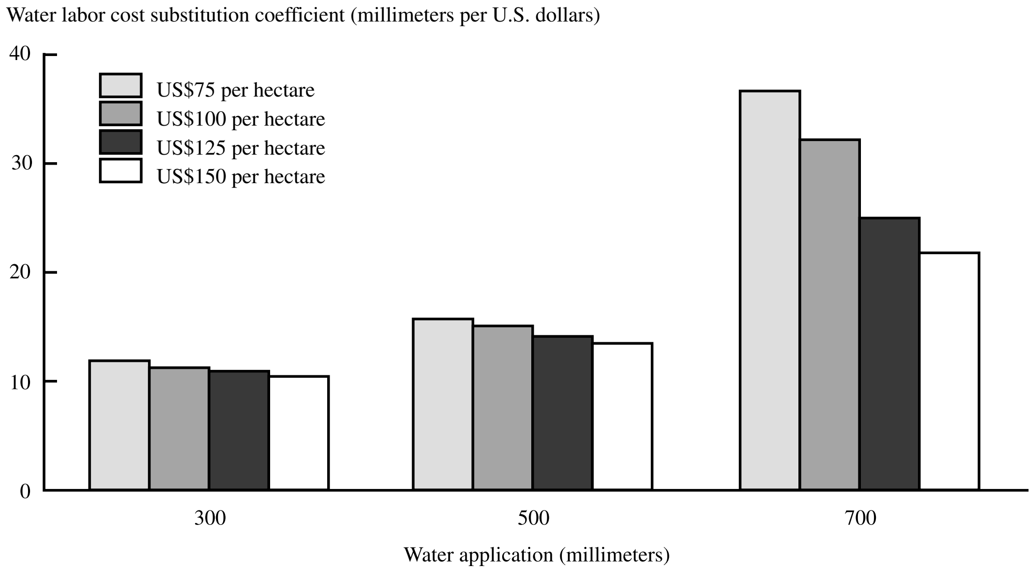


Table 9.5 presents the changes for agricultural inputs and net profits (total values and values per hectare) under FOPS compared to BAS in absolute and percentage terms, respectively; Table 9.6 presents these results for SUB and BAS. Under FOPS, almost all inputs increase for all irrigation districts compared with BAS. Thus, increasing water and other inputs, within prescribed ranges, is the preferred strategy under profit maximization. Larger increases of water application occur in some downstream irrigation districts such as A3, A5, and A7, and smaller increases in some upstream irrigation districts such as A1 and A8, where water is relatively less constrained. In percentage terms, the increase in pesticide usage is lowest, followed by water. Compared with BAS, total water application increases by 301 million cubic meters, the total cost for other inputs increases by US$66.6 million, and net benefits increase by US$11.0 million.

Although FOPS does not show any potential for substitution between water and other agricultural inputs, which are complementary, Table 9.6 shows substitution effects when water fees change under the SUB scenario. If water and other inputs are allowed to change over prescribed ranges, increases in water fees by a factor of eight result in the substitution effects shown in Table 9.6, while net profits are maintained. From a basin perspective, higher substitutions of water are found with seed (reflecting agricultural research) and labor; lower substitutions are found with pesticides and machinery, respectively. A reduction of water application by 326 million cubic meters leads to cost increases by other inputs of US$43.2 million. A "shadow price" for water of US$0.13 per cubic meter can be derived from this analysis.[3] Table 9.7 presents this water shadow price for individual irrigation districts, ranging from US$0.04 to US$0.44 per cubic meter. This variation relates to differences in cropping patterns, net profit per unit area, and per unit of water application by demand site, as shown in Table 9.7. In irrigation sites A3, A5, and A7, the share of low-value crops is higher, but profits per

[3] This value is derived by dividing the cost increases by the amount of water saved.

Table 9.4 Agricultural inputs and net profit, by irrigation demand site, under the Baseline scenario

		Demand site								
Input	**Unit**	**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**Basin**
Water	(million cubic meters)	664	244	382	15	476	47	17	168	2013
	(cubic meters per hectare)	15,415	15,298	16,351	14,190	15,869	15,201	15,782	14,486	15,580
Irrigation investment	(million U.S. dollars)	12.1	4.3	5.1	0.3	6.9	0.9	0.2	3.5	33.2
	(U.S. dollars per hectare)	280	272	217	241	230	275	150	305	257
Fertilizer	(million U.S. dollars)	7.4	2.7	3.7	0.2	4.8	0.5	0.1	1.7	21.1
	(U.S. dollars per hectare)	172	167	157	169	159	168	129	149	163
Pesticide	(million U.S. dollars)	5.2	2	2.3	0.1	3.1	0.4	0.1	1.4	14.6
	(U.S. dollars per hectare)	122	124	100	107	103	124	72	121	113
Seed	(million U.S. dollars)	6.9	2.4	3.3	0.2	4.3	0.5	0.1	1.5	19.3
	(U.S. dollars per hectare)	161	153	140	182	144	156	120	131	149
Labor	(million U.S. dollars)	38.1	14.6	14.7	0.7	19.7	2.9	0.4	10.3	101.4
	(U.S. dollars per hectare)	884	917	629	679	658	931	335	885	785
Machinery	(million U.S. dollars)	15.9	6	8.8	0.3	11	1.2	0.3	4.5	48.1
	(U.S. dollars per hectare)	370	379	378	327	368	378	265	383	372
Net profit	(million U.S. dollars)	34.9	13.1	13	0.6	17.9	2.6	0.3	10.5	93.0
	(U.S. dollars per hectare)	810	822	555	622	598	830	282	905	720

Table 9.5a Changes in agricultural inputs and net profits, by irrigation demand site under the Full optimization scenario compared with the Baseline scenario

		Demand site								
Input		**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**Basinwide**
Water	(million cubic meters)	78.0	38.0	68.0	3.0	89.0	7.0	4.0	14.0	301.0
	(cubic meters per hectare)	343.0	356.0	661.0	622.0	820.0	395.0	978.0	117.0	512.0
Irrigation investment	(million U.S. dollars)	2.0	1.0	1.1	0.0	1.3	0.1	0.0	0.5	6.2
	(U.S. dollars per hectare)	20.0	22.0	18.0	5.0	13.0	22.0	–7.0	14.0	17.0
Fertilizer	(million U.S. dollars)	2.4	0.8	1.0	0.0	1.2	0.2	0.1	0.5	6.2
	(U.S. dollars per hectare)	37.0	29.0	19.0	35.0	19.0	31.0	–1.0	25.0	27.0
Pesticide	(million U.S. dollars)	0.8	0.3	0.3	0.0	0.3	0.0	0.0	0.2	2.0
	(U.S. dollars per hectare)	6.0	3.0	–2.0	3.0	–2.0	5.0	–13.0	8.0	3.0
Seed	(million U.S. dollars)	3.2	1.2	1.3	0.1	1.8	0.2	0.1	0.6	8.3
	(U.S. dollars per hectare)	53.0	47.0	34.0	56.0	36.0	48.0	15.0	37.0	43.0
Labor	(million U.S. dollars)	13.0	5.4	3.7	0.2	5.5	1.0	0.0	3.6	32.4
	(U.S. dollars per hectare)	202.0	193.0	65.0	73.0	85.0	195.0	14.0	230.0	145.0
Machinery	(million U.S. dollars)	3.2	1.4	2.6	0.1	3.1	0.2	0.1	0.9	11.5
	(U.S. dollars per hectare)	35.0	30.0	53.0	31.0	49.0	28.0	61.0	50.0	43.0
Net profit	(million U.S. dollars)	3.4	1.8	1.9	0.2	2.5	0.3	0.1	0.9	11.0
	(U.S. dollars per hectare)	4.0	7.0	9.0	34.0	6.0	–1.0	4.0	10.0	3.0
Total cost[a]	(million U.S. dollars)	24.6	10.1	10.0	0.4	13.2	1.7	0.3	6.3	66.6

[a]Excludes water cost.

Table 9.5b Percentage change in agricultural inputs and net profits, by irrigation demand site, under the Full optimization scenario compared with the Baseline scenario

		Demand site								
Input		**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**Basinwide**
Water	Total	11.7	15.6	17.8	20.0	18.7	14.9	23.5	8.3	15.0
	Per hectare	2.2	2.3	4.0	4.4	5.2	2.6	6.2	0.8	3.3
Irrigation investment	Total	16.5	23.3	21.6	0.0	18.8	11.1	0.0	14.3	18.7
	Per hectare	7.1	8.1	8.3	2.1	5.7	8.0	–4.7	4.6	6.6
Fertilizer	Total	32.4	29.6	27.0	0.0	25.0	40.0	97.2	29.4	29.4
	Per hectare	21.5	17.4	12.1	20.7	11.9	18.5	–0.8	16.8	16.6
Pesticide	Total	15.4	15.0	13.0	0.0	9.7	0.0	0.0	14.3	13.7
	Per hectare	4.9	2.4	–2.0	2.8	–1.9	4.0	–18.1	6.6	2.7
Seed	Total	46.4	50.0	39.4	50.0	41.9	40.0	99.2	40.0	43.0
	Per hectare	32.9	30.7	24.3	30.8	25.0	30.8	12.5	28.2	28.9
Labor	Total	34.1	37.0	25.2	28.6	27.9	34.5	0.0	35.0	32.0
	Per hectare	22.9	21.0	10.3	10.8	12.9	20.9	4.2	26.0	18.5
Machinery	Total	20.1	23.3	29.5	33.3	28.2	16.7	33.3	20.0	23.9
	Per hectare	9.5	7.9	14.0	9.5	13.3	7.4	23.0	13.1	11.6
Net profit	Total	9.7	13.7	14.6	33.3	14.0	11.5	33.3	8.6	11.8
	Per hectare	0.5	0.9	1.6	5.5	1.0	–0.1	1.4	1.1	0.4
Total cost[a]	Total	28.7	31.6	26.4	22.2	26.5	26.6	25.0	27.5	28.0

[a]Excludes water cost.

Table 9.6a Changes in agricultural inputs and net profits, by irrigation demand site, under the Substitution among water and other inputs scenario compared with the Baseline scenario

		Demand site								
Input		**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**Basinwide**
Water	(million cubic meters)	–88.0	–17.0	–101.0	–1.0	–98.0	–4.0	0.0	–17.0	–326.2
	(cubic meters per hectare)	–1,891.0	–1,362.0	–3,923.0	–991.0	–2,996.0	–1,573.0	–1,181.0	–1,268.0	–2,365.0
Irrigation investment	(million U.S. dollars)	1.5	0.8	0.6	0.0	0.8	0.1	0.0	0.4	4.3
	(U.S. dollars per hectare)	40.0	42.0	37.0	20.0	32.0	43.0	–3.0	36.0	37.1
Fertilizer	(million U.S. dollars)	1.2	0.4	0.3	0.0	0.4	0.1	0.0	0.3	2.6
	(U.S. dollars per hectare)	29.0	23.0	19.0	25.0	17.0	25.0	–3.0	23.0	23.0
Pesticide	(million U.S. dollars)	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.5
	(U.S. dollars per hectare)	8.0	5.0	2.0	3.0	2.0	6.0	–13.0	11.0	5.4
Seed	(million U.S. dollars)	2.1	0.8	0.8	0.1	1.2	0.1	0.1	0.4	5.4
	(U.S. dollars per hectare)	50.0	44.0	42.0	54.0	42.0	45.0	18.0	36.0	44.8
Labor	(million U.S. dollars)	10.8	4.5	2.1	0.2	3.6	0.9	0.0	3.1	25.1
	(U.S. dollars per hectare)	265.0	256.0	114.0	113.0	135.0	263.0	15.0	283.0	205.9
Machinery	(million U.S. dollars)	1.8	0.9	0.7	0.1	1.0	0.1	0.1	0.6	5.2
	(U.S. dollars per hectare)	46.0	42.0	42.0	41.0	42.0	41.0	45.0	61.0	45.3
Net profit	(million U.S. dollars)	–0.3	0.4	0.0	0.1	0.1	0.0	0.0	–0.2	0.0
	(U.S. dollars per hectare)	2.0	7.0	19.0	29.0	14.0	–3.0	–22.0	–2.0	8.2
Total cost[a]	(million U.S. dollars)	17.7	7.5	4.5	0.4	7.0	1.3	0.2	4.9	43.2

[a]Excludes water costs.

Table 9.6b Percentage change in agricultural inputs and net profits, by irrigation demand site, under the Substitution among water and other inputs scenario compared with the Baseline scenario

		Demand site								
Input		**A1**	**A2**	**A3**	**A4**	**A5**	**A6**	**A7**	**A8**	**Basinwide**
Water	Total	–13.3	–7.0	–26.4	–6.7	–20.6	–8.5	0.0	–10.1	–16.2
	Per hectare	–12.3	–8.9	–24.0	–7.0	–18.9	–10.3	–7.5	–8.8	–15.2
Irrigation investment	Total	12.4	18.6	11.8	0.0	11.6	11.1	0.0	11.4	13.1
	Per hectare	14.3	15.4	17.1	8.3	13.9	15.6	–2.0	11.8	14.4
Fertilizer	Total	16.2	14.8	8.1	0.0	8.3	20.0	0.0	17.6	12.5
	Per hectare	16.9	13.8	12.1	14.8	10.7	14.9	–2.3	15.4	14.1
Pesticide	Total	5.8	5.0	0.0	0.0	0.0	0.0	0.0	7.1	3.5
	Per hectare	6.6	4.0	2.0	2.8	1.9	4.8	–18.1	9.1	4.8
Seed	Total	30.4	33.3	24.2	50.0	27.9	20.0	100.0	26.7	28.1
	Per hectare	31.1	28.8	30.0	29.7	29.2	28.8	15.0	27.5	30.0
Labor	Total	28.3	30.8	14.3	28.6	18.3	31.0	0.0	30.1	24.7
	Per hectare	30.0	27.9	18.1	16.6	20.5	28.2	4.5	32.0	26.2
Machinery	Total	11.3	15.0	8.0	33.3	9.1	8.3	33.3	13.3	10.7
	Per hectare	12.4	11.1	11.1	12.5	11.4	10.8	17.0	15.9	12.2
Net profit	Total	–0.9	3.1	0.0	16.7	0.6	0.0	0.0	–1.9	–0.1
	Per hectare	0.2	0.9	3.4	4.7	2.3	–0.4	–7.8	–0.2	1.1
Total cost[a]	Total	20.7	23.4	11.9	22.2	14.1	20.3	16.7	21.4	18.2

[a]Excludes water costs.

unit of area and water are lower than for other irrigation districts, which results in lower shadow prices.

Substituting between Water and One Other Input. Six scenarios are analyzed to assess the substitution between water applied and irrigation investment, labor, machinery, fertilizer, pesticides, and seed, respectively. Under each of these scenarios, the model is run over a series of water charges, ranging from US$0.003 per cubic meter to US$0.022

Table 9.7 Net profit of water, share of low-value crops, and inferred shadow prices of water, by irrigation demand site

Demand site	Net profit per unit area (U.S. dollars per hectare)	Net profit per unit water (U.S. dollars per cubic meter)	Low-value crop area[a] (percent)	Shadow price (U.S. dollars per cubic meter)
A1	810	0.053	0.44	0.20
A2	822	0.054	0.44	0.44
A3	555	0.034	0.64	0.04
A4	622	0.040	0.55	0.40
A5	598	0.038	0.60	0.07
A6	830	0.055	0.43	0.33
A7	282	0.018	0.79	NA
A8	905	0.063	0.34	0.29
Basinwide	720	0.046	0.50	0.13

Note: NA indicates that the GAMS solver could not find a solution.
[a]Low-value crops include wheat, corn, annual forage, and prairie.

per cubic meter. The substitutions between water application and other individual inputs under increasing water charges are plotted in Figure 9.6. The figures show a monotonic substitution relationship between water and the inputs irrigation, investment, labor, machinery, and pesticides, respectively. Whereas water and fertilizer have a complementary relationship, the relationship between water and seed is more complex. At a water price range of US$0.003–0.013 per cubic meter, water and seed are substitutes; beyond this range, water and seed are complements. This shows the possibility of dynamic relationships between water and other inputs under different economic instruments.

It can be noted that the model with the crop yield function reflecting the water–salinity–irrigation technology relationship shows that irrigation water withdrawals do not change significantly when water fees increase from 0 to US$0.08 per cubic meter (see Table 5.13), which is not consistent with the changes of irrigation water application shown here. It should be noted, however, that results in Table 5.13 are based on fixed irrigation technology (and fixed irrigation water salinity) and that water is not allowed to be substituted with irrigation technology, whereas the results shown in Figure 9.6 are based on substitutions between water and specific other agricultural inputs, which allows more flexibility for changes in water use when water prices change.

Summary

There are two major differences between the model applied to the analysis of this chapter and those in other chapters. First, the model here uses an alternative, quadratic crop-yield function, which is described in Chapter 3; second, the model is calibrated to the baseline level and represents a positive model, which is more appropriate for the substitution analysis presented in this chapter.

Figure 9.6a Relationship between water application and irrigation investment under changing water prices

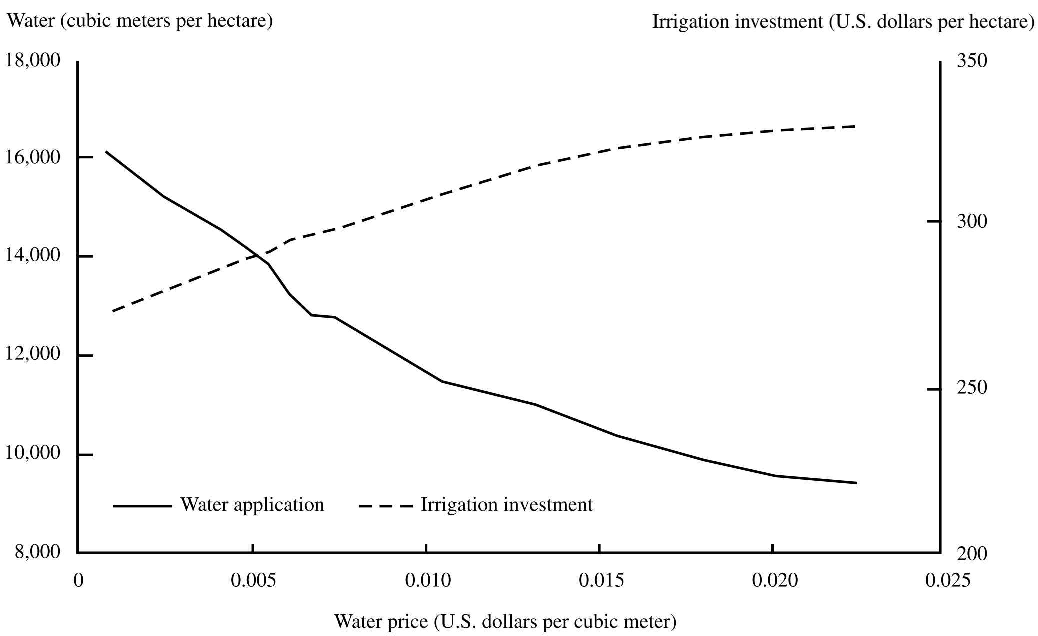


Figure 9.6b Relationship between water application and labor cost under changing water prices

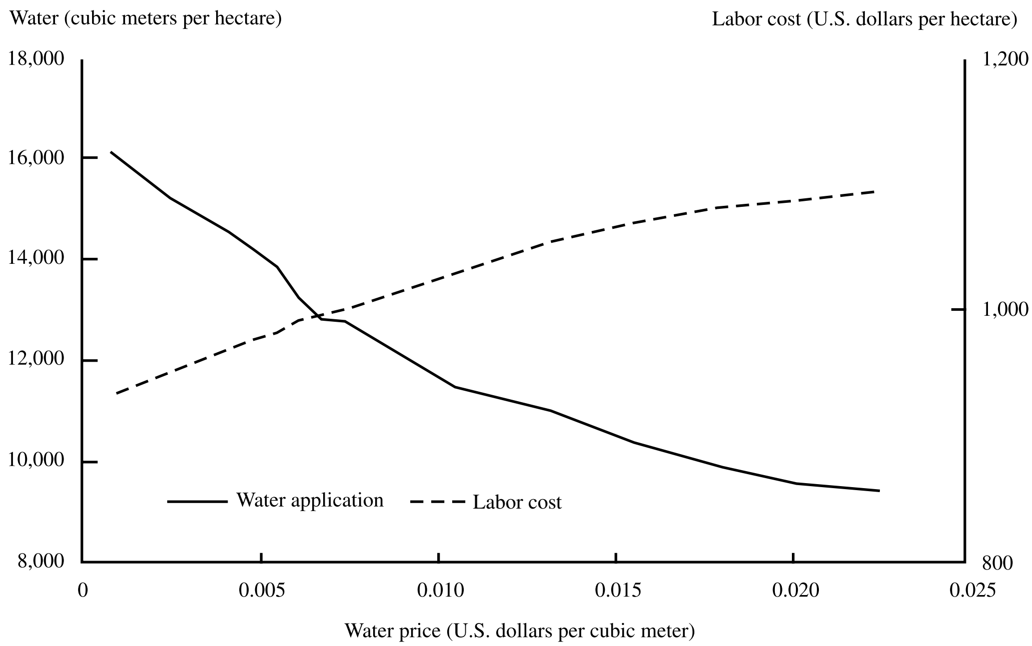


Figure 9.6c Relationship between water application and machinery cost under changing water prices

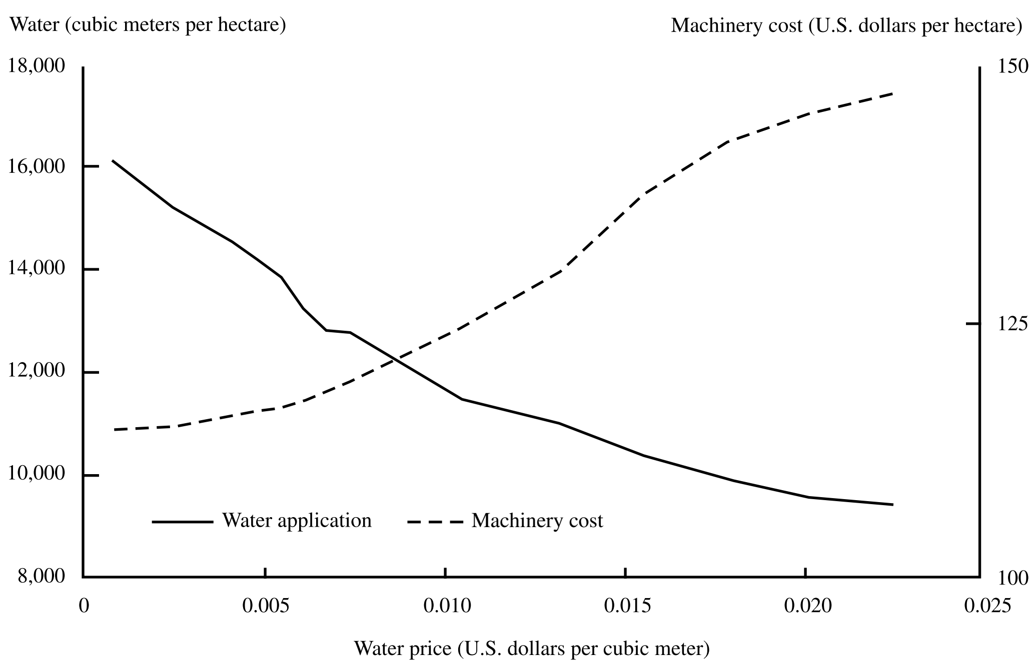


Figure 9.6d Relationship between water application and fertilizer cost under changing water prices

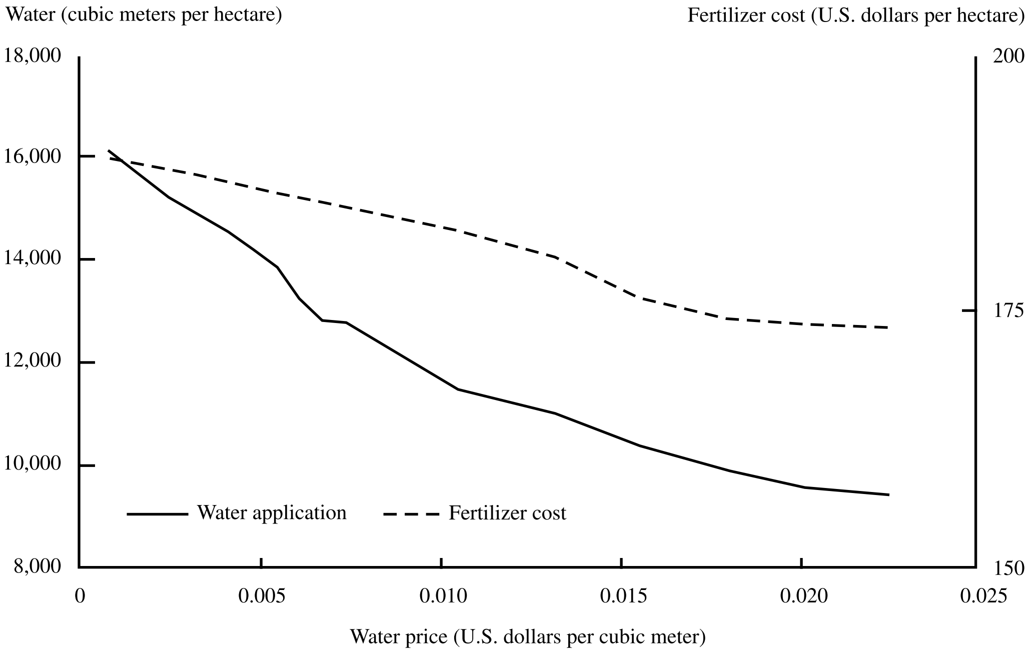


Figure 9.6e Relationship between water application and pesticide cost under changing water prices

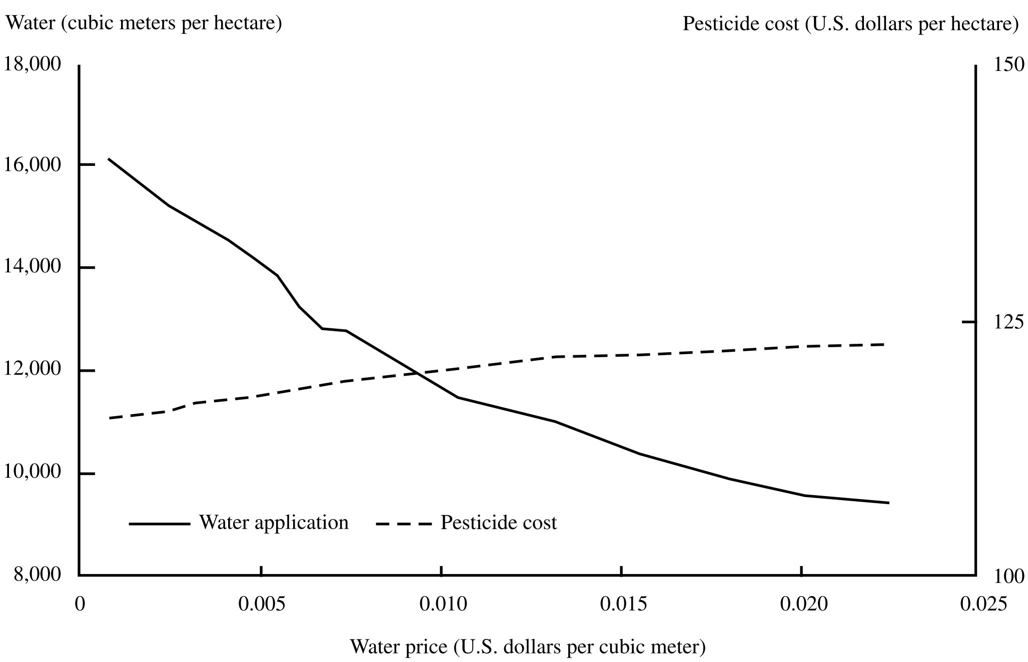
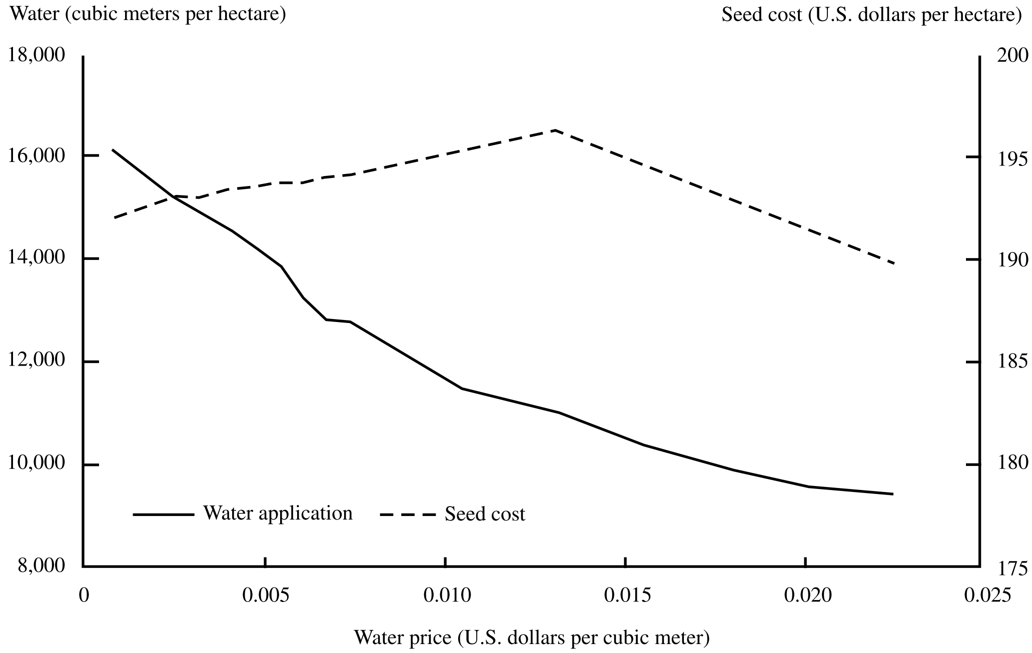


Figure 9.6f Relationship between water application and seed cost under changing water prices



This chapter explores the potential substitutions between water and other agricultural inputs through an integrated hydrologic–economic modeling framework. Compared with the multi-input–multi-output production framework, the modeling framework used here represents essential hydrologic and environmental relations determining both water supply and demand endogenously, which allows a more detailed substitution analysis between water and other inputs.

Findings based on several model scenarios indicate that the shift from a baseline scenario to full basin optimization leads to increasing use of all inputs. A tradeoff between additional water use of 301 million cubic meters and additional net profits of US$11.0 million was calculated. Potential adverse environmental impacts would also need to be accounted for in this tradeoff, including reduced environmental flows, and additional applications of fertilizer and pesticides. Under the economic incentives scenario (representing an increase in water prices by a factor of eight), a reduction in water withdrawals by 326 million cubic meters is traded for other additional inputs that cost US$43.2 million while the total profit of the basin is maintained at the baseline level. Substitutions between water and other crop inputs vary substantially by irrigation district, depending on the relative cropping patterns and crop profitability with respect to water and land use. For those demand sites with a high fraction of low-value crops, the cost per unit of water saving through the substitution is lower than that at other demand sites. At the basin level, when water is substituted with a single other crop input (keeping other inputs fixed), irrigation investment, labor, machinery, and pesticide use each rise, whereas fertilizer use falls. Seed can substitute for water when water prices are low, and it can complement water application when prices are higher.

CHAPTER 10

Conclusions and Recommendations

Today we are faced largely with a “mature” water economy (Randall 1981), and most research is conducted with an explicit recognition and focus on coping with resource limits. Most recent work under this framework has been motivated by expanding municipal demands within a context of static or more slowly growing agricultural demand. More recently, expanding instream environmental demands have been added. On the supply side, conjunctive use of surface water and groundwater has been considered in addition to simple limits on surface water availability. In addition, research increasingly focuses on waterlogging and water quality (primarily salinity) effects. The work presented in this report examines a complex water economy: one in which demands grow differentially not only within sectors but also between sectors, and one in which limited opportunities exist for increasing consumptive use. In particular, the growth of high-value irrigated crop production (for example, table grapes) within the case study basin (the Maipo River Basin in Chile) together with the rapidly growing urban area provides a rich context in which the general problem of basin-level water resources management can be examined.

Following the literature review on integrated basin-scale water resources management modeling (McKinney et al. 1999), this report presents the methodology and application of an integrated hydrologic–economic river basin model. The methodology presented is simulation with embedded optimization. Basinwide simulation of flow and salinity balances and crop growth are embedded within the optimization of water allocation, reservoir operation, and irrigation scheduling. The model’s main advantage lies in its ability to reflect the interrelationships among essential hydrologic, agronomic, and economic components and to explore both economic and environmental consequences of various policy choices. The modeling framework is developed based on a river basin network, including multiple source nodes (reservoirs, aquifers, river reaches, and so on) and multiple demand sites along the river, such as consumptive use locations for agricultural, municipal and industrial (M&I), and instream water uses. Economic benefits to water use are evaluated for different demand management instruments, including markets in tradable water rights, based on production and benefit functions with respect to water for the agricultural and urban-industrial sectors. Thus, the model can be used as a decision-support tool to assist water management authorities and policymakers in the choice of appropriate water policies and in the establishment of priorities for reform of institutions and incentives that affect water resource allocation. Moreover, this modeling framework relies on multiple techniques, such as hydrologic modeling, spatial econometrics, geographic information system (GIS), and large-scale systems optimization, among others. Although these techniques have been adapted in other studies, this study represents a new effort to bring them to bear in an integrated fashion in analyzing water management in a river basin context.

The Maipo River Basin in Chile is chosen as the case study site because of (1) increasing demands and increasing competition among the major water-using sectors of agriculture, urban areas, and industries; (2) growing concerns over how these demands can be met in an efficient, equitable, and sustainable manner; (3) increasing concerns over water pollution from agricultural, urban, and industrial users; and (4) advanced water management and allocation policies in the basin, including markets in tradable water rights. Different from previous economic studies, this study combines economic relationships and water management institutions with a reasonably detailed physical setting, which depicts the basin hydrology, water supply facilities, water availability and water quality, and water use systems.

The model is applied to the Maipo Basin to address site-specific research questions regarding several important policy aspects of basin management. The report demonstrates that the modeling framework developed is effective in analyzing various policy instruments for water demand management in the Maipo River Basin. The policy findings are summarized in the following.

Findings from the Case Study Basin

Policy Implications of Full Optimization

Under full basin optimization, assuming an omniscient decisionmaker with perfect foresight optimizing the entire water-related basin economy, and under current irrigation system and water supply charges, crop area in the basin can increase by 15 percent, with an increase of up to 50 percent in high-value crops and a decline of 40 percent of low-value crops, such as maize and annual prairie, in terms of total crop revenue; under this scenario, total agricultural water withdrawal is slightly above estimates by local experts, whereas domestic and industrial withdrawals almost double.

A series of sensitivity analyses for changes in hydrologic inflows, crop prices, source salinity levels, and water prices show that, in general, agricultural water withdrawals are more sensitive to changes in these parameters than are domestic and industrial withdrawals. Of particular importance for farm incomes, proportional changes over all crop prices in the range of ±25 percent have only small effects on irrigation water withdrawals but large effects on farmers' profits. Doubled source salinity will influence cropping patterns in the basin, with a decline in the harvested area of crops with lower salt tolerance. A doubling of water prices will reduce agricultural withdrawals by 10 percent but will not affect M&I withdrawals, but profits from both agriculture and M&I will decline significantly.

Policy Implications from Water Rights Trading

Water rights trading can support water to move into higher-value domestic and industrial uses without adversely affecting farm incomes. In fact, net farm incomes can increase substantially if water rights trading is allowed. When water rights are traded, declines in agricultural production are small, while the economic efficiency of water use increases. Net benefits for some irrigation districts can be even larger than under full basin optimization, where no restrictions or water institutions are assumed, as farmers can reap substantial benefits from selling their unused water rights to M&I areas during the months with little or no crop production. The benefits from water rights trading can be significantly enhanced when transaction costs are reduced—both the volume of water traded and the benefits from trading increase.

Moreover, a shift from fixed to tradable water rights can lead to substantial gains in economic efficiency without any changes in physical irrigation efficiency levels. Tradable water rights induce improvements in physical efficiency as it becomes more profitable for farmers to invest in improved irrigation technologies and to sell their surplus water to urban areas.

Policy Implications for Irrigation Efficiency at the Irrigation System and Basin Level

Physical efficiency alone is not a strong predictor for the net benefit of water use or economic efficiency, as changes in water allocation institutions alone, for example, in the form of tradable water rights, can result in larger net benefits of water use without the need to change physical settings affecting irrigation efficiency.

Economic incentives, for example, in the form of water fees, can increase instream flows, as withdrawals for less valuable crops are reduced. However, increased physical irrigation system efficiency can negatively affect instream flows as water consumption may increase, even though actual water withdrawals may decline. Moreover, although some water allocation mechanisms, such as fixed water rights, can help protect instream flows, because the economic efficiency principle is typically not fully realized for offstream uses, the ideal strategy would be to determine the value of these uses and reflect such values in marketable water rights, thereby taking these uses explicitly into account in the determination of optimal water allocation strategies.

Allowing for changes in irrigation technologies can generate large economic gains in irrigated agriculture and simultaneously increase physical efficiency levels. Physical improvements in both the conveyance system and on-farm irrigation technology can increase physical efficiency substantially, but this is warranted from an economic point of view only as long as the marginal benefits of additional water use are larger than the marginal costs of additional improvements.

Higher water charges result in higher basin irrigation efficiency, as farmers reduce water use, shift from lower-valued to higher-value crops, and shift to higher levels of irrigation technology for some crops. Moreover, the improvement of physical structures can strengthen the effectiveness of water prices, but incentive prices have little effect on physical efficiency at low levels of infrastructure development. Farmer incomes (and total basin profits) decline with increased water fees when water cannot be allocated or sold to higher-valued uses, an outcome reflected in the model results. At higher levels of local infrastructure development, the contribution to basin efficiency from water demand management will be more significant.

There are large gains to be made through increasing local system efficiency. Effective efficiency is higher than local irrigation efficiency at the system level, and overall basin efficiency is higher than efficiency levels at individual demand sites, with the difference depending on the amount of return flows relative to withdrawals. Thus, the potential for water savings from increases in water use efficiency in irrigation in a basin context is lower than individual system efficiencies might indicate. However, within a significant range, local efficiency improvement does improve basinwide economic efficiency. Only once local efficiency reaches a fairly high level will the contribution to basin profits from further improvements in local efficiency be minimal.

Basins typically fall into one of three situations regarding water scarcity and basin efficiency. At low water availability compared with demand, basin efficiencies tend to be high, the marginal value of water large, and additional water sources, such as water transfers from other basins, or infrastructure development to store water, can be attractive from an economic point of view. Furthermore, as the cost for infrastructure improvement measures increases rapidly after a certain (high) level of physical irrigation efficiency has been reached, the cost factor could become the major constraint for improving economic efficiency of water use through structural investments. Thus, in highly developed river basins where the costs of physical improvements are very large, meeting future water demands will require a shift toward nonstructural measures that enhance both economic and physical water use efficiencies.

At high water availability compared with demand, possibly excessive water withdrawals can be reduced to more optimal levels through incentive prices, which can result in both higher physical efficiency and higher economic efficiency. At points between severe water scarcity and abundance, water use profits can be increased with increased withdrawals, while basin irrigation efficiency and profit per unit of water decline only slightly. In this range, a combination of appropriate physical and nonstructural improvements can enhance both physical and economic efficiency.

Policy Implications for Irrigation Technology Choice

Increasing water stress in agriculture and increasing environmental and financial costs for water supply development require increasingly careful irrigation technology choices. Irrigation technology choices depend on many factors. In this report we show that, for the Maipo River Basin, water fees and water quality (in the form of salinity in the irrigation water) can significantly influence outcomes for investments in field irrigation technology. We also present a detailed analysis of the effects of hydrologic uncertainty on irrigation technology choice. Major policy conclusions include:

- Higher levels of irrigation technology are more profitable for higher-value crops; meanwhile, decisions on irrigation technology choice for low-value crops are less sensitive to hydrologic uncertainties.
- Without perfect information regarding future hydrologic uncertainties, a higher level of irrigation technology than that resulting from an average deterministic model may be more profitable.
- For the case of the Maipo River Basin, the annualized capital cost per hectare should be within a range of US$105–130, which is the range for tradeoff analysis between maximizing the expected profit and minimizing the risk of profit loss under drought conditions.

Policy Implications for Substitution among Water and Other Crop Inputs

The shift from a baseline scenario, which is calibrated to actual conditions, to full basin optimization leads to increasing use of those inputs that are complementary to water, in particular, seed and labor. However, this result does not take the environmental value of water explicitly into account. The tradeoff here is between additional water use of 301 million cubic meters and additional net profits of US$11.0 million; an additional concern is the possible negative effect on the environment from additional use of fertilizers and pesticides.

Under economic incentives (represented as an increase in water fees by a factor of eight), a reduction of water withdrawals by 326 million cubic meters is traded off with costs of US$43.2 million for other crop inputs, particularly seed and labor, that will ensure that profits can be maintained. Substitutions between water and other crop inputs vary substantially by irrigation district, depending on the relative cropping patterns, net profit per unit area, and net profit per unit of water application. Substitutions between water and other inputs are also related to the current levels of different inputs. If economic incentives change, the relationship between water and other inputs may move from substitute to complement or vice versa.

Concerns Related to Modeling Techniques

The report uses two different crop-yield functions. One crop-yield function includes water application, irrigation water salinity, and field irrigation technology as variables; the other is based on agricultural inputs including water, irrigation investment, fertilizer, pesticides, labor, machinery, and seed.

Both functions are based on regression analysis, but they use different methodologies. The first function is developed from a water-salinity–crop simulation model, whereas the second uses samples from a field survey. One model formulation is applied for normative analysis, addressing what might be the best solution, whereas the second formulation is calibrated for positive analysis, based on which policy instruments can be applied to analyze solutions that differ from the baseline. In this study, the water-salinity-technology formulation is applied for most of the analyses, whereas the yield function based on agricultural inputs is applied for substitution analysis. The results from these alternative techniques differ in terms of, for example, the role of water fees.

It should be emphasized that river basin management is too complex to identify one particular formulation as being ideal. Therefore, the formulation of a basin management model should always relate to the particular problem at hand; and model solutions need to be considered as one and not the exclusive source of information for possible pathways of reform or action.

Any model will raise the question of whether sufficient components of the real world are included or reflected in the modeling framework. This question relates to scale, science policy, and modeling techniques. Obviously, emerging policy issues in river-basin management call for solid and integrated information from various sciences (such as hydrology, agronomy, and environmental sciences) and for the application of various modeling techniques, including simulation and optimization.

The model developed and applied for this study presents a framework for water allocation among sectors and among demand sites; water allocation among instream ecological water demand and off-stream demand is not explicitly studied because valuation of environmental water demand is highly complex in the Maipo Basin and elsewhere. The introduction of such a function in the future will be valuable for water resource management in many basins, given the increasing conflict among ecological water requirements and off-stream water consumption.

Future Work

Future research should include extension of the model formulation and its application. The model formulation can be extended in the following aspects:

- Adding a component of land management and developing an integrated land and water management framework, which can include land use benefits from nonagricultural uses and the hydrological effects of various land uses.
- Adding a representation of instream flow requirements, including flow regimes needed by riverine ecosystems and environmental benefits.
- Adding a decision framework to account for the objectives of individual demand sites in addition to the objective of the whole basin as represented currently in the model.
- Extending the current short-term analysis to a long-term analysis, reflecting the socioeconomic dynamics and cumulative environmental effects.
- Coupling the model with a regional macroeconomic model (for example, a computable general equilibrium model [Diao and Roe 2000]) to incorporate the basin model into a macroeconomic framework.

Although several model applications have been presented in this report, they are still limited regarding the many important water research questions that need to be addressed in today's water-scarce economies. For example, the model can be used to support macroeconomic analysis. In many countries, a larger share of the water may be preserved for environmental use to benefit global biodiversity. Or, water used in crop production can be exported to other markets. Similarly, the model can be used to analyze nonstationarity such as that in water availability, demand, and changing preferences. More specifically, the model can be used to simulate the effects of population growth, changes in tax/subsidy policies (for example, crop subsidies), variation in water availability, and shifts in cropping patterns from exogenous factors (for example, a new export initiative, a global trade agreement, or the creation of new markets).

APPENDIX A

Model Formulation

Indexes and Sets

Indexes

pd	time periods (month)
rn	river reaches
un	upstream river reaches
ln	downstream river reaches
rv	reservoirs
ur	upstream reservoirs
lr	downstream reservoirs
gw	groundwater aquifers
pw	power stations
d	demand sites, including irrigation sites and municipal and industrial sites
cp	crop types

Links in the Network Representation of the River Basin System

RVLINK(un, rn)	river reaches to river reaches
NDLINK(rn, d)	river reaches to demand sites
DNLINK(d, rn)	return flow from demand sites river reaches
NRLINK(rn, rv)	river reaches to reservoirs
NPLINK(rn, pw)	river reaches and power stations
RDLINK(rv, d)	reservoirs to demand sites
RNLINK(rv, rn)	reservoirs to river reaches
RPLINK(rv, pw)	reservoirs and power stations
RRLINK(ur, rv)	reservoirs to reservoirs
GWDLINK(gw, d)	aquifers to demand sites
GWRLINK(gw, rn)	aquifers to river reaches

Crop Irrigation Period Definition

CP_PD(cp, pd)	crop types and irrigation periods

Crop Patterns in Each Demand Site

DEM_CP(d, cp)	demand sites and crop types

Data List

Source Data

source(rn, pd)	inflow to river reaches
locs(d, pd)	local sources (mainly groundwater, also ponds, etc.)
er(d, cp, pd)	effective rainfall
er_sn (d, cp)	effective seasonal rainfall
cs(rn)	salt concentration in inflow
cls(d)	salt concentration in local source
rechg(gw, pd)	groundwater recharge
crehg(gw)	salt concentration in natural recharge

Reservoir Data

r_up(rv)	maximum active reservoir storage
r_evap(rv, pd)	reservoir surface evaporation rate
a(rv), b(rv), c(rv)	reservoir topologic quadratic relationships (volume vs. area)
d(rv), e(rv), f(rv)	reservoir topologic quadratic relationships (volume vs. elevation)

Groundwater Data

gwa(gw)	surface area of aquifer
kh(gw)	saturated hydraulic conductivity
s(gw)	aquifer yield
mih(gw)	aquifer bottom elevation
mah(gw)	maximum allowed water table
trans(gw)	transmissivity coefficient

Hydropower Station Data

pwst_cp(pw)	power production capacity
pwst_te(pw)	average tailwater elevation (for stations with reservoirs)
pwst_ef(pw)	production efficiency
pwst_cf(pw)	power generation coefficient (for run-of-river stations)
pprice(pw)	power selling price
pcost(pw)	power generation cost

Water Delivery Data

ridm_cp(rn, d)	water delivery capacity
runoff(rn, d)	runoff coefficient in irrigation field
rtn_loss (d)	seepage, evaporation, etc., of return flow
rwru (d)	ratio of reuse water to total return flow
loss (d)	water delivery loss (in canals, etc.)
maxflow(rn, pd)	maximum allowed flow at a river node
minflow(rn, pd)	minimum required flow at a river node
pump_mcap(d)	groundwater pump capcity to municipal demand sites
pump_icap(d, cp)	groundwater pump capacity to irrigation
req_fl(pd)	minimum required downstream flow

Crop Data

b1(d, cp)–b9(d, cp)	crop production regression function coefficients based on crop yield and water-irrigation technology-salinity simulations (see the production equation in the equation description part)
etm(d, cp)	potential crop evapotranspiration, (can be calculated according to the FAO-24 method, based on temperature, relative humidity, wind speed, regional adjusting coefficient, and crop evapotranspiration coefficients)
miw(cp)	minimum required water for crop growth
ep(d)	pan evaporation
pm(d, cp)	max crop yield
ky(cp, pd)	Food and Agriculture Organization of the United Nations (FAO) crop yield response coefficient
kc(cp, pd)	crop evapotranspiration coefficient
tarea(d)	total available planting area

Municipal Water Use Data

mwd(d, pd)	maximum water diversion
comsp(d)	ratio of consumptive use
cm(d)	salt concentration in municipal discharge

Initial Hydrologic Condition

rev_st0(rv)	initial reservoir storage
h0(rv)	initial reservoir surface elevation
gwh0(gw)	initial water table

Economic Data

$p_0(d)$	marginal value of water in municipal demand sites
$\alpha\ (d)$	elasticity of demand for water in municipal demand sites
tc (d, cp)	irrigation technology cost
fc (d, cp)	fixed cost for crop planting
p(d, cp)	crop selling price
tranc	transaction cost in water trading
wps (d)	surface water price
wpg (d)	groundwater price

Decision Variables

rev_dem(rv, d, pd)	water delivered to each demand site from reservoirs
rev_rn(rv, rn, pd)	water released from reservoirs to river reaches
rev_rev(rv,rv,pd)	release from one reservoir to its downstream reservoir
rn_dem(rn, d, pd)	water delivered to each demand site from river reaches
wreu (d, cp, pd)	drainage reuse for each crop at each demand site in each month
pump(gw, d, cp, pd)	groundwater pumping to each crop in each growth month
pumpm(d, pd)	groundwater pumping to municipal demand sites in each month
acp(d, cp)	irrigated area for each crop at each demand site
tek(d, cp)	irrigation technologies for each crop at each demand site
wl(d, pd)	water sold by demand sites in periods

wb(d, pd)	water bought by demand sites in periods
wtp	water trading price

State or Intermediate Variables

obj	objective variable (see objective function)
arval(d)	profit from irrigation demand sites
muval(d)	profit from municipal demand sites
flow(rn, ln, pd)	flow from a river node to a downstream river node
rn_rev(rn, rv, pd)	flow from a river node to a reservoir
rev_st(rv, pd)	reservoir storage
h(rv, pd)	reservoir surface elevation
area(rv, pd)	reservoir surface area
power(pw, pd)	power generation at each station in each month
tot_inf(d, pd)	total water diverted to a demand site including local source
wcp(d, cp, pd)	water applied to each crop, excluding effective rainfall
twacp(d, cp, pd)	water available to each crop, including effective rainfall and reuse
ws(d, pd)	total surface water withdrawal to a demand site
wg(d, pd)	total groundwater water withdrawal to a demand site
y(d, cp)	crop yield (tons per hectare)
eta_sn(d, cp)	seasonal actual crop evapotranspiration
dp_sn(d, cp)	seasonal deep percolation
eta_stg(d, cp)	stage actual crop evapotranspiration
dp_stg(d, cp)	stage deep percolation
srw(d, cp)	seasonal relative water to pan evapotranspiration
dft(d, cp, pd)	stage crop yield deficit, defined in FAO-33
mdft(d, cp)	max yield deficit among stages
effi(d, cp)	irrigation application efficiency, assumed the same for all stages
rflow (d, pd)	return flow from demand site to river reaches
sepg(d, pd)	seepage from municipal and industrial demand sites
dischg(gw, rn, pd)	groundwater discharge to river reaches
gwh(gw, pd)	groundwater water table
cn(rn)	annual average salt concentration in river reaches
cg(gw)	annual average salt concentration in aquifers
cr(rv)	annual average salt concentration in reservoirs
cwcp(d)	seasonal average salt concentration in diverted water
cwacp(d, cp)	seasonal average salt concentration in water application
cdp(d, cp)	seasonal average salt concentration in deep percolation
crt(d)	annual average salt concentration in return flow

Other intermediate variables are defined with equations in the following.

Variable Bounds

Lower and upper bounds are specified for some decision/state variables. They include, for example, the minimum required irrigated area for a crop in a demand site, upper bound for reservoir storage, power generation capacity limit, and irrigation application ranges. In the model implementation in the GAMS language, some variable bounds are specified for mathematical requirements, for example, the divisors should not equal zero.

Model Formulation

Objective Function

$$Max\ Obj = \sum_{irr-d} VA^d + \sum_{mun-d} VM^d + \sum_{pw} VP^{pw} - wgt \cdot PENALTY, \quad (A.1)$$

where *VA* is the profit from irrigation (equation A.4), *VM* is the profit from municipal and industrial (M&I) water uses (equation A.9), *VP* is the profit from power production (equation A.16), *wgt* is the weight for the penalty, and *PENALTY* is the penalty item, which is calculated as:

$$PENALTY = \sum_{d} \sum_{cp} pm^{cp} \cdot p^{cp} \cdot (mdft^{d,cp} - adft^{d,cp}), \quad (A.2)$$

where *mdft* is the maximum stage deficit within a crop growth season (equations A.43 and A.44) and *adft* is the average stage deficit within a crop growth season (equation A.45), with

$$dft = ky \cdot (1 - E_a/E_{\max}), \quad (A.3)$$

where *dft* is the stage deficit; *ky* is the yield response factor; and E_a is the actual evapotranspiration (millimeters), as defined in Doorenbos and Kassam (1979).

Profit Calculation in an Irrigation Demand Site

The function for profits from irrigation (*VA*) is specified as follows:

$$VA^d = \sum_{cp} ACP^{d,cp} Y^{d,cp} p^{d,cp} - \sum_{cp} ACP^{d,cp}(fc^{d,cp} + tc^{d,cp}) - \sum_{pd} (ws^d_{pd} \cdot wps^d + wg^d_{pd} \cdot wpg^d), \quad (A.4)$$

in which

$$tc = \mathrm{k}_0 \cdot 10^{(-\mathrm{k}_1 \cdot tek)}, \quad (A.5)$$

where the crop yield is calculated as a function of seasonal relative water (to maximum crop evapotranspiration), salinity in irrigation water, and irrigation technology. Equation A.5 calculates the cost for irrigation technology following Dinar and Letey (1996). Irrigation technology is represented by the Christiansen Uniformity Coefficient (CUC), and k_0 and k_1 are regression coefficients.

The concept of CUC is explained in the following. A field is apportioned to *N* plots. The infiltrated water at any location on the field, *W*(*n*), can be related to the average water application, $\overline{W}$, on the field, that is,

$$W(n) = \beta(n) \cdot \overline{W}, \quad (A.6)$$

where β(*n*) is a random parameter whose distribution over the field might be associated with the irrigation technology system existing in the field. Letey, Vaux, and Feinerman (1984) assume that β(*n*) has a finite number (*N*) of distinct values, $\beta_1, \beta_2, \ldots, \beta_N$. The fractional area of the field (A_n) in which $\beta = \beta_n$ is equal to the probability that $\beta = \beta_n$. Based on this assumption, CUC can be represented as:

$$CUC = 100 \cdot \left(1 - \frac{\sum |W_n - \overline{W}|}{\sum W_n}\right). \quad (A.7)$$

Crop Yield Function

$$\begin{aligned} y^{d,cp} = {} & pm^{d,cp} \cdot [b1^{d,cp} + b2^{d,cp}] \cdot tek^{d,cp} \\ & + b3^{d,cp} \cdot srw^{d,cp} + b4^{d,cp} \cdot salt^{d,cp} \\ & + b5^{d,cp} \cdot srw^{d,cp} \cdot salt^{d,cp} \\ & + b6^{d,cp} \cdot srw^{d,cp} \cdot salt^{d,cp} \\ & + b7^{d,cp} \cdot \ln[srw^{d,cp}] \\ & + b8^{d,cp} \cdot \ln[srw^{d,cp}] \cdot tek^{d,cp} \\ & + b9^{d,cp} \cdot \ln[srw^{d,cp}] \cdot salt^{d,cp}. \end{aligned} \quad (A.8)$$

This regression function has been determined based on a crop simulation model adapted from Letey and Dinar (1986; see also Dinar and Letey 1996). The input parameters to the model are presented in Table B.1. The model was run for various combinations of water (*srw*), salinity (*salt*), and irrigation technology (*tek*). The outputs (crop yield) together with the inputs were used to determine the regression coefficients (*b*1–*b*9). The regression coefficients for 15 irrigated crops in the Maipo River Basin are presented in Table B.8 of Appendix B.

Municipal and Industrial Water Use Benefit Function

The benefit from industrial and municipal water uses is expressed as:

$$VM^d = wm_0 p_0^d/(1 + \alpha)\,[(wm^d/wm_0^d)^\alpha + 2\alpha + 1] - wm^d \cdot wp^d, \qquad \text{(A.9)}$$

in which wm is the actual municipal and industrial water use, and wm_0 is the normal municipal and industrial water use. Note that groundwater use is not included in this equation.

The following steps were undertaken to derive the benefit function for M&I demand sites. The function is derived from an inverse demand function of the Cobb-Douglas form and includes the following assumptions:

- elasticity of demand is –0.45,
- willingness to pay for water at full use is US$0.35 per cubic meter, and
- water is more valuable in M&I demand sites: the per-unit value of water for M&I is 3.5 times the per-unit value in agriculture.

The inverse demand function is (see also Booker and Colby 1995):

$$p = p_0(wm/w_0)^\alpha \quad \text{for } 0 \le wm \le wm_0, \qquad \text{(A.10)}$$

in which p_0 is the willingness to pay for additional water at full use, e is the price elasticity of demand, and $\alpha = 1/e$.

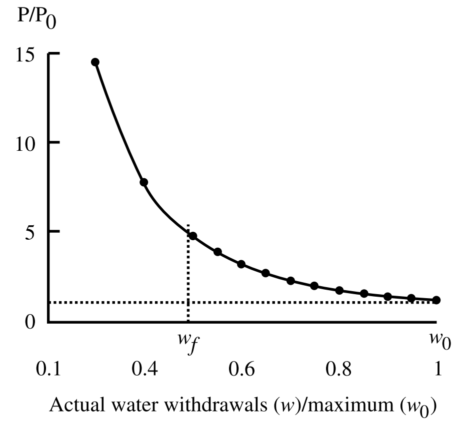
The benefit of water use, wm, is found directly by integration of A.10:

$$V = \int p_0(wm/wm_0)^\alpha dx = w_0 p_0(wm/wm_0)^\alpha/(1 + \alpha) + C, \qquad \text{(A.11)}$$

in which C is a constant.

To determine the constant in equation A.11, a reference point in the curve of the inverse demand function needs to be defined (equation A.10 and Figure A.1). Water withdrawals at this reference point are defined as w_f. If water use profits $V(wm)$ are zero at the reference point, $V(wm_f) = 0$, then at points where $wm > wm_f$, $V(wm) > 0$, $V(wm)$ represents the absolute value of the M&I water use benefit in the model.

Figure A.1 Price versus water withdrawal



To determine the reference point, wm_f, the relative values of agricultural water use benefits, calculated based on crop production, crop price and cost, and M&I water use benefits have to be taken into account. Currently, it is assumed that the total M&I water use benefit is 2.5 times the total agricultural water use benefit in the entire basin; or per unit of water value for M&I water use is about 3.5 times of that for agricultural water use. The resulting reference point is $wm_f = 0.346\, wm_0$, or $V(0.346 wm_0) = 0$.

Then:

$$V(wm_0) - V(0.346wm_0) = V(wm_0) = \int_{0.346w_0}^{w_0} p_0(wm/wm_0)^\alpha dx = wm_0 p_0[1 - (0.346wm/wm_0)^\alpha]/(1 + \alpha). \qquad \text{(A.12)}$$

Through substitution of $e = –0.45$, we have:

$$V(wm_0) = 2wm_0 p_0. \qquad \text{(A.13)}$$

Set $w = w_0$ and substitute equation A.13 into equation A.11, and then the constant C is:

$$C = wm_0 p_0(2\alpha + 1)/(\alpha + 1). \qquad \text{(A.14)}$$

Finally, we have:

$$V(wm) = wm_0 p_0/(1+\alpha)[(wm/w_0)^{\alpha} + 2\alpha + 1]. \quad (A.15)$$

The M&I function currently applies only to surface water. The small amount of local groundwater use (about 12 percent of total M&I water or 95 million cubic meters) is treated as a fixed amount in M&I water use.

Profit Function for Power Generation (*VP*)

$$VP^{pw} = \sum_{pd} power_{pd}^{pw} \cdot [pprice^{pw} - p\cos t^{pw}]. \quad (A.16)$$

Other constraints and physical relationships are described in the rest of this appendix.

Water Flow Balance

Water Balance and Transfer in River Reaches

$$\sum_{\substack{un-rn\in\\RVLINK}} flow_{pd}^{un,rn} + source_{pd}^{rn} + \sum_{\substack{rv-rn\in\\RRLINK}} rv\_rn_{pd}^{rv,rn} + \sum_{\substack{d-rn\in\\NDLINK}} rflow_{pd}^{d} + \sum_{\substack{gw\in\\GWDLINK}} dischg_{pd}^{gw,rn} = \sum_{\substack{rn-ln\in\\RVLINK}} flow_{pd}^{rn,ln} + \sum_{\substack{rv-rn\in\\RRLINK}} rn\_rv_{pd}^{rn,rv} + \sum_{\substack{rn-dem\in\\NDLINK}} rn\_d_{pd}^{rn,d}. \quad (A.17)$$

Return Flow from Irrigation Demand Sites

$$rflow_{pd}^{d} = rtn\_loss^{d} \cdot \Big[\sum_{\substack{(d,cp)\in\\DEM\text{-}CP}} wcp_{pd}^{d,cp} \cdot roff^{d,cp} + \sum_{\substack{(d,cp)\in\\DEM\text{-}CP}} dp\_stg_{pd}^{d,cp} \cdot drn^{d} - \sum_{\substack{(d,cp)\in\\DEM\_CP}} wreu_{pd}^{d,cp}\Big]. \quad (A.18)$$

The *return flow* from irrigation demands includes surface runoff from irrigation fields and subsurface drainage. Total return flow to the river system is the sum of these items, discounted by a loss rate (*rtn_loss*) resulting from seepage to groundwater, evaporation to the atmosphere, and other processes. This loss rate can be estimated from return flow observation records along the river.

Return Flow from Industrial and Municipal Demand Sites

$$rflow_{pd}^{d} = rtn\_loss^{d} \cdot \Big[\sum_{\substack{(rn,d)\in\\NDLINK}} rn\_d_{pd}^{rn,d} + \sum_{\substack{(rv,d)\in\\RDLINK}} rv\_d_{pd}^{rv,d} + los_{pd}^{d}\Big] \cdot [1 - comsp_{pd}^{d}] \cdot drn^{d}. \quad (A.19)$$

Reservoir Flow Balance

$$rv\_st_{pd-1}^{rv} + \sum_{\substack{(rv\_up,rv)\in\\RRLINK}} rv\_rv_{pd}^{ur,rv} + \sum_{\substack{(rn,rv)\in\\NRLINK}} rn\_rv_{pd}^{rn,rv} = rv\_st_{pd}^{rv} + evap_{pd}^{rv} \cdot area_{pd}^{rv} + \sum_{\substack{(rv\_lrev)\in\\RRLINKL}} rv\_rv_{pd}^{rv.lr} + \sum_{\substack{(rv,d)\in\\RDLINK}} rv\_d_{pd}^{rv,d} + \sum_{\substack{(rv,rn)\in\\RNLINK}} rv\_rn_{pd}^{rv,rn}. \quad (A.20)$$

Reservoir Volume and Surface Elevation Relations

$$rv\_st_{pd}^{rv} = a^{rv} \cdot h_{pd}^{rv2} + b^{rv} \cdot h_{pd}^{rv} + c^{rv}. \quad (A.21)$$

Reservoir Storage Volume–Surface Area Relationship

$$area_{pd}^{rv} = d^{rv} \cdot rv\_st_{pd}^{rv2} + e^{rv} \cdot rv\_st_{pd}^{rv} + f^{rv}. \quad (A.22)$$

Calculating Power Generation for Stations with Reservoirs

$$power_{pd}^{pw}(\text{if } pw \subset RPLINK) \le \sum_{\substack{(rv,pw)\in\\RPLINK}} \{H\_NET_{pd}^{rv} \cdot R\_NET_{pd}^{rv} \cdot pw\_ef^{pw} C\}, \quad (A.23)$$

where C is a constant for unit transformation.

$$R\_NET_{pd}^{rv} = \sum_{\substack{(rv,rn \in \\ RNLINK}} rv\_rn_{pd}^{rv,rn} + \sum_{\substack{(rv,lr)\in \\ RRLINKL}} rv\_rv_{pd}^{rv,lr}, \tag{A.24}$$

$$H\_NET_{pd}^{rv} = \frac{h_{pd}^{rv} + h_{pd-1}^{rv}}{2} pw\_te^{pw}. \tag{A.25}$$

Calculating Power Generation for Run-of-River Power Stations

$$power_{pd}^{pw}(\text{if } pw \subset NPLINK) \leq \sum_{\substack{(rv,pw)\in \\ RPLINK}} \{N\_NET_{pd}^{rn} \cdot pw\_ef^{pw} \cdot pw\_cf^{pw} \cdot C\}, \tag{A.26}$$

where:

$$N\_NET_{pd}^{rn} = \sum_{\substack{(rn,ln)\in \\ RNLINK}} flow_{pd}^{rn,ln} + \sum_{\substack{(rn,rv)\in \\ NRLINKL}} rn\_rv_{pd}^{rn,rv}. \tag{A.27}$$

Groundwater Balance

$$\begin{aligned} s^{gw} \cdot gwa^{gw} \cdot (gwh_{pd}^{gw} - gwh_{pd-1}^{gw}) &= rechg_{pd}^{gw} + \sum_{\substack{d\in \\ GWDLINK}} \sum_{\substack{cp\in \\ D\_CP}} dp\_stg_{pd}^{d,cp} \cdot (1 - drn^{d}) \\ &+ \sum_{\substack{d\in GWDLINK \\ \&muni.}} sepg_{pd}^{d}(\in \textit{muni.} \text{ sites}) \\ &- \sum_{\substack{d\in \\ GWDLINK}} \Big[\sum_{rn} rn\_d_{pd}^{rn,d} + \sum_{rev} rv\_d_{pd}^{rv,d}\Big] \cdot loss^{d} \\ &- \sum_{\substack{d\in \\ GWDLKINK}} \sum_{\substack{cp\in \\ DM\_CP}} pump_{pd}^{gw,d,cp} \\ &- \sum_{\substack{d\in GWLINK \\ \&muni.\ sites}} pumpm_{pd}^{gw,d} \\ &- \sum_{\substack{rn\in \\ GWRLINK}} dischg_{pd}^{gw,rn}, \end{aligned} \tag{A.28}$$

in which the seepage from municipal and industrial demand sites is calculated as:

$$\begin{aligned} sepg_{pd}^{d}&(\in \text{municipal \& industrial demand sites}) \\ &= \Big(\sum_{\substack{rn\in \\ NDLINK}} rn\_d_{pd}^{rn,d} + \sum_{\substack{rn\in \\ NDLINK}} rv\_d_{pd}^{rv,d}\Big)(1 - loss^{d}) \\ &\cdot (1 - comsp^{d}) \cdot (1 - drn^{d}), \end{aligned} \tag{A.29}$$

and the discharge from an aquifer to a river reach is calculated as:

$$dischg_{pd}^{gw,m} = gwa^{gw} \cdot s^{gw} \cdot (gwh_{pd}^{gw} - mih^{gw}) \cdot trans_{rn}^{gw}. \tag{A.30}$$

Other Constraints Related to Water Balance

Calculating Total Water Supply to a Demand Site, Including Local Source

$$\Big[\sum_{\substack{(rn,d)\in \\ NDLINK}} rn\_d_{pd}^{rn,d} + \sum_{\substack{(rv,d)\in \\ RDLINK}} rev\_d_{pd}^{rv,d}\Big] \cdot (1 - loss^{d}) + locs_{pd}^{d} = tot\_inf_{pd}^{d}. \tag{A.31}$$

Water Allocation among Crops in an Irrigation Demand Site

$(d, cp) \in DEM\_CP$, for one demand site, considering only the crops, defined by DEM_CP

$(cp, pd) \in CP\_PRD$, for one crop, considering only its irrigation periods, defined by CP_PRD.

These relations are also used for other equations related to irrigation.

$$\sum_{cp\in DEM\_CP} wcp^{d,cp} = tot\_inf_{pd}^{d}. \tag{A.32}$$

Water Application to Crop Fields

$$wacp_{pd}^{d,cp} = wcp_{pd}^{d,cp} + \sum_{\substack{gw\in \\ GWDLINK}} pump_{pd}^{gw,d,cp} + wreu_{pd}^{d,cp}. \tag{A.33}$$

Total Water Available to Crop Fields

$$twacp_{pd}^{d,cp} = wacp_{pd}^{d,cp} + er_{pd}^{d,cp} * ACP^{d,cp}. \tag{A.34}$$

Total Drainage Reuse Limit within a Demand Site in a Period

$$\sum_{cp\in DEM\_CP} wreu_{pd}^{d,cp} \leq rwru^{d} \cdot \sum_{cp\_DEM\_CP} rflow_{pd}^{d}, \tag{A.35}$$

in which *rwru* is a specified ratio of reuse water to total return flow from an agricultural demand site.

Salinity Balance

Salinity balance is conducted annually (for river reaches, reservoirs, and aquifers) and seasonally (for the crop water balance). For each demand site, diverted water is assumed totally mixed, and for each crop, diverted water is mixed with groundwater and drainage reuse. It is assumed that in return flows there is a mix of distribution losses, irrigation tailwater, and municipal discharge and drainage.

Salinity Balance in River Reaches

$$\begin{aligned}\sum_{pd}\Big[&\sum_{\substack{(ur,mrn)\in\\ RVLINK}} flow_{pd}^{un,rn}\cdot cn^{un} + source_{pd}^{rn} \cdot cs^{rn} + \sum_{\substack{(rv,rn)\in\\ RRLINK}} rv\_rn_{pd}^{rv,rn}\cdot cr^{rv} \\ &+ \sum_{\substack{gw\in\\ GWDLINK}} dischg_{pd}^{gw,rn}\cdot cg^{gw} + \sum_{\substack{(d,rn)\in\\ NDLINK}} rflow_{pd}^{d}\cdot crf^{d}\Big] \\ = \Big[&\sum_{\substack{(rn,lrn)\in\\ RVLINK}} flow_{pd}^{rn,ln} + \sum_{\substack{(rv,rn)\in\\ RRLINK}} rn\_rv_{pd}^{rn,rv} + \sum_{\substack{rn\_d\in\\ NDLINK}} rn\_d_{pd}^{rn,d}\Big]\cdot cn^{rn}.\end{aligned} \tag{A.36}$$

Salinity Balance in Reservoirs

$$\begin{aligned}\sum_{pd}\Big[&rv\_st_{pd-1}^{rv}\cdot cr^{rv} + \sum_{\substack{(ur,rv)\in\\ RRLINK}} rv\_rv_{pd}^{ur,rv}\cdot cr^{ur} + \sum_{\substack{(rn,rv)\in\\ NRLINK}} rn\_rv_{pd}^{rn,rv}\cdot cn^{rn}\Big] \\ = \sum_{pd}\Big[&rv\_st_{pd}^{rv} + evap_{pd}^{rv}\cdot area_{pd}^{rv} + \sum_{\substack{(lr,rv)\in\\ RRLINKL}} rv\_rv_{pd}^{rv,lr} + \sum_{\substack{(rv,d)\in\\ RDLINK}} rv\_d_{pd}^{rv,d} + \sum_{\substack{(rv,rn)\in\\ RNLINK}} rv\_rn_{pd}^{rv,rn}\Big]\cdot cr^{rv}.\end{aligned} \tag{A.37}$$

Salinity Balance in Return Flow from an Irrigation Field

$$\begin{aligned}\sum_{pd} rflow_{pd}^{d}\cdot crf^{d} = \sum_{pd}\Big[&\sum_{\substack{(d,cp)\in\\ DEM\_CP}} wcp_{pd}^{d,cp}\cdot roff^{d,cp}\cdot cwcp^{d,cp} \\ &+ \sum_{\substack{(d,cp)\in\\ DEM\_CP}} dp\_stg_{pd}^{d,cp}\cdot drn^{d}\cdot cdp^{d,cp} - \sum_{\substack{(d,cp)\in\\ DEM\_CP}} wreu_{pd}^{d,cp}\cdot cdn^{d}\Big].\end{aligned} \tag{A.38}$$

Salinity Balance in Return Flow from an Industrial and Municipal Demand Site

$$\begin{aligned}\sum_{pd} rflow_{pd}^{d}\cdot crf_{pd}^{d} = \sum_{pd}\Big[&\sum_{\substack{(rn,d)\in\\ NDLINK}} rn\_d_{pd}^{rn,d}\cdot cn_{pd}^{rn} + \sum_{\substack{(rv,d)\in\\ RDLINK}} rv\_d_{pd}^{rv,d}\cdot c_{pd}^{rv} \\ &+ locs_{pd}^{d}\cdot cls_{pd}^{d}\Big]\cdot drn^{d}.\end{aligned} \tag{A.39}$$

Salinity in Water Application to the Field (Not Mixed with Precipitation)

$$\begin{aligned}\sum_{pd}\Big\{\Big[&\sum_{\substack{(rn,d)\in\\ NDLINK}} rn\_d_{pd}^{rn,d}\cdot cn^{rn} + \sum_{\substack{(rv,d)\in\\ RDLINK}} rv\_d_{pd}^{rv,d}\cdot cr^{rv}\Big]\cdot(1-loss^{d}) \\ &+ \sum_{\substack{gw\in\\ GWDLINK}} pump_{pd}^{gw,d,cp}\cdot cg^{gw} + wreu_{pd}^{d,cp}\cdot crf^{d} + locs_{pd}^{d}\cdot cls^{d}\Big\} \\ = \sum_{pd}& wcp_{pd}^{d,cp}\cdot cwcp^{d,cp}.\end{aligned} \tag{A.40}$$

Salinity in Water Available to Crops

Diverted sources mixed with local groundwater, reused drainage, and rainfall

$$\begin{aligned}twacp^{d,cp}\cdot cwacp_{cp}^{d} = \sum_{pd}\Big[&WCP_{pd}^{d,cp}\cdot cwcp^{d} + \sum_{\substack{gw\in\\ GWDLINK}} pump_{pd}^{gw,d,cp}\cdot cg^{gw} \\ &+ wreu_{pd}^{d,cp}\cdot crf^{d}\Big].\end{aligned} \tag{A.41}$$

Salinity Balance in Aquifers

$$
\begin{aligned}
&\sum_{pd}\Big[s^{gw} \cdot gwa^{gw} \cdot (gwh_{pd}^{gw} - gwh_{pd-1}^{gw}) \\
&+ \sum_{\substack{rn\in \\ GWRLINK}} dischg_{pd}^{gw,rn} \\
&+ \sum_{\substack{d\in \\ \text{GWDLINK}}} \sum_{\substack{cp\in \\ DEM\_CP}} pump_{pd}^{gw,d,cp} \\
&+ \sum_{\substack{d\in GWLINK \\ \&muni.\ sites}} pumpm_{pd}^{gw,d}\Big] \cdot cg^{gw} \\
&= \sum_{pd}\{rechg_{pd}^{gw} \cdot crehg^{gw} \\
&+ \sum_{\substack{d\in \\ GWDLINK}} \sum_{\substack{cp\in \\ DEM\_CP}} dp\_sn^{d,cp} \\
&\cdot (1 - drn^{d}) \cdot csp^{d,cp} \\
&+ \sum_{\substack{d\in \\ GWDLINK}} \Big[\sum_{rn} rn\_d_{pd}^{rn,d} \cdot cn^{rn}) \\
&+ \sum_{rv} rv\_d_{pd}^{rv,d} \cdot cr^{rv}\Big] \cdot loss^{d} \\
&+ \sum_{pd} \sum_{\substack{d\in GWDLINK \\ \&muni.}} sepg_{pd}^{d} (\in\ muni.\ \text{sites}) \cdot cm^{d}.
\end{aligned} \tag{A.42}
$$

Crop Field Water Allocation and Agronomic–Hydrologic Relations

Calculating the Seasonal Relative Water to Maximum Crop Evapotranspiration

$$
\frac{\sum_{pd\in DEM\_CP} twacp_{pd}^{d,cp}}{\sum_{pd\in DEM\_CP} ep^{d} \cdot ACP^{d,cp}} = srw^{d,cp}. \tag{A.43}
$$

Calculating Seasonal Actual Crop Evapotranspiration

$$
eta\_sn^{d,cp} = \sum_{pd} twacp_{p}^{d,cp} - dp\_sn^{d,cp}. \tag{A.44}
$$

Calculating Seasonal Deep Percolation

$$
\begin{aligned}
&dp\_sn^{d,cp} = ep^{d}/etm\_sn^{d,cp} \\
&\cdot [srw^{d,cp} - yld^{d,cp}/pm^{d,cp} \\
&\cdot (1 - E_{\min}^{d,cp}) - E_{\min}^{d,cp}],
\end{aligned} \tag{A.45}
$$

in which *etm_sn* is the seasonal maximum crop evapotranspiration,

$$
etm\_sn^{d,cp} = \sum_{pd\in CP\_PD} etm_{pd}^{d,cp}, \tag{A.46}
$$

and $E_{\min}$ is the minimum required water for crop growth:

$$
E_{\min} = miw^{d,cp}/etm\_sn^{d,cp}. \tag{A.47}
$$

Calculating Irrigation Application Efficiency, Assuming the Same Efficiency for all Growth Stages, as Well as the Season

$$
\begin{aligned}
&effi^{d,cp} = [eta\_sn^{d,cp} \\
&- er\_sn^{d,cp} \cdot ACP^{d,cp} \\
&- \sum_{\substack{pd\in \\ CP\_PD}} wreu_{pd}^{d,cp}] / \sum_{\substack{pd\in \\ CP\_PD}} wcp_{pd}^{d,cp}.
\end{aligned} \tag{A.48}
$$

Calculating Stage Actual Evapotranspiration

$$
\begin{aligned}
eta\_stg_{pd}^{d,cp} = &\frac{wcp_{pd}^{d,cp}}{ACP^{d,cp}} \cdot effi^{d,cp} \\
&+ er_{pd}^{d,cp} + wreu_{pd}^{d,cp}.
\end{aligned} \tag{A.49}
$$

Calculating Stage Deep Percolation

$$
dp\_stg_{pd}^{d,cp} = twacp_{pd}^{d,cp} - eta\_stg_{pd}^{d,cp}. \tag{A.50}
$$

Calculating Crop Yield Deficit

$$
dft_{pd}^{d,cp} = ky_{pd}^{d,cp} \cdot \left(1 \frac{eta_{pd}^{d,cp}}{etm_{pd}^{d,cp}}\right), \tag{A.51}
$$

and the seasonal crop yield deficit is (Doorenbos and Kassam 1979):

$$
dft\_sn^{d,cp} = kys^{d,cp} \cdot \left(1 \frac{eta\_sn^{d,cp}}{etm\_sn^{d,cp}}\right). \tag{A.52}
$$

Defining the Maximum Crop Deficit

$$
\begin{aligned}
mdft^{\text{d,cp}} = \max_{\substack{pd\in \\ CP\_PD}} &\left\{kys^{d,cp} \cdot \left(1 - \frac{\text{eta\_sn}^{d,cp}}{etm\_sn^{d,cp}}\right),\right. \\
&\left. ky_{pd}^{d,cp} \cdot \left(1 - \frac{eta_{\text{pd}}^{d,cp}}{etm_{pd}^{d,cp}}\right)\right\}.
\end{aligned} \tag{A.53}
$$

For forage,

$$
mdft^{d,cp} = dft\_sn^{d,cp}. \tag{A.54}
$$

Land Limit in an Irrigation Demand Site in Each Month

$$\sum_{\substack{cp\in \\ DEM\_CP}} ACP^{d,cp} \le tarea^{d}, \text{ for each period (pd).} \quad (A.55)$$

Representation of Water Trading among Demand Sites

Objective Function: Maximization of Total Net Profits

$$\text{Max } tot\_nprft = \sum_{d} nprft^{\text{d}}. \quad (A.56)$$

For Irrigation Demand Sites

$$\begin{aligned} nprft^{d} = & \sum_{cp} ACP^{d,cp} \cdot (y^{d,cp} \cdot p^{d,cp} \\ & - fc^{d,cp} - tc^{d,cp}) \\ & - \sum_{pd} [wps^{d} \cdot ws^{d}_{pd} \\ & - tc \cdot (wb^{d}_{pd} + wl^{d}_{pd})] \\ & - \sum_{pd} [wtp^{d} * (wl^{d,cp} - wb^{d,cp})]. \end{aligned} \quad (A.57)$$

For M&I Demand Sites

$$\begin{aligned} nprft^{d} = & \, nprft0^{d} \\ & - \sum_{pd} \Big[wps^{\text{d}}_{pd} \cdot ws\textstyle\sum^{d}_{pd} \\ & - tc * (wb^{d}_{pd} + wl^{d}_{pd}) \Big] \\ & - \sum_{pd} [wtp * (wl^{d}_{pd} - wb^{d}_{pd})] \end{aligned} \quad (A.58)$$

where *nprft*0 is the net profit for M&I water use resulting from the case with water rights but where no water trading is allowed.

Additional Constraints for Water Trading

Balance of Traded Water

$$\sum_{d} wl^{d}_{pd} = \sum_{d} wb^{d}_{pd}, \text{ for each } pd, \quad (A.59)$$

and

$$wl^{d}_{pd} \cdot wb^{d}_{pd} = 0, \text{ for each } d \text{ and } pd. \quad (A.60)$$

The first equation makes sure that the total amount of water sold is equal to that of water bought for each time period; and the second one specifies that within one time period, one demand site can only buy or sell water.

Limit on Equilibrium Price, the Water Trading Price

$$wtp^{d} = \mu^{d}(w^{d}, \theta^{d}), \quad (A.61)$$

in which w is the annual total water withdrawal, θ represents other parameters related to the demand sites, and μ is the shadow price for each demand site.

Water Balances with Water Trade

$$ws^{d}_{pd} \le wg^{d}_{pd} - wl^{d}_{pd} + wb^{d}_{pd}, \quad (A.62)$$

in which wg is water allocated to a demand site in each period under prescribed water rights:

$$wg^{g}_{pd} = twa_{pd} \cdot (1 - pv_{pd}) \cdot pr^{d}_{pd}, \quad (A.63)$$

where twa is the total water availability in the basin, accounting for natural drainage and return flow; pv is the proportion for environment water use and pr is the proportion specifying water allocation to demand sites.

APPENDIX B

Input Parameters and Model Output

Input Parameters

The Crop-Water Simulation Model

Input parameters into the Fortran model provided by Dinar and Letey (1996) include the minimum and maximum water requirements by crop, the minimum and maximum yields, the irrigation water salt concentration, the yield and salinity relationship, the irrigation uniformity probability distribution, the forage and marketable yield relationship, and the range of water applications, shown in Table B.1. Results are shown in Table B.8.

Quadratic Crop Yield Function

An alternative quadratic crop yield function is estimated from survey data. Results are shown in Tables B.9 and B.10.

Demand Sites

Based on the irrigation districts in the Maipo Basin, eight irrigation demand sites were created (see also Chapter 4 and Table B.2).

Two municipal demand sites were created, based on the water demands of the (then) two major water companies, EMOS and Lo Castillo. These water companies satisfied a great percentage of their demand from groundwater wells (11.2 and 11.8 percent, respectively: see Table B.3).

Crop Data

Currently, the model includes the 15 most important irrigated crops in the Maipo Basin. To derive these 15 crops, the original set of crops was aggregated according to their phenological characteristics; crops using less than 5 percent of irrigated area and irrigation water were added to the already existing category "other crops," and walnuts were combined with peaches, cabbage with onions, lettuce with carrots, and beans with peas (see Table B.4). The following other crop input parameters were estimated or derived from FAO publications: effective rainfall was estimated based on the evapotranspiration/precipitation ratio method (Doorenbos and Pruitt 1977). Effective rainfall is computed from the average monthly crop evapotranspiration, mean monthly rainfall, and the soil water storage capacity. It was assumed that the adjusting factor based on soil water storage was a constant parameter.

The yield response coefficients from FAO (Doorenbos and Kassam 1979) were adapted to the new crop aggregates.

Table B.1 Input parameters for the simulation program

Crop category	PEVAT (centimeters per hectare)	MIN_YLD (metric tons per hectare)	MAX_YLD	SPROD (metric tons per centimeter per hectare)	B (millimhos per centimeter)	SSALT (percent per EC)	MIN_W (centimeters per hectare)	MAX_W	MIN_WA	MAX_WA
Wheat	44.8	0.0	6.0	0.586	6.0	7.1	27.7	44.8	17.3	179.2
Corn	52.0	0.0	15.0	0.180	1.7	12.0	34.5	52.0	21.6	130.0
Annfor	78.0	0.0	15.0	0.21	4.0		7.8	78	4.9	312.0
Grapes	74.4	0.0	22.0	0.317	1.5	9.6	31.6	74.4	19.8	186.0
Peaches	32.2	0.0	17.0	0.582	1.5	14.0	21.3	32.2	13.3	80.5
Potatoes	64.7	0.0	104.0	1.601	1.7	12.0	26.9	64.7	16.8	162.0
Pumpkins	62.3	0.0	65.0	1.130	1.2	13.0	23.1	62.3	0.0	14.4
Lemons	70.8	0.0	67.0	1.018	4.6	7.6	33.6	70.8	21.0	177.0
Othjan	65.8	1.5	30.0	0.448	3.0	10.0	26.6	65.8	16.6	164.5
Othjul	50.9	1.5	30.0	0.448	3.0	10.0	20.6	50.9	12.9	127.3
Avocados	91.6	0.0	18.0	0.208	1.6	24.0	38.9	91.6	24.3	229.0
Onions	50.8	0.0	60.0	1.339	1.2	16.0	14.2	50.8	8.9	127.0
Carrots	34.8	0.0	38.0	1.275	1.0	14.0	12.9	34.8	8.1	87.0
Peas	71.4	0.0	24.0	0.360	1.7	21.0	39.3	71.4	24.6	178.5
Prairie	124.4	0.0	106.0	0.926	1.6	15.0	12.4	124.4	7.8	311.0

Notes: PEVAT indicates regional pan evaporation (the region where the production is applied to); MIN_YLD, the minimum forage yield that obtains zero marketable yield; MAX_YLD, maximum crop yield; SPROD, slope of the production function; B, threshold salinity; SSALT, slope of the yield salinity curve; MIN_W, quantity of applied water when yield is zero; MAX_W, quantity of applied water when yield is the maximum yield; MIN_WA, lowest quantity of applied water for the analysis; MAX_WA, highest quantity of applied water for the analysis; and SPROD = (1 – [minimum yield/maximum yield])/(1 – MIN_W/EP). SPROD values were derived from Dinar and Letey (1996), and SSALT values were derived from Maas and Hoffman (1977). Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table B.2 Area of irrigation demand sites

Demand site	Irrigated area (hectares)
A1	45,236
A2	16,600
A3	25,433
A4	1,278
A5	33,954
A6	2,672
A7	3,657
A8	15,913
Total	144,743

Table B.3 Total water supply for municipal and industrial demand sites

Demand site	Surface water	Groundwater (million cubic meters)	Total
M1	541.43	72.45	613.38
M2	163.86	22.01	185.87

Table B.4 Crop parameters by crop category

Crop category	Actual yield (metric tons per hectare)	Maximum yield (metric tons per hectare)	Crop price (US$ per metric ton)	Actual area (hectares)	Other input costs (US$ per hectare)	Technology cost parameter (intercept)	Technology cost parameter (elasticity)
Wheat	5	6	220	22,046	342	0.562	0.034
Corn	9	10	150	18,215	524	3.254	0.021
Annfor	13	15	90	14,780	500	3.429	0.023
Grapes	17	19	376	12,940	2,397	4.429	0.024
Peaches	18	18	354	10,631	2,895	3.447	0.022
Potatoes	41	45	90	7,354	1,607	2.988	0.025
Pumpkins	27	30	190	4,675	2,289	3.447	0.024
Lemons	27	30	355	5,404	5,665	2.947	0.028
Othjan	13	15	440	7,923	2,500	2.988	0.025
Othjul	13	15	440	7,923	1000	2.988	0.025
Avocados	8	10	620	2,991	2,589	2.273	0.022
Onions	25	28	236	3,350	3,056	3.447	0.028
Carrots	23	25	267	3,339	2,790	3.447	0.021
Peas	6	7	379	4,201	964	2.988	0.022
Prairie	14	16	75	9,261	382	1.562	0.022

Note: Results are based on an exchange rate of 417.58 Chilean pesos per U.S. dollar. Price/production data for 1994–96 were averaged. Internal market prices were used (for the lowest processing stage, when applicable). Crop categories are aggregated as follows: wheat (wheat, barley); corn (two types of maize); grapes (wine and table grapes, kiwi fruit); peaches (almonds, apricots, cherries, nectarines, peaches, plums, two types of apples, two types of pears, persimmons, quinces, walnuts); potatoes (jalapeño peppers, potatoes, tobacco, tomatoes); pumpkins (melons, watermelons, pumpkins, zucchini); lemons; othjan (other crops planted in January); othjul (other crops planted in July); avocados (avocados, custard apples, loquats, lucumos, olives, prickly pears); onions (broccoli, brussels sprouts, cauliflowers); carrots (carrots, celery, lettuce); peas (beans, green beans, bean/squash/carrot mix, lima beans, peas); prairie (artichokes, oregano, prairie). Annfor indicates annual forage.

Table B.5 Potential crop evapotranspiration, demand site A1 (millimeters)

Crop category	January	February	March	April	May	June	July	August	September	October	November	December	Seasonal total
Wheat	55	0	0	0	0	1	0	31	61	93	157	137	536
Corn	209	197	121	52	0	0	0	0	0	41	107	154	883
Annfor	183	155	0	0	0	0	0	0	39	84	144	173	778
Grapes	165	138	72	0	0	0	0	0	26	73	115	155	744
Peaches	165	138	86	0	0	0	0	0	29	57	101	138	714
Potatoes	191	154	100	0	0	0	0	0	0	41	107	172	765
Pumpkins	174	121	0	0	0	0	0	0	0	47	108	173	623
Lemons	110	104	86	57	36	20	13	18	33	57	79	95	708
Othjan	183	172	144	104	66	0	0	0	0	0	0	0	669
Othjul	0	0	0	0	0	0	0	37	66	104	144	172	523
Avocados	137	129	108	73	46	24	17	26	46	73	108	129	916
Onions	92	121	144	99	52	0	0	0	0	0	0	0	508
Carrots	0	0	0	0	0	11	13	29	65	115	115	0	348
Peas	0	0	0	0	0	0	8	18	52	115	129	0	322
Prairie	201	190	144	94	52	29	21	29	56	94	144	150	1,244

Notes: Values change by demand site and crop category. Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table B.6 Effective rainfall, demand site A1 (millimeters)

Crop category	January	February	March	April	May	June	July	August	September	October	November	December	Seasonal total
Wheat	3	0	0	0	0	61	0	15	21	21	12	5	138
Corn	6	11	7	15	0	0	0	0	0	13	7	2	61
Annfor	6	11	0	0	0	0	0	0	21	19	11	5	73
Grapes	6	11	7	0	0	0	0	0	20	19	11	5	79
Peaches	6	11	7	0	0	0	0	0	20	18	10	5	77
Potatoes	6	11	7	0	0	0	0	0	0	17	10	5	56
Pumpkins	6	11	0	0	0	0	0	0	0	18	10	5	50
Lemons	6	11	7	13	36	20	13	18	20	18	10	5	177
Othjan	6	11	7	14	58	0	0	0	0	0	0	0	96
Othjul	0	0	0	0	0	0	0	37	22	20	11	5	95
Avocados	6	11	7	13	46	24	17	26	21	19	10	5	205
Onions	6	11	7	14	52	0	0	0	0	0	0	0	90
Carrots	0	0	0	0	0	11	13	29	22	21	11	0	107
Peas	0	0	0	0	0	0	64	18	21	21	11	0	135
Prairie	6	11	7	14	52	29	21	29	21	20	11	5	226

Notes: Values change by demand site and crop category. Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table B.7 Within-season yield response coefficients, Ky

Crop category	January	February	March	April	May	June	July	August	September	October	November	December
Wheat	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.65	0.55	0.10
Corn	0.40	0.90	1.50	0.50	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Annfor	0.45	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.25	0.35	0.65	0.75
Grapes	0.85	0.85	0.50	0.00	0.00	0.00	0.00	0.00	0.65	0.75	0.85	0.85
Peaches	0.85	0.85	0.85	0.00	0.00	0.00	0.00	0.00	0.45	0.45	0.65	0.85
Potatoes	0.70	0.70	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.65	0.65	0.20
Pumpkins	0.80	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.60	0.80
Lemons	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Othjan	0.60	0.45	0.35	0.33	0.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Othjul	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.30	0.40	0.45
Avocados	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Onions	0.45	0.65	0.65	0.50	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Carrots	0.00	0.00	0.00	0.00	0.00	0.60	0.60	0.70	0.60	0.50	0.40	0.00
Peas	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.90	0.90	0.70	0.40	0.00
Prairie	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70	0.70

Notes: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table B.8 Production function coefficients: Regression coefficients based on outputs from the simulation model

Crop category	*b1*	*b2*	*b3*	*b4*	*b5*	*b6*	*b7*	*b8*	*b9*
Wheat	0.285	1.153	0.183	–0.056	–0.811	0.031	0.142	1.181	–0.032
Corn	0.628	0.588	–0.035	–0.103	–0.374	0.042	0.459	0.567	–0.077
Annfor	0.628	0.431	0.017	–0.041	–0.209	0.017	0.273	0.224	–0.011
Grapes	0.425	0.940	0.092	–0.137	–0.623	0.072	0.272	0.875	–0.089
Peaches	0.363	1.130	0.131	–0.233	–0.817	0.132	0.204	1.258	–0.172
Potatoes	0.505	1.096	0.098	–0.171	–0.745	0.099	0.282	0.841	–0.096
Pumpkins	0.501	0.813	0.050	–0.167	–0.518	0.081	0.323	0.712	–0.108
Lemons	0.262	1.158	0.204	–0.049	–0.806	0.025	0.129	1.130	–0.020
Othjan	0.384	0.976	0.123	–0.086	–0.642	0.046	0.225	0.871	–0.043
Othjul	0.388	0.951	0.119	–0.087	–0.618	0.046	0.232	0.830	–0.044
Avocados	0.521	0.893	0.032	–0.236	–0.596	0.125	0.339	0.869	–0.160
Onions	0.577	0.636	0.020	–0.173	–0.370	0.078	0.341	0.477	–0.100
Carrots	0.506	0.776	0.049	–0.177	–0.488	0.083	0.329	0.667	–0.116
Peas	0.196	1.311	0.245	–0.204	–0.995	0.118	0.049	1.573	–0.163
Prairie	0.652	0.440	0.009	–0.132	–0.220	0.057	0.292	0.249	–0.057

Note: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Hydropower Generation Data

Because of the lack of water flow data for hydroelectric plants, these data were estimated based on electricity generation. The data on the monthly production of energy (megawatt-hour), covering 1985–94, were obtained from the Anuario Estadístico del Centro de Despacho Económico de Carga del Sistema Interconectado Central (CDEC-SIC) and from ENDESA publications. The necessary volume of water to generate each monthly energy production was estimated with the equation of power of a hydroelectric turbine; formally:

$$Volume\ (m^3/month) = \frac{Generated\ energy\ [Megawatt - hour] \cdot 3600\left[\frac{\sec}{hour}\right] \cdot 10^6\left[\frac{watt}{megawatt}\right]}{0.80 \cdot 9.8\left[\frac{m}{s^2}\right] \cdot 1000\left[\frac{kg}{m^3}\right] height\ [m]},$$

where 0.80 is a yield coefficient that defines the operating efficiency of the station's turbine, 1,000 corresponds to the specific mass of water, and 9.8 is the acceleration of gravity. The height data were taken from the height of the hydroelectric plant (for data, see Table B.11).

Water Flow Data

Water flow data were taken from 19 fluviometric measuring stations in the Maipo River Basin.

Ten years of flow record data were available. This was not enough to estimate long-term average hydrologic levels such as dry, normal, and wet years. Therefore, the 10-year average was defined as normal, the year with the lowest inflow was chosen as a dry year, and the year with the highest inflow as a wet year. Based on the primary inflow values, the inflow for each separate river segment was estimated. The data we used in the model are the inflow for separate river segments (Tables B.12 and B.13).

Table B.9 Agricultural inputs: Average values from the field survey

Demand site	Crop category	Water	Irrigation	Machinery	Fertilizer	Pesticide	Seed	Labor
A1	Wheat	841.6	96.0	210.0	161.8	71.4	92.5	154.3
	Corn	819.5	119.8	220.0	297.9	105.4	167.5	195.9
	Annfor	686.6	89.8	228.7	68.0	50.0	50.0	200.0
	Grapes	1,569.5	420.0	449.6	228.4	205.2	0.0	1,913.3
	Peaches	1,642.3	500.3	780.0	69.8	151.6	0.0	1,465.7
	Potatoes	1,254.3	325.1	188.4	146.1	54.2	230.0	980.4
	Pumpkins	1,334.6	420.6	216.3	206.4	71.4	220.0	1,532.3
	Lemons	1,686.5	600.0	1,493.3	240.3	246.3	0.0	2,550.2
	Othjan	1,325.3	316.4	306.6	180.9	103.0	216.0	522.0
	Othjul	1,273.9	313.6	304.4	179.6	102.6	214.4	516.1
	Avocados	2,235.5	455.9	286.9	231.6	374.9	50.0	1,350.4
	Onions	1,305.1	355.7	344.2	204.5	113.9	245.8	575.5
	Carrots	886.0	405.1	312.5	203.7	170.1	171.8	294.6
	Peas	843.7	242.9	263.1	81.0	103.0	50.0	200.0
	Prairie	2,170.9	104.3	492.7	52.6	50.0	0.0	368.2
A2	Wheat	871.3	88.5	200.0	136.6	67.8	84.6	150.0
	Corn	846.1	117.7	200.0	292.3	104.3	164.6	189.7
	Annfor	708.2	86.6	221.4	50.0	50.0	50.0	200.0
	Grapes	1,702.1	416.6	448.6	227.2	205.2	0.0	1,887.1
	Peaches	1,741.7	496.6	771.9	69.6	151.1	0.0	1,430.3
	Potatoes	1,306.8	321.4	188.0	145.3	54.4	230.0	961.3
	Pumpkins	1,400.3	414.8	215.5	204.4	71.5	220.0	1,496.8
	Lemons	1,749.1	600.0	1,500.0	240.2	246.2	0.0	2,541.3
	Othjan	1,385.5	313.4	304.1	179.8	102.6	214.5	515.3
	Othjul	1,403.7	315.7	305.4	179.3	102.6	214.5	518.2
	Avocados	2,517.3	449.5	285.6	227.5	372.6	50.0	1,324.8
	Onions	1,442.6	354.6	344.2	202.8	113.4	244.6	573.3
	Carrots	985.2	404.2	311.7	203.1	167.4	170.8	281.3
	Peas	934.3	236.1	259.9	79.8	97.7	50.0	200.0
	Prairie	2239.0	104.2	492.9	52.6	50.0	0.0	367.9
A3	Wheat	895.8	118.1	225.4	218.8	78.1	114.0	209.3
	Corn	853.4	115.3	200.0	287.4	103.4	162.1	183.5
	Annfor	727.1	92.1	365.1	50.0	50.0	100.8	222.5
	Grapes	1,710.3	418.4	449.9	227.9	205.0	0.0	1,907.7
	Peaches	1,753.6	496.6	772.0	69.6	151.1	0.0	1,431.8
	Potatoes	1,337.1	319.5	187.8	144.8	54.5	230.0	951.2
	Pumpkins	1,414.7	414.5	215.4	204.4	71.5	220.0	1,495.4
	Lemons	1,756.3	600.0	1500.0	240.2	246.2	0.0	2,539.9
	Othjan	1,378.5	312.2	303.1	179.5	102.4	214.0	512.6
	Othjul	1,374.8	315.0	306.0	179.7	102.8	214.9	519.6
	Avocados	2,509.5	449.7	285.6	227.6	372.7	50.0	1,325.5
	Onions	1,442.6	354.6	344.2	202.8	113.4	244.6	573.3
	Carrots	979.0	404.3	311.8	203.1	167.5	170.9	282.0
	Peas	932.0	236.3	260.0	79.8	97.8	50.0	200.0
	Prairie	2,239.3	104.2	492.9	52.6	50.0	0.0	367.9

Table B.9—Continued

Demand site	Crop category	Water	Irrigation	Machinery	Fertilizer	Pesticide	Seed	Labor
A4	Wheat	873.5	107.8	200.0	186.7	74.5	102.3	178.9
	Corn	843.6	117.4	200.0	288.7	103.9	162.3	185.2
	Annfor	746.5	83.8	217.9	50.0	50.0	50.0	200.0
	Grapes	1,799.0	417.6	450.3	227.6	204.8	0.0	1,907.1
	Peaches	1795.0	498.8	776.5	69.8	151.5	0.0	1,460.2
	Potatoes	1316.0	320.4	188.0	145.0	54.5	300.0	955.3
	Pumpkins	1,415.1	419.1	216.1	206.0	71.4	320.0	1,523.9
	Lemons	1759.0	600.0	1,500.0	240.1	246.2	0.0	2,531.9
	Othjan	1,395.9	310.5	301.6	178.8	102.2	213.1	508.7
	Othjul	1,450.6	314.1	305.4	179.1	102.6	214.4	517.9
	Avocados	3,633.1	424.7	280.6	211.9	364.0	50.0	1,226.6
	Onions	1,450.9	354.6	344.4	202.8	113.4	244.6	573.1
	Carrots	905.9	405.0	312.4	203.6	169.6	171.6	291.3
	Peas	866.3	242.2	262.7	80.9	102.2	50.0	200.0
	Prairie	2132.4	104.3	495.8	52.5	50.0	0.0	365.4
A5	Wheat	871.9	118.1	225.6	219.2	78.1	114.0	209.5
	Corn	816.2	116.6	200.0	285.8	103.5	160.5	180.3
	Annfor	719.5	89.9	342.2	50.0	50.0	90.4	210.5
	Grapes	1,643	417.2	448.5	227.4	205.2	0.0	1,888.9
	Peaches	1,705.7	497.5	774.0	69.7	151.2	0.0	1,438.1
	Potatoes	1,296.5	319.2	187.8	144.7	54.5	300.0	949.0
	Pumpkins	1,364.7	415.2	215.5	204.5	71.5	320.0	1,499
	Lemons	1,754.4	600.0	1,500.0	240.2	246.2	0.0	2,540.3
	Othjan	1,332.9	311.5	302.3	179.3	102.3	213.7	510.8
	Othjul	1,246.5	309.7	300.9	178.4	102.1	212.6	507.0
	Avocados	2,403.5	452.1	286.1	229.2	373.5	50.0	1,335.1
	Onions	1,414.1	354.6	344.1	203.1	113.5	244.7	573.3
	Carrots	947.3	404.5	312.0	203.3	168.4	171.2	285.9
	Peas	901.1	238.5	261.0	80.2	99.6	50.0	200.0
	Prairie	2,239.3	104.2	492.9	52.6	50.0	0.0	367.9
A6	Wheat	855.3	83.9	200.0	123.4	65.8	80.8	150.0
	Corn	834.9	120.5	200.0	299.2	105.6	168.2	198.2
	Annfor	689.0	90.6	229.9	50.0	50.0	50.0	200.0
	Grapes	1,796.5	417.6	450.2	227.6	204.8	0.0	1,907.1
	Peaches	1,643.7	501.1	781.7	69.9	151.8	0.0	1,475.2
	Potatoes	1,267.1	325.1	188.4	146.1	54.2	230.0	980.8
	Pumpkins	1,338.6	422.7	216.6	207.1	71.3	250.0	1,545.5
	Lemons	1,758.9	600.0	1,500	240.2	246.2	0.0	2,539.3
	Othjan	1,312.5	318.8	308.7	181.7	103.4	217.2	527.6
	Othjul	1,202.4	312.3	303.0	179.4	102.4	213.9	512.6
	Avocados	2,173.7	457.4	287.2	232.5	375.4	50.0	1,356.0
	Onions	1,435.0	354.6	344.2	202.9	113.5	244.6	573.3
	Carrots	8,64.3	405.4	312.7	203.8	170.8	172.1	298.0
	Peas	828.5	2,44.1	263.7	81.2	103.9	50.0	200.0
	Prairie	2,231.5	1,04.2	492.9	52.6	50.0	0.0	368.0

(continued)

Table B.9—Continued

Demand site	Crop category	Water	Irrigation	Machinery	Fertilizer	Pesticide	Seed	Labor
A7	Wheat	858.7	116.1	221.2	213.8	77.4	111.8	204.2
	Corn	868.6	115.2	200.0	273.5	101.7	155.6	174.5
	Annfor	713.2	91.7	330.2	50.0	50.0	83.9	203.9
	Grapes	1,784.9	416.2	457.8	217.4	205.4	0.0	1,911.3
	Peaches	1,736.5	499.8	773.2	69.7	151.5	0.0	1,447.6
	Potatoes	1,246.5	320.5	188.2	145.2	54.5	230.0	958.2
	Pumpkins	1,316.5	419.6	216.4	205.5	71.1	250.0	1,523.8
	Lemons	1,912.2	600.0	1,500.0	240.9	246.5	0.0	2,610.0
	Othjan	1,497.9	336.3	324.7	186.7	105.8	224.8	567.9
	Othjul	1,313.2	315.9	307.0	180.2	102.9	215.6	521.9
	Avocados	2,012.8	460.2	287.3	233.9	375.3	50.0	1,374.9
	Onions	1,430.6	353.6	343.1	204.2	113.6	244.2	574.4
	Carrots	835.2	407.0	311.2	202.1	170	173.3	306.1
	Peas	830.9	245.4	263.8	81.2	104.4	50.0	200.0
	Prairie	2,235.2	104.2	493.0	52.6	50.0	0.0	367.8
A8	Wheat	825.9	96.9	200.0	165.1	71.9	93.9	157.8
	Corn	808.2	121.9	200.0	305.1	106.6	171.5	204.7
	Annfor	655.0	90.5	237.3	50.0	50.0	50.0	200.0
	Grapes	1,533.7	420.5	449.6	228.6	205.2	0.0	1,915.6
	Peaches	1,598.4	500.6	780.8	69.8	151.6	0.0	1,465.6
	Potatoes	1,230.5	326.4	188.5	146.4	54.1	230.0	987.0
	Pumpkins	1,301.0	421.8	216.5	206.7	71.3	250.0	1,539.1
	Lemons	1,688.0	600.0	1,493.6	240.3	246.3	0.0	2,550.2
	Othjan	1,277.5	323.4	312.7	183.3	104.0	219.4	538.3
	Othjul	1,222.7	319.4	308.2	181.2	103.3	216.6	526.3
	Avocados	2,237	455.9	286.9	231.6	374.9	50.0	1,350.2
	Onions	1,205.7	346.4	335.4	201.6	112.1	241.1	552.5
	Carrots	883.7	405.1	312.5	203.7	170.2	171.9	294.9
	Peas	836.8	243.4	263.4	81.1	103.4	50.0	200.0
	Prairie	2,239.3	104.2	492.9	52.6	50.0	0.0	367.9

Note: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table B.10a Production function coefficients from the generalized maximum entropy program: Linear coefficients (α)

Crop category	Water	Irrigation	Machinery	Fertilizer	Pesticide	Seed	Labor
Wheat	0.00101	0.01025	0.00756	0.00631	0.01161	0.00757	0.00640
Corn	0.00131	0.01092	0.00687	0.00874	0.01117	0.00923	0.00696
Annfor	0.00208	0.01804	0.01133	0.02905	0.04956	0.01128	0.00951
Grapes	0.00226	0.00838	0.00933	0.01406	0.02356	0.00000	0.00296
Peaches	0.00291	0.00821	0.00608	0.05089	0.02548	0.00000	0.00375
Potatoes	0.00426	0.01972	0.03180	0.03758	0.08832	0.01314	0.01566
Pumpkins	0.00208	0.01094	0.01445	0.01905	0.03969	0.00653	0.00739
Lemons	0.00322	0.00509	0.00458	0.02842	0.02676	0.00000	0.00312
Othjan	0.00195	0.00957	0.00999	0.01417	0.02578	0.01283	0.00692
Othjul	0.00216	0.00958	0.01001	0.01420	0.02582	0.01285	0.00694
Avocados	0.00031	0.00234	0.01999	0.00118	0.00144	0.00000	0.00178
Onions	0.00427	0.01692	0.01751	0.02266	0.03944	0.02092	0.01066
Carrots	0.00551	0.01168	0.01927	0.01298	0.01507	0.04013	0.00597
Peas	0.00189	0.00564	0.00992	0.00724	0.00556	0.00543	0.00249
Prairie	0.00175	0.01779	0.01245	0.02760	0.04628	0.01179	0.00984

Note: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table B.10b Production function coefficients from the generalized maximum entropy program (b): Nonlinear intersectoral coefficients (γ for a crop with input *i* and input *j*)

Crop category	Input	Water	Irrigation	Machinery	Fertilizer	Pesticide	Seed	Labor
Annfor	Water	7.72E–07	–4.40E–08	–2.37E–07	–6.10E–08	–9.20E–08	–1.32E–07	–1.78E–07
	Irrigation	–4.40E–08	8.85E–05	–6.46E–06	3.78E–06	–7.25E–07	–1.67E–06	–5.55E–06
	Machinery	–2.37E–07	–6.46E–06	5.00E–06	–1.70E–06	–1.34E–06	–2.72E–07	–1.19E–06
	Fertilizer	–6.10E–08	3.78E–06	–1.70E–06	2.97E–04	–1.23E–05	–5.15E–06	–1.38E–05
	Pesticide	–9.20E–08	–7.25E–07	–1.34E–06	–1.23E–05	1.26E–03	–1.12E–05	–3.80E–05
	Seed	–1.32E–07	–1.67E–06	–2.72E–07	–5.15E–06	–1.12E–05	1.03E–05	–1.26E–06
	Labor	–1.78E–07	–5.55E–06	–1.19E–06	–1.38E–05	–3.80E–05	–1.26E–06	1.12E–05
Avocados	Water	5.00E–09	–3.00E–09	–6.00E–09	–6.00E–09	–2.00E–09	0.00E+00	–2.00E–09
	Irrigation	–3.00E–09	8.41E–06	–2.85E–06	–9.94E–07	–1.29E–06	0.00E+00	–1.63E–06
	Machinery	–6.00E–09	–2.85E–06	6.85E–05	–4.33E–06	–2.20E–05	0.00E+00	–1.17E–07
	Fertilizer	–6.00E–09	–9.94E–07	–4.33E–06	7.59E–06	1.60E–06	0.00E+00	–8.42E–07
	Pesticide	–2.00E–09	–1.29E–06	–2.20E–05	1.60E–06	1.75E–05	0.00E+00	–2.66E–07
	Seed	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Labor	–2.00E–09	–1.63E–06	–1.17E–07	–8.42E–07	–2.66E–07	0.00E+00	6.58E–07
Corn	Water	5.02E–07	–9.30E–08	–1.37E–07	–4.00E–08	–2.30E–08	–4.90E–08	–1.73E–07
	Irrigation	–9.30E–08	5.38E–05	–2.24E–06	–4.07E–06	–9.18E–06	–1.13E–06	–5.45E–06
	Machinery	–1.37E–07	–2.24E–06	4.04E–06	4.89E–07	3.91E–07	2.09E–07	–6.24E–07
	Fertilizer	–4.00E–08	–4.07E–06	4.89E–07	4.55E–06	–9.54E–07	–4.49E–07	1.79E–07
	Pesticide	–2.30E–08	–9.18E–06	3.91E–07	–9.54E–07	2.97E–05	–1.17E–06	2.03E–06
	Seed	–4.90E–08	–1.13E–06	2.09E–07	–4.49E–07	–1.17E–06	9.95E–06	–1.20E–06
	Labor	–1.73E–07	–5.45E–06	–6.24E–07	1.79E–07	2.03E–06	–1.20E–06	3.86E–06
Grapes	Water	5.05E–07	1.22E–07	2.80E–08	1.22E–07	1.42E–07	0.00E+00	5.20E–08
	Irrigation	1.22E–07	7.77E–06	1.34E–07	9.62E–07	7.00E–07	0.00E+00	–6.02E–07
	Machinery	2.80E–08	1.34E–07	7.64E–06	1.01E–06	6.23E–07	0.00E+00	–3.61E–07
	Fertilizer	1.22E–07	9.62E–07	1.01E–06	1.96E–05	6.08E–06	0.00E+00	–6.33E–07
	Pesticide	1.42E–07	7.00E–07	6.23E–07	6.08E–06	3.85E–05	0.00E+00	1.23E–07
	Seed	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Labor	5.20E–08	–6.02E–07	–3.61E–07	–6.33E–07	1.23E–07	0.00E+00	2.45E–07
Lemons	Water	9.55E–07	4.60E–08	–1.08E–07	1.09E–07	–3.00E–09	0.00E+00	1.50E–08
	Irrigation	4.60E–08	1.19E–06	–5.10E–08	–1.42E–07	–1.17E–07	0.00E+00	–1.16E–07
	Machinery	–1.08E–07	–5.10E–08	7.31E–07	–6.80E–08	–1.00E–07	0.00E+00	–3.40E–08
	Fertilizer	1.09E–07	–1.42E–07	–6.80E–08	7.64E–05	–2.02E–05	0.00E+00	–2.81E–07
	Pesticide	–3.00E–09	–1.17E–07	–1.00E–07	–2.02E–05	6.96E–05	0.00E+00	–8.70E–08
	Seed	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Labor	1.50E–08	–1.16E–07	–3.40E–08	–2.81E–07	–8.70E–08	0.00E+00	8.10E–08
Onions	Water	1.39E–06	1.20E–08	–1.20E–07	4.15E–07	3.43E–07	1.77E–07	–3.40E–08
	Irrigation	1.20E–08	2.46E–05	–1.39E–06	–1.98E–06	–3.39E–06	–1.25E–06	–1.94E–06
	Machinery	–1.20E–07	–1.39E–06	1.89E–05	7.89E–07	1.87E–06	–4.30E–07	4.13E–07
	Fertilizer	4.15E–07	–1.98E–06	7.89E–07	4.59E–05	–7.84E–06	1.50E–06	–4.90E–08
	Pesticide	3.43E–07	–3.39E–06	1.87E–06	–7.84E–06	1.92E–04	1.36E–05	–1.07E–05
	Seed	1.77E–07	–1.25E–06	–4.30E–07	1.50E–06	1.36E–05	2.73E–05	–2.28E–07
	Labor	–3.40E–08	–1.94E–06	4.13E–07	–4.90E–08	–1.07E–05	–2.28E–07	8.38E–06

Table B.10b—Continued

Crop category	Input	Water	Irrigation	Machinery	Fertilizer	Pesticide	Seed	Labor
Peaches	Water	5.34E–07	1.27E–07	1.25E–07	1.45E–07	1.09E–07	0.00E+00	9.20E–08
	Irrigation	1.27E–07	5.61E–06	–3.79E–07	–1.36E–07	–2.36E–07	0.00E+00	–1.47E–07
	Machinery	1.25E–07	–3.79E–07	1.88E–06	–8.80E–08	–1.78E–07	0.00E+00	–4.20E–08
	Fertilizer	1.45E–07	–1.36E–07	–8.80E–08	4.03E–04	–1.13E–05	0.00E+00	–1.88E–06
	Pesticide	1.09E–07	–2.36E–07	–1.78E–07	–1.13E–05	8.73E–05	0.00E+00	–8.76E–07
	Seed	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
	Labor	9.20E–08	–1.47E–07	–4.20E–08	–1.88E–06	–8.76E–07	0.00E+00	3.02E–07
Peas	Water	5.74E–07	–3.00E–09	1.12E–07	–5.90E–08	2.64E–07	1.71E–07	–2.40E–08
	Irrigation	–3.00E–09	4.48E–06	–3.55E–07	–6.34E–07	–1.46E–06	9.50E–08	–2.92E–07
	Machinery	1.12E–07	–3.55E–07	1.16E–05	–2.39E–06	–1.40E–07	2.15E–06	–4.62E–07
	Fertilizer	–5.90E–08	–6.34E–07	–2.39E–06	3.75E–05	–3.14E–06	–4.44E–06	–6.22E–07
	Pesticide	2.64E–07	–1.46E–06	–1.40E–07	–3.14E–06	1.11E–05	1.15E–06	–3.93E–07
	Seed	1.71E–07	9.50E–08	2.15E–06	–4.44E–06	1.15E–06	1.23E–05	–9.21E–07
	Labor	–2.40E–08	–2.92E–07	–4.62E–07	–6.22E–07	–3.93E–07	–9.21E–07	4.90E–07
Potatoes	Water	9.43E–07	2.19E–07	1.58E–07	1.27E–07	1.63E–07	1.32E–07	1.04E–07
	Irrigation	2.19E–07	2.96E–05	–4.50E–06	–6.50E–06	–6.99E–07	–7.33E–07	–2.43E–06
	Machinery	1.58E–07	–4.50E–06	7.14E–05	–3.64E–06	–4.89E–06	–2.99E–06	2.19E—06
	Fertilizer	1.27E–07	–6.50E–06	–3.64E–06	1.18E–04	4.18E–06	6.66E–07	–1.41E—06
	Pesticide	1.63E–07	–6.99E–07	–4.89E–06	4.18E–06	5.61E–04	1.12E–06	8.59E—06
	Seed	1.32E–07	–7.33E–07	–2.99E–06	6.66E–07	1.12E–06	1.59E–06	1.70E–08
	Labor	1.04E–07	–2.43E–06	2.19E–06	–1.41E–06	8.59E–06	1.70E–08	3.11E–06
Wheat	Water	2.78E–07	–5.00E–09	–5.00E–08	3.00E–09	–2.40E–08	–7.50E–08	–7.30E–08
	Irrigation	–5.00E–09	4.87E–05	–1.31E–06	–6.85E–06	–3.14E–06	–1.77E–06	–1.88E–06
	Machinery	–5.00E–08	–1.31E–06	8.66E–06	–1.38E–06	–1.13E–07	1.99E–07	–2.65E–07
	Fertilizer	3.00E–09	–6.85E–06	–1.38E–06	8.14E–06	1.87E–06	6.27E–07	–4.90E–07
	Pesticide	–2.40E–08	–3.14E–06	–1.13E–07	1.87E–06	5.21E–05	–7.29E–06	9.60E–07
	Seed	–7.50E–08	–1.77E–06	1.99E–07	6.27E–07	–7.29E–06	2.55E–05	–3.98E–06
	Labor	–7.30E–08	–1.88E–06	–2.65E–07	–4.90E–07	9.60E–07	–3.98E–06	7.94E–06
Carrots	Water	1.90E–06	1.00E–09	1.56E–07	–2.70E–08	6.19E–07	8.34E–07	5.50E–08
	Irrigation	1.00E–09	7.76E–06	–1.27E–06	–8.16E–07	–2.21E–06	1.29E–06	–2.09E–07
	Machinery	1.56E–07	–1.27E–06	1.87E–05	–3.42E–06	–4.32E–07	9.28E–06	–4.89E–07
	Fertilizer	–2.70E–08	–8.16E–07	–3.42E–06	2.82E–05	–1.50E–06	–5.07E–06	–6.30E–07
	Pesticide	6.19E–07	–2.21E–06	–4.32E–07	–1.50E–06	2.36E–05	5.99E–06	–6.74E–07
	Seed	8.34E–07	1.29E–06	9.28E–06	–5.07E–06	5.99E–06	7.46E–05	–1.26E–06
	Labor	5.50E–08	–2.09E–07	–4.89E–07	–6.30E–07	–6.74E–07	–1.26E–06	5.45E–07
Pumpkins	Water	4.73E–07	3.70E–08	1.00E–08	–2.30E–08	2.80E–08	2.20E–08	9.00E–09
	Irrigation	3.70E–08	1.62E–05	–1.43E–06	–2.56E–06	–2.73E–07	–9.14E–07	–1.59E–06
	Machinery	1.00E–08	–1.43E–06	3.05E–05	–1.09E–06	–3.43E–06	–1.98E–06	4.19E–07
	Fertilizer	–2.30E–08	–2.56E–06	–1.09E–06	5.43E–05	1.22E–06	–5.24E–07	–1.71E–06
	Pesticide	2.80E–08	–2.73E–07	–3.43E–06	1.22E–06	2.23E–04	–9.95E–07	1.73E–06
	Seed	2.20E–08	–9.14E–07	–1.98E–06	–5.24E–07	–9.95E–07	8.34E–07	2.10E–08
	Labor	9.00E–09	–1.59E–06	4.19E–07	–1.71E–06	1.73E–06	2.10E–08	1.21E–06

(continued)

Table B.10b—Continued

Crop category	Input	Water	Irrigation	Machinery	Fertilizer	Pesticide	Seed	Labor
Prairie	Water	4.64E–07	–5.20E–08	–1.99E–07	–6.50E–08	–7.60E–08	–9.50E–08	–1.45E–07
	Irrigation	–5.20E–08	8.69E–05	–6.53E–06	3.47E–06	–1.92E–06	–2.30E–06	–7.05E–06
	Machinery	–1.99E–07	–6.53E–06	4.49E–06	–1.66E–06	–1.27E–06	–1.30E–07	–1.08E–06
	Fertilizer	–6.50E–08	3.47E–06	–1.66E–06	2.96E–04	–1.57E–05	–6.19E–06	–1.65E–05
	Pesticide	–7.60E–08	–1.92E–06	–1.27E–06	–1.57E–05	1.25E–03	–1.37E–05	–4.10E–05
	Seed	–9.50E–08	–2.30E–06	–1.30E–07	–6.19E–06	–1.37E–05	9.54E–06	–1.02E–06
	Labor	–1.45E–07	–7.05E–06	–1.08E–06	–1.65E–05	–4.10E–05	–1.02E–06	1.02E–05
Othjan	Water	5.29E–07	3.00E–08	4.00E–09	1.10E–07	9.10E–08	5.60E–08	1.40E–08
	Irrigation	3.00E–08	1.11E–05	9.40E–08	–5.00E–08	–2.95E–07	9.80E–08	–3.84E–07
	Machinery	4.00E–09	9.40E–08	1.03E–05	6.60E–07	8.60E–07	1.77E–07	2.76E–07
	Fertilizer	1.10E–07	–5.00E–08	6.60E–07	2.84E–05	–1.64E–06	1.48E–06	1.01E—07
	Pesticide	9.10E–08	–2.95E–07	8.60E–07	–1.64E–06	1.16E–04	8.26E–06	–4.33E—06
	Seed	5.60E–08	9.80E–08	1.77E–07	1.48E–06	8.26E–06	1.69E–05	1.31E—07
	Labor	1.40E–08	–3.84E–07	2.76E–07	1.01E–07	–4.33E–06	1.31E–07	4.72E—06
Othjul	Water	6.55E–07	3.70E–08	5.00E–09	1.37E–07	1.13E–07	7.00E–08	1.70E—08
	Irrigation	3.70E–08	1.11E–05	9.60E–08	–4.80E–08	–2.94E–07	1.00E–07	–3.83E–07
	Machinery	5.00E–09	9.60E–08	1.03E–05	6.62E–07	8.61E–07	1.79E–07	2.78E—07
	Fertilizer	1.37E–07	–4.80E–08	6.62E–07	2.84E–05	–1.64E–06	1.48E–06	1.01E—07
	Pesticide	1.13E–07	–2.94E–07	8.61E–07	–1.64E–06	1.16E–04	8.25E–06	–4.33E–06
	Seed	7.00E–08	1.00E–07	1.79E–07	1.48E–06	8.25E–06	1.69E–05	1.31E—07
	Labor	1.70E–08	–3.83E–07	2.78E–07	1.01E–07	–4.33E–06	1.31E–07	4.73E—06

Note: Annfor indicates annual forage; othjan, other crops planted in January; and othjul, other crops planted in July.

Table B.11 Data for hydropower stations

Station	Owner	Installation	Flow (cubic meters)	Capacity (million kilowatt-hours)	Date
Alfalfal	Chilegener Sociedad Anonima	1991	30.0	600	1991–94
Maitenes	Chilegener Sociedad Anonima	1923/89	11.3	250	1985–87; 1990–94
Queltehues	Chilegener Sociedad Anonima	1928	28.1	120	1985–94
Volcán	Chilegener Sociedad Anonima	1944	9.1	240	1985–94
Puntilla	Compañía Manufacturera de Papeles y Cartones	NA	18.8	100	1986–89
Los Bajos	Carbomet Energía	NA	16.4	300	1986–89
Carena	Compañía Manufacturera de Papeles y Cartones	NA	11.2	200	1986–89
La Ermita	Compañía Minerva Disputada de Las Condes	NA	3.0	230	1986–89
Florida	Sociedad de Canalistas del Maipo	1909	22.0	230	1985–94
Planchada					1986–89

Source: Donoso 1997.

Notes: The Florida hydropower station obtains its water from the Canal San Carlos at the Puente Negro capture point at Casa Viejas and returns the water to the Canal at the paradero 21 of Vicuña Mackenna; the capture point of Central Ermita is Corral Quemado, where the Esteros San Francisco and Yerba Loca unite. This plant returns the water to the Estero San Francisco. The Planchada hydropower station ceased operation in 1989, approximately. It is located at 18 kilometers from the Ermita plant. During operation it extracted water from the Estero Molina. NA indicates that data were unavailable.

Table B.12 Fluviometric stations in the Maipo River Basin

Station	Code	Latitude	Longitude	Height (meters)	Surface (square kilometers)	Date
Río Maipo en las Hualtatas	05701001	33°59′	70°10′	1,820	843	1985–94
Río Maipo en las Melosas	05701002	33°50′	70°12′	1,527	1,488	1985–93
Río Volcan en Queltehue	05702001	33°48′	70°12′	1,365	523	1985–94
Estero Glaciar Echaurren	05703006	33°35′	70°08′	3,000	4	1985–92
Río Maipo en San Alfonso	05704006	33°44′	70°18′	1,108	2,850	1985–94
Río Colorado before joining Río Olivares	05705001	33°30′	70°08′	1,500	834	1985–94
Río Olivares before joining Río Colorado	05706001	33°29′	70°08′	1,500	531	1985–94
Río Colorado before joining Río Maipo	05707002	33°59′	70°22′	890	1,713	1985–94
Río Maipo en el Manzano	05710001	33°35′	70°24′	850	4,968	1985–94
Río Angostura en Valdivia de Paine	05716001	33°48′	70°52′	350	1,394	1985–94
Estero yerba Loca before joining San Francisco	05721001	33°21′	70°22′	1,300	NA	1986–94
Estero Arrayan en La Montosa	05722001	33°21′	70°29′	880	219	1985–94
Río Mapocho en Los Almendros	05722002	33°22′	70°28′	1,024	620	1985–94
Quebrada de Ramón en Recinto EMOS	05730008	33°28′	70°32′	710	26	1991–94
Estero Polpaico en Chicauma	05734001	33°13′	70°55′	500	1,098	1985–94
Canal Colina en Peldehue	05735001	33°11′	70°44′	860	NA	1985–94
Río Mapocho en Rinconada de Maipú	05737002	33°30′	70°49′	420	4,068	1985–94
Río Maipo en Cabimbao	05748001	33°47′	70°32′	35	15,040	1985–94
Estero Puangue en Boquerón	05741001	33°17′	70°08′	488	137	1985–94
Estero Puangue en Ruta 78	05746001	33°29′	70°21′	100	1,670	1985–94

Source: Donoso 1997.
Note: NA indicates that data were not available.

Table B.13 Inflow to rivers and tributaries in a normal year (million cubic meters)

River/ tributary	January	February	March	April	May	June	July	August	September	October	November	December	Annual
up_strm	164.2	104.9	80.5	50.1	47.1	40.7	37.1	34.7	62.4	67.1	122.2	160.0	971.0
quelt_in	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
yeso_in	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
olivar_in	7.3	18.0	19.8	11.4	13.6	13.2	13.8	17.0	21.0	38.5	44.4	31.4	249.4
paine_in	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
choca_in	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
puang_in	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
mapo_in	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
down_strm	9.4	9.1	14.0	15.8	17.3	42.2	57.8	12.9	13.0	8.3	3.1	12.8	215.7
Volcan	55.8	33.7	20.8	8.3	9.2	7.1	9.4	11.7	7.0	13.3	33.7	54.1	264.1
Olivares	61.6	42.3	27.2	9.8	8.1	6.2	7.0	6.8	7.9	11.6	19.4	32.9	240.8
mapocho2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
mapocho1	10.8	2.7	2.0	2.2	4.1	7.1	2.8	7.5	10.4	15.6	15.9	12.6	93.7
arrayan	3.9	2.1	1.9	1.8	2.5	3.8	8.6	4.2	3.4	4.9	7.4	6.3	50.8
plomo	5.7	4.9	3.3	1.1	1.0	0.8	1.1	1.3	1.5	2.5	4.4	4.9	32.5
Lampo	0.6	0.5	0.6	0.7	1.0	2.4	18.1	9.4	4.1	0.7	0.6	0.8	39.5
Colina_u	4.1	1.9	2.0	3.4	2.1	5.3	5.9	5.2	6.2	6.5	6.2	3.6	52.4
peloehue	1.1	0.8	0.8	2.7	8.5	3.2	3.2	1.2	1.4	1.3	0.8	0.8	25.8
tiltil	3.6	3.1	2.1	0.7	0.6	0.5	0.7	0.8	0.9	1.6	2.8	3.1	20.5
Puangue	13.9	16.1	25.4	33.1	39.9	40.3	74.4	52.3	29.7	24.3	20.6	16.0	386.0
Chocalan	8.0	6.9	30.2	2.7	46.0	7.3	4.8	8.1	8.1	3.9	8.4	7.4	141.8
Angostura	45.0	41.4	46.6	43.7	52.4	68.6	83.8	74.0	53.1	50.7	57.5	51.5	668.3
Maitenes	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
Los_baigo	8.9	24.4	24.2	14.4	16.7	16.7	16.9	20.8	26.6	47.2	56.2	38.5	311.5
Planchada	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
Colorado	72.6	45.7	33.2	24.2	20.6	18.0	19.9	17.9	18.7	21.6	39.7	63.5	395.6
Yeso	43.8	24.2	22.9	14.4	10.8	9.4	8.1	6.2	8.3	12.2	23.4	38.3	222.0
maipo_up	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
maipo_md	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
maipo_dw	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
Mapocho3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	1.2
Queltehue	1.9	1.1	1.1	4.4	13.6	7.0	7.0	2.5	3.8	2.6	1.0	2.0	48.0

Source: Donoso 1997.

Note: Data are net inflows. Return flows are discounted.

Table B.14 Parameters for groundwater sources

Groundwater	Initial head (meters)	Maximum head (meters)	Minimum head (meters)	Aquifer area (hectares)	Yield coefficient
GW-A1	165	180	155	40,000	0.33
GW-A2	165	180	155	21,000	0.32
GW-A3	165	180	155	30,000	0.32
GW-A4	165	180	155	1,200	0.33
GW-A5	165	180	155	30,000	0.34
GW-A6	165	180	155	3,000	0.34
GW-A7	165	180	155	2,000	0.34
GW-A8	165	180	155	15,000	0.32
GW-M	165	180	155	15,000	0.33

APPENDIX C

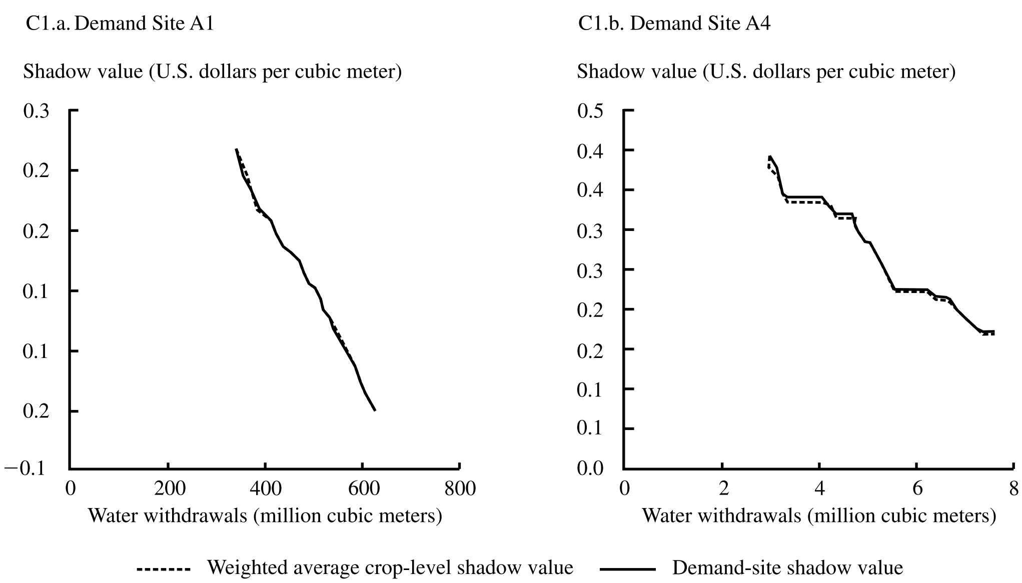
Average Crop-Level Shadow Prices versus Demand-Site Level Shadow Values

In this section, we show that the potential error from averaging net profit–weighted shadow prices from the crop-level water balances instead of demand-site level shadow values is minimal.

To do this, we substituted the weighted average crop-level-based shadow values with demand site-level shadow values (one single value per demand site), as this represents a measure of aggregate crop water demand.

As can be seen in Figure C.1, which compares the weighted average crop-level shadow values and the demand-site shadow values under alternative water withdrawals for irrigation demand sites A1 and A4, the resulting relationships are basically the same. The only difference occurs for low-value crops, such as annual forage or prairie, where the forced lower crop area boundaries can result in negative shadow prices. But these crops receive little weight in the crop-level shadow values because of their weighting by net profits.

Figure C.1 Comparison of weighted average crop-level shadow values and demand-site shadow value under alternative water withdrawals for irrigation demand sites A1 and A4



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