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Integrated economic–hydrologic water modeling at the basin scale: the Maipo river basin

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Abstract

Increasing competition for water across sectors increases the importance of the river basin as the appropriate unit of analysis to address the challenges facing water resources management; and modeling at this scale can provide essential information for policymakers in their resource allocation decisions. This paper introduces an integrated economic–hydrologic modeling framework that accounts for the interactions between water allocation, farmer input choice, agricultural productivity, non-agricultural water demand, and resource degradation in order to estimate the social and economic gains from improvement in the allocation and efficiency of water use. The model is applied to the Maipo river basin in Chile. 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.

Keywords: River basin model; Water policy; Water market

1. Introduction

With growing scarcity and increasing competition for water across sectors, the need for efficient, equitable, and sustainable water allocation policies has increased in importance in water resources management. These policies can best be examined at the river basin level, which links essential hydrologic, economic, agronomic, and institutional relationships as well as water uses and users and their allocation decisions.

To carry out this analysis, an integrated economic–hydrologic modeling framework at the basin level has been developed that accounts for the interactions between water allocation, farmer input choice, agricultural productivity, non-agricultural water demand, and resource degradation in order to estimate the social and economic gains from improvement in the allocation and efficiency of water use. An application to the Maipo river basin in Chile is presented. The following sections give an overview on the research site, introduce the modeling framework, and present results of the model application.

2. 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

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and increasing competition for scarce water resources across sectors. The basin is characterized by a very dynamic agricultural sector — serving an irrigated area of about 127,000 ha (out of a total catchment area of 15,380 km^2) — and a rapidly growing industrial and urban sector — in particular in and surrounding the capital city of Santiago with a population of more than 5 million people. More than 90% of the irrigated area depends on water withdrawals from surface flows. Annual flows in the Maipo river average 4445 million m^3. River fluctuations are predominantly glacial in nature, with considerable flows in summer (November–February) and very pronounced reductions in winter (April–June).

In the mid-1990s, total water withdrawals at the off-take level in the Maipo river basin were estimated at 2144 million m^3. Agriculture accounted for 64% of total withdrawals, domestic uses for 25%, and industry for the remaining 11%. The basin includes eight large irrigation districts with areas of 1300–45,000 ha. Irrigated area in the basin has been gradually declining due to increasing demands by the domestic and industrial sectors for both water and land resources, among other factors. By the mid-1970s, urban Santiago had already encroached on more than 30,000 ha of productive irrigated land (Court Moock et al., 1979). However, the closeness to the capital city also provides a profitable outlet for high-value crop production both for the local market and for the dynamic export sector.

The largest municipal water company, EMOS, supplies about 85% of Santiago's population as well as other urban areas. It owns about 17% of the volume of flow in the upper Maipo river, plus the storage of the El Yeso reservoir with a capacity of about 256 million m^3 (Donoso, 1997). 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. All hydropower stations in the basin are of the run-of-the river type.

Competition among the different water users and uses, in particular, agriculture and domestic and industrial water uses, is increasing rapidly. According to Anton (1993), agricultural areas are mostly flood irrigated, and irrigation efficiencies range from 20 to 60% depending on local conditions. EMOS estimates an increase in domestic water demand of about 330 million m^3 between 1997 and 2022, which it intends to meet chiefly through better use of existing water rights, the purchase of additional rights from irrigation districts, and additional extraction of groundwater. However, in the past, EMOS has been unable to purchase sufficient shares from irrigation districts, and both industry and agriculture are competing for groundwater sources at levels surpassing the recharge capacities of the aquifers in the metropolitan area (Hearne, 1998; Bolelli, 1997). Moreover, increasing competition for scarce water resources in the basin has led to growing pollution problems that have yet to be addressed by policy solutions (Anton, 1993). Although Chile has established the economic instrument of markets in tradable water rights following the Water Law of 1981, which promotes the allocation of water to the uses with the highest values, room for improvement in the areas of water rights for environmental and hydropower (non-consumptive) uses has become evident. These challenges in the Maipo basin will be addressed with the integrated economic–hydrologic modeling framework introduced in the following.

3. The river basin model

3.1. Modeling approach

The river basin modeling system is developed as a node–link network, in which nodes represent physical entities and links represent the connection between these entities (Fig. 1). The nodes included in the network are: (1) source nodes, such as rivers, reservoirs, and groundwater aquifers; and (2) demand nodes, such as irrigation fields, industrial plants, and households. Each distribution node is a location where water is diverted to different sites for beneficial use. The inflows to these nodes include water flows from the headwaters of the river basin and rainfall drainage entering the entities. No prior storage is assumed for the river nodes. A number of agricultural and municipal and industrial (M&I) demand sites or nodes have been spatially connected to the basin network. Agricultural demand sites are delineated according to the irrigation districts. At each agricultural demand site, water is allocated to a series of crops, according to their water requirements and economic profitability. Both crop area and yield are determined endogenously in the model. Two demand sites have been allocated to the major urban area, Santiago.

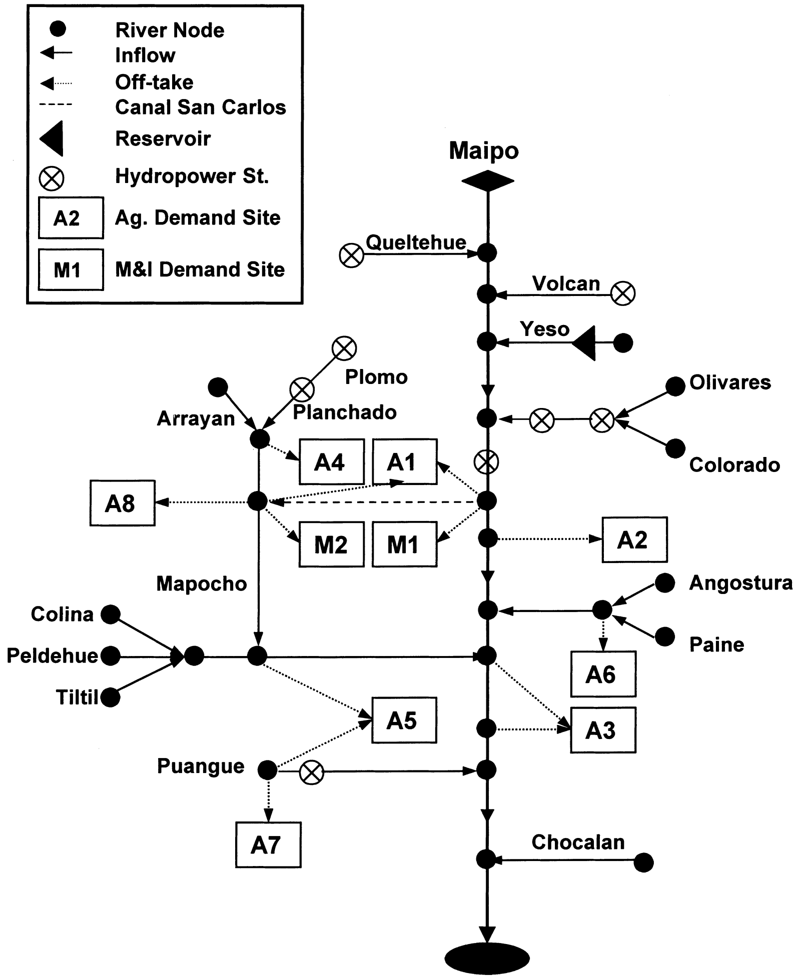

Fig. 1. The Maipo river basin network.

An existing hydrologic model, successfully applied to the Amu Darya and Syr Darya river basins in Central Asia, has been adapted to the Chilean context (McKinney and Cai, 1997). In addition, a prototype economic optimization model has been developed in order to estimate economic returns to water use. Although the model has been developed as an optimization model, simulation components have been included to better solve the complex optimization problem. Hydrologic flow and salinity balance and tranport are simulated endogenously within the optimization model and an external crop–water simulation model is used to estimate the crop yield function, with water, salinity and irrigation technology as variables.

Both instream and off-stream water uses are considered in the model. Instream uses include flows for waste dilution and hydropower generation. Off-stream uses include water diversion for agriculture and M&I water uses. The valuation of instream and off-stream uses is implemented in a unified economic objective function, which is constrained by hydrologic, environmental, and institutional relations. Water demand is determined endogenously within the model by using empirical agronomic production functions (yield versus water, irrigation technology, salinity) and an M&I water demand function based on a market inverse demand function. Water supply is determined through the hydrologic water balance in the river basin with extension to the irrigated crop fields at each irrigation demand site. Water demand and water supply are then integrated into an endogenous system and balanced based on the economic objective of maximizing benefits from water use, including irrigation, hydropower, and M&I benefits. Both water quantity and water quality in terms of salinity are simulated in the model. The salt concentration in the return flow from irrigated areas is explicitly calculated in the model. This allows the endogenous consideration of this externality with respect to upstream and downstream irrigation districts. The model includes all the essential relationships of these components in a 1-year time horizon with a monthly time step.

3.2. Model components

Thematically, the modeling framework includes three components: (1) hydrologic components, including the water and salt balance in reservoirs, river reaches and aquifers within the river basin; (2) water use components, including water for irrigation and M&I water uses; and (3) economic components, including the calculation of benefits from irrigation, hydropower, and M&I demand sites.

Hydrologic relations and processes are based on the flow network, which is an abstracted representation of the spatial relationships between the physical entities in the basin. The major hydrologic relations/processes include: flow transport and balance from river outlets/reservoirs to crop fields or M&I demand sites; salt transport and balance from river outlets/reservoirs to irrigated crop fields; return flows from irrigated and urban areas; interaction between surface and groundwater; evapotranspiration in irrigated areas, and hydropower generation as well as physical bounds on storage, flows, diversions and salt concentrations. The mathematical expressions for these relations, as well as the calculation of deep percolation, return flow from agricultural and M&I demand sites, and the interaction between surface and groundwater can be found in Rosegrant et al. (1999). It is assumed that the water supply starts from rivers and reservoirs. Effective rainfall is calculated outside of the model, and included into the model as a constant parameter.

The agronomic relations involved in the simulation model are adapted from Dinar and Letey (1996), (see also Letey and Dinar, 1986, and Dinar et al., 1991). A curve–linear relationship is assumed between crop yield and seasonally applied non-saline water. Crop yield is simulated under given water application, irrigation technology (the Christiensen Uniformity Coefficient or CUC), and irrigation water salinity. Based on these simulation results, a regression function of crop yield with water application, irrigation uniformity, and salinity was derived through the estimation of the parameters a_0–a_2 and b_0–b_8 in Eq. (1). The function, with specific parameters that have been estimated for all crops in the model, is directly used in the optimization model to calculate crop yields with varying water application, salt concentration, and CUC.

The crop yield function is specified as follows:

$$Y_a = Y_{max}[a_0 + a_1(w_i/E_{max}) + a_2 \ln(w_i/E_{max})] \quad (1)$$

where

$$a_0 = b_0 + b_1 u + b_2 c, \quad a_1 = b_3 + b_4 u + b_5 c,$$
$$a_2 = b_6 + b_7 u + b_8 c$$

and where Y_a is the crop yield (metric tons (mt)/ha), Y_{max} the maximum attainable yield (mt/ha), a_0, a_1, a_2 are regression coefficients, b_0–b_8 are regression coefficients, w_i is infiltrated water (mm), E_{max} the maximum evapotranspiration (mm), c the salt concentration in water application (dS/m), and u the Christiensen Uniformity Coefficient (CUC).

Uniformity (CUC) is used as a surrogate for both irrigation technology and irrigation management activities. The CUC value varies from approximately 50 for flood irrigation, to 70 for furrow irrigation, 80 for sprinklers, and 90 for drip irrigation, and also varies with management activities. By including explicit representation of technology, the choice of water application technology can be determined endogenously. The profit from agricultural demand sites is equal to crop revenue minus fixed crop cost, irrigation technology improvement cost, and water supply cost. The function for profits from irrigation (VA) at demand site dm, is specified as follows:

$$\begin{aligned} \mathrm{VA(dm)} = & \sum_{\mathrm{cp}} A(\mathrm{dm,cp}) Y_a(\mathrm{dm,cp})\, p(\mathrm{dm,cp}) \\ & - \sum_{\mathrm{cp}} A(\mathrm{dm,cp})\,(\mathrm{fc(dm,cp)} + \mathrm{tc(dm,cp)}) \\ & - \sum_{\mathrm{pd}} w(\mathrm{dm,pd})\,\mathrm{wp(dm)} \end{aligned} \quad (2)$$

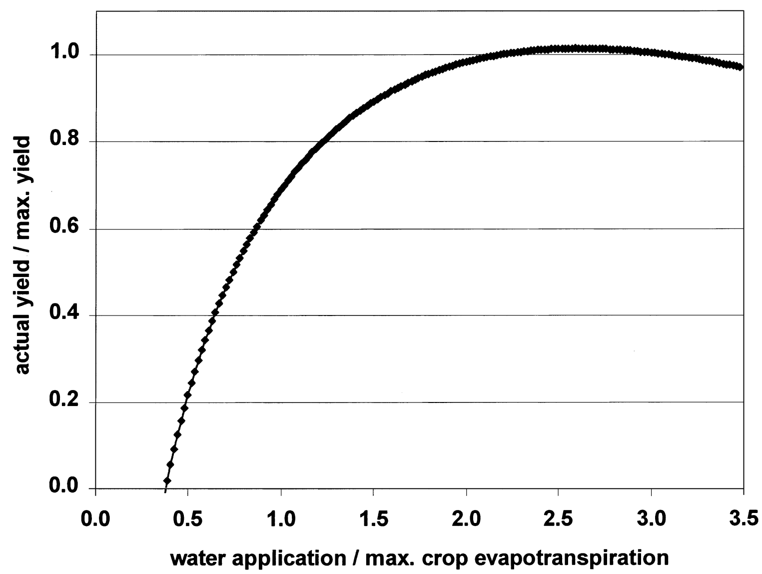

Fig. 2. Crop yield function, crop yield (wheat) vs. water application (CUC = 70, Salinity = 0.7 dS/m).

in which A is harvested area (ha), cp the crop type, p the crop price (US$/mt), fc the fixed crop cost (US$/ha), tc $= k_0 10^{(-k_1 u)}$ the technology cost (US$/ha) (formulation following Dinar and Letey (1996) — higher CUC values are associated with greater capital cost for irrigation and/or management costs), wp the water price (US$/m^3), w the water delivered to demand sites (m^3), k_0 the intercept of the technology cost function, and k_1 cost coefficient per unit of u.

A typical crop yield function for wheat in the Maipo river basin is shown in Fig. 2. The function drives the seasonal water allocation among crops, but is not able to distribute the diverted water among crop growth stages according to the water demanded by each stage. In order to achieve consistency with the water balance in the hydrologic system — to fill the gap between the agronomy and hydrology in the optimization model — an empirical yield–evapotranspiration relationship given by Doorenbos and Kassam (1979) has been used to account for the stage effect. This relationship was applied by including a penalty term into the objective function, based on the maximum stage yield deficit (see below for the specification of the penalty term). The penalty drives the water application according to the water demands in crop growth stages.

The net benefit function for M&I water use is derived from an inverse demand function for water. Net benefit is calculated as water use benefit minus water supply cost.

$$\mathrm{VM}(w) = w_0 p_0/(1+\alpha)\left[(w/w_0)^{\alpha} + 2\alpha + 1\right] - w\,\mathrm{wp} \tag{3}$$

where VM is the benefit from M&I water use (US$), w_0 the maximum water withdrawal (m^3), p_0 the willingness to pay for additional water at full use (US$), α is $1/e$, e the price elasticity of demand (currently -0.45).

The function is based on synthesis of partial secondary data and in its current form only applies to surface water. The willingness to pay for water at full use is estimated at US$ 0.35 per m^3. 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 withdrawal to irrigation and to M&I in the base year model solution matches historical values. The small amount of local groundwater use (about 12% of annual M&I withdrawals or 95 million m^3) is treated as a fixed amount. Fig. 3 shows the relationship between water

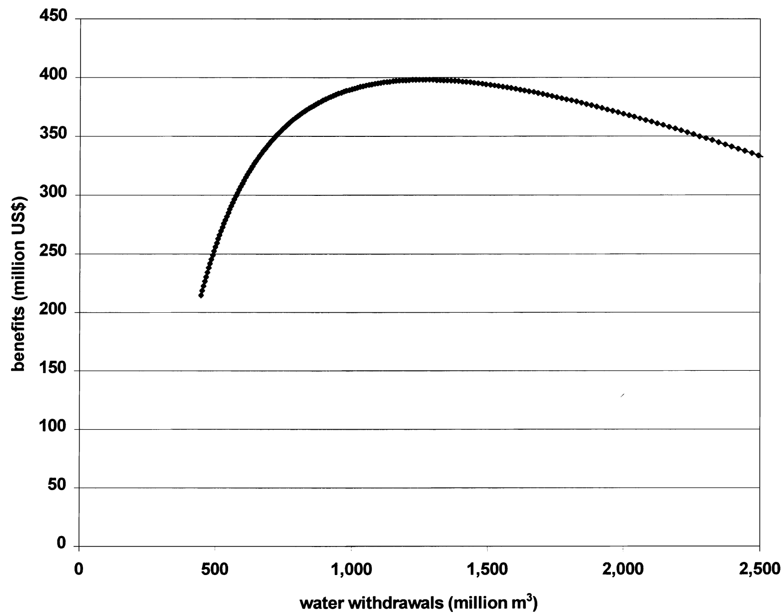

Fig. 3. Relationship between water withdrawals and M&I benefits.

withdrawals and benefits for the M&I net benefit function.

Benefits from power generation are relatively small in the Maipo Basin compared to off-stream water uses. The profit from power generation (VP) at a power station, pwst, is calculated as

$$\mathrm{VP}(\mathrm{pwst}) = \sum_{\mathrm{pd}} \mathrm{power}(\mathrm{pwst}, \mathrm{pd}) \times [\mathrm{pprice}(\mathrm{pwst}) - \mathrm{pcost}(\mathrm{pwst})] \tag{4}$$

where power is the power production, for each power station and period (kW h), which is a function of water flow for runoff stations, and of water release and reservoir head for stations with dams, as well as hydropower generating capacity and efficiency; pprice is the price of power production for each power station (US$/kWh); and pcost is the cost of power production, for each power station (US$/kW h).

The model also includes a series of institutional rules, including minimum required water supply to a demand site, minimum and maximum crop production, flow requirement through a river reach for environmental and ecological purposes, and maximum allowed salinity in the water system. The objective is to maximize economic profit from water supply for irrigation, M&I water use, and hydroelectric power generation, subject to institutional, physical, and other constraints. The objective function is specified as follows:

$$\mathrm{Max\ Obj} = \sum_{\mathrm{irr-dem}} \mathrm{VA}(\mathrm{dm}) + \sum_{\mathrm{mun-dem}} \mathrm{VM}(\mathrm{dm}) + \sum_{\mathrm{pwst}} \mathrm{VP}(\mathrm{pwst}) - \mathrm{wgt\ penalty} \tag{5}$$

where wgt is the weight for the penalty, and penalty is defined as

$$\mathrm{penalty} = \sum_{\mathrm{dem}} \sum_{\mathrm{cp}} \mathrm{pm}(\mathrm{cp}) \times \mathrm{cpprice}(\mathrm{cp}) \times (\mathrm{mdft}(\mathrm{dem}, \mathrm{cp}) - \mathrm{adft}(\mathrm{dem}, \mathrm{cp})) \tag{6}$$

where, over all demand sites and crops, pm is maximum crop production (mt), cpprice the crop selling price (US$/mt), mdft the maximum stage deficit within a crop growth season, and adft the average stage deficit within a crop growth season.

with

$$\mathrm{dft} = k_{\mathrm{y}} \left(1 - \frac{E_a}{E_{\max}}\right) \tag{7}$$

where dft is the stage deficit, k_y the yield response factor, and E_a the actual evapotranspiration (mm), as defined in Doorenbos and Kassam (1979).

3.3. Model solution

The model has been coded in the modeling language of the General Algebraic Modeling System (GAMS) (Brooke et al., 1988), a high-level modeling system for mathematical programming problems. Since the model is highly non-linear and includes a large number of variables and equations, it is solved in two steps. In the first step, the salinity variable is fixed. The solution of this model is used for the initial values of the variables in the second model with variable salt concentration (see Cai, 1999).

4. Results and policy analysis

The focus of the modeling in this paper is on the agriculture sector and to a lesser extent on the non-agricultural water sectors.

4.1. Basin-optimizing solution ('baseline')

Assumptions in the basin-optimizing solution include a water price in M&I demand sites of US\$ 0.1 per m^3 and in agricultural demand sites of US\$ 0.04 per m^3. Crop technology is fixed at CUC equal to 70. Moreover, it is assumed that 15% of the inflow is reserved for environmental (instream) uses. The source salinity is 0.3 g/l. No water right is set up and water withdrawals to demand sites depend on their respective demands with the objective of maximizing basin benefits.

The model incorporates 15 crops, but the five main crops with regard to harvested (irrigated) area are annual forage, corn, grapes, peach and other orchard trees, and wheat. Table 1 presents the production for these crops determined by the model for the irrigation demand sites in the basin, compared with the actual production data for 1994–1996. As can be seen, the basin-optimizing solution estimates a higher overall production, compared to the 1994–1996 values. Moreover, the solution favors the crops with higher profit per unit of water supplied, such as peach and grapes. Table 2 shows the baseline harvested area derived from the model and a comparison with the actual situation in the basin in the mid-1990s. The total harvested area estimated by the model is 146,007 ha, compared to an area under production in 1994–1996 of 127,111 ha. Again, crops that demand large amounts of water and/or have lower economic values account for relatively less area in the model result compared to the actual data. Moreover, water withdrawals in the M&I demand sites reach the benefit-maximizing demand level at 1457 million m^3.

Under the baseline, total effective rainfall is estimated at 116 million m^3. Total water withdrawals are

Table 1
Crop production in the basin, basin-optimizing result and actual data[a]

Crop	Wheat (mt)	Corn (mt)	Ann. for. (mt)	Grape (mt)	Peach (mt)	Other (mt)	Total (mt)
A1	31022	38267	28620	176022	129252	532849	936032
A2	10734	14319	10721	72171	50142	189975	348061
A3	21827	48169	22321	20218	27935	288623	429093
A4	744	2278	869	995	2814	12296	19995
A5	41466	30419	28875	36397	51232	360569	548960
A6	1678	3545	1941	14316	9885	37544	68908
A7	2656	174	3706	29	30	7734	14328
A8	13473	478	5428	48675	46631	129140	243825
Basin	123600	137647	102482	368822	317921	1558730	2609202
Actual prod.	105159	165210	192140	220109	193271	1004935	1880824

[a] Actual production is average for 1994–1996. As crop diversity in the basin is extremely high, some crops are averages of aggregate production of similar crops. Peach, for example, includes almond, apricot, cherry, nectarines, peach, and plum. Source of actual production data: Donoso, 1997.

Table 2
Harvested area, basin-optimizing result[a]

Crop	Wheat (ha)	Corn (ha)	Annual forage (ha)	Grape (ha)	Peach (ha)	Other (ha)	Total (ha)
A1	5607	4196	2529	9264	6463	20271	48329
A2	1925	1574	936	3798	2527	7035	17795
A3	3899	5219	1925	1064	1401	12620	26128
A4	135	248	76	52	141	505	1157
A5	7446	3344	2521	1916	2574	15840	33642
A6	302	384	170	753	494	1367	3471
A7	482	19	325	2	2	397	1227
A8	2440	53	481	2562	2346	6377	14258
Basin	22235	15037	8963	19412	15947	64412	146007
Model/actual	1.0	0.8	0.6	1.5	1.5	1.3	1.1

[a] Source of actual harvested area: Donoso, 1997.

estimated at 3817 million m^3, 86% of the total inflows of 4445 million m^3. Water withdrawals are lowest in the months of June and July, as only perennial crops are present during this time. An apparent excess use of surface water — withdrawals exceed source flows — 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 m^3 or 20% of total inflows. Actual crop evapotranspiration is estimated at 954 million m^3, 99.7% of the total potential crop evapotranspiration of 956 million m^3. This value compares well with the data estimated in Donoso (1997) of 972 million m^3. According to the model results, total agricultural water withdrawals amount to 2360 million m^3, which again is close to the 2107 million m^3 estimated in Donoso (1997). The difference can be explained, in part, by the different irrigation efficiencies. The overall efficiency estimated by local experts is about 45%, whereas the efficiency according to model results is 40.4%.

4.2. Sensitivity analysis

Four sensitivity analyses are presented in the following to test the robustness of the model results: changes in hydrologic levels, irrigation technology cost, crop price, and source salinity (Table 3). According to the sensitivity analyses, M&I water withdrawals and benefits barely change with the

Table 3
Sensitivity analysis, various parameters[a]

	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
Technology cost	75	100.0	100.0	102.5	100.0
	125	100.0	100.0	97.5	100.0
	150	100.0	100.0	95.1	100.0
Crop price	75	94.8	100.0	39.8	100.0
	125	101.6	100.0	161.0	100.0
Salinity in source	50	95.5	100.0	102.8	100.0
	150	101.6	100.0	96.4	100.0
	200	105.1	100.0	86.4	100.0

[a] Sensitivity analyses, except for the inflow scenarios, were carried out based on normal flow. All percentages are relative to the baseline.

Table 4
Sensitivity analysis for irrigation water price at 50% of normal inflow

Scenarios	I	II	III	IV
Irrigation water price (US$/m^3)	0	0.02	0.04	0.08
Irrigation withdrawals (million m^3)	1387	1380	1351	1326
Crop area (irrigated) (ha)	115200	115191	115176	115032
M&I water withdrawal (million m^3)	1258	1263	1283	1303
Irrigation profits (million US$)	224	196	165	130
M&I profits (million US$)	550	552	558	570
Total profits (million US$)	774	748	722	700

changing range of technology cost, crop price, and source salinity under conditions of normal flow. This is because, at normal inflows, the 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 (see Table 4).

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% and M&I benefits decline by 9% compared to normal inflows. Moreover, water withdrawals plunge by 42% for irrigation and by 13% in M&I demand sites. Thus, in the case of drought, the agriculture sector is much more affected. Agricultural water withdrawals are not sensitive to the cost of irrigation technology and profits from irrigation vary only slightly with changes in technology cost. Proportional changes over all crop prices in the range of ±25% have only small effects on irrigation water withdrawals. However, farmer incomes from irrigation are significantly affected. With a reduction of crop prices by 25%, irrigation water withdrawals decline by 5%, whereas profits from irrigation drop by 60%.

A doubling of the source salinity leads to an increase in irrigation water withdrawals for salt leaching by 5%. Increased salt leaching reduces profits from irrigation by 14%. 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 from 10 to 8% of total area planted whereas the area planted with wheat — a more salt tolerant crop — increases from 15 to 18%.

Table 4 shows the effects of changes in the water price for agriculture on water withdrawals and incomes in the irrigation and M&I sectors for a drought-year case (50% of normal inflows). With an increase in the water price for irrigation from zero to US$ 0.08 per m^3, water withdrawals for agriculture decline by 5%, from 1387 to 1326 million m^3. However, changes in the water price barely affect the crop area. Irrigated area is maintained because farmers shift on the margin to more water efficient crops and reduce water use per hectare. Although both water withdrawals and irrigated crop area barely change with varying water prices, farmer incomes can drop drastically under this 'administrative price scenario': by 42% from US$ 224 million to US$ 130 million with increasing prices. M&I benefits, on the other hand, increase steadily with continuing water price increases in agriculture, from US$ 550 million to US$ 570 million and M&I water withdrawals increase by 3.6%. With water prices already quite high (higher than what most farmers in the United States pay), further price increases are 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.

4.3. Economic analysis of water trading

There are two fundamental strategies for dealing with water scarcity in river basins, supply management and demand management; the former involves activities to locate, develop, and exploit new sources of water, and the latter addresses the incentives and mechanisms that promote water conservation and efficient use of water.

The primary alternative to quantity-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 (Rosegrant et al., 1995; Gardner, 1983). The choice between administered prices and markets should be largely a function of which system has the lowest administrative and transaction costs (TC). Markets in tradable water rights can reduce information costs; increase farmer acceptance and participation; empower water users; and provide security and incentives for investment and for internalizing the external costs of water uses. 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 and Binswanger, 1994; 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. Tradable water rights could lead to massive transfers of water to urban and industrial centers. Therefore, farmers need to be protected by adequate institutions and organizations. 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 the allocation of water within and between sectors are realized through markets in tradable water rights (for details, see Gazmuri Schleyer and Rosegrant, 1996; Hearne and Easter, 1995).

The integrated economic–hydrologic river basin model allows for a fairly realistic representation and analysis of water markets. Water trading in the basin is constrained by the hydrologic balance in the river basin network; water is traded taking account of the physical and technical constraints of the various demand sites, reflecting their relative profitability in trading prices; water trades reflect the relative seasonal water scarcity in the basin that is influenced by both basin inflows and the cropping pattern in agricultural demand sites (whereas the M&I water demands are more stable); and negative externalities, like increased salinity in downstream reaches due to incremental irrigation water withdrawals upstream, are endogenous to the model framework.

4.3.1. Model formulation for water trading

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, the model is run separately for each demand site with varying water withdrawals as inputs and shadow prices or marginal values as output derived from the water balance equations (each irrigation demand site includes a water balance equation for each of up to 15 crops). These shadow prices are then averaged over all crops to obtain one shadow price for each water supply level for each demand site. Based on these input and output values a regression function is estimated for the shadow price — water withdrawal relationship for each demand site. Fig. 4 shows the model results and the regression relationship between shadow price and water withdrawals for an agricultural demand site.

Water rights are allocated proportionally to total inflows based on historical withdrawals for 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. The water right refers to surface water only. To determine the lower bound for profits from water trade by demand site (it is assumed that no demand site can lose from trading), the model is solved for the case of water rights without trading. Finally, the regression relationships of shadow price

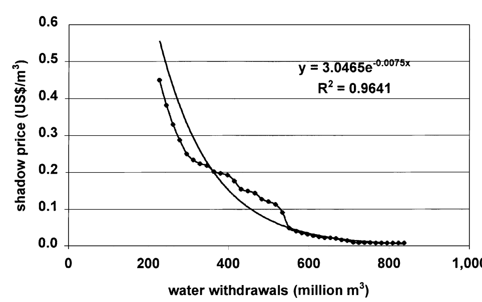

Fig. 4. Relationship between shadow prices and water withdrawals (demand site A5).

versus water withdrawal for all agricultural and M&I demand sites, the water rights, and other water trading related constraints (see Rosegrant et al., 1999) are added to the basin model. It is assumed that the trading price for each demand site is equal to its shadow price for water. This model is then solved to determine the water trading price, wtp, and the volume of water bought and sold by demand site.

Trade is allowed on a monthly basis and throughout the basin and TC are incurred by both buyer and seller (US$ 0.04 per m^3). Up to 4 months of the realized monthly water right can be traded as the monthly balances had been found as too tight of a constraint on water supply for crop growth.

4.3.2. *Water trading analysis*

Three scenarios are compared to assess the impact of water trading: a baseline with omniscient decision-maker optimizing benefits for the entire basin (BO); water rights with no trading permitted (WR), and water rights with trading (WRT). The salinity variable is fixed for all three water trading scenarios. The results compare two cases for each of these three scenarios: hydrologic level at 100% of the normal inflow and at 60% of the normal inflow (Table 5). In addition, three TC scenarios are analyzed based on normal inflow (Table 6). The description of results will concentrate on the drought-year scenario (case B, 60% of normal inflow), as the benefits vary more clearly by economic instrument employed.

In the case of a drought year, total water withdrawals are highest for the basin optimizing case (BO), as each and every demand site can withdraw according to its monthly needs subject to an optimum result for the basin as a whole. These needs are thus only confined by physical parameters, such as relative location in

Table 5
Scenario analysis: basin-optimizing solution, water rights without trade, and water rights trading

Site	Withdrawals			Water right	Net trade	Net profits			'Gains'[b]	Shadow price of water		
	BO (million m^3)	WR	WRT[a]	WR&WRT	WRT	BO (million US$)	WR	WRT	WRT	BO (US$/$m^3$)	WR	WRT
Case A: 100% 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	3581	2977	3108	3778	0	939	749	850	101			
Case B: 60% 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	3067	2296	2437	2272	0	874	389	696	307			

[a] These withdrawals are net of water traded.
[b] Gains are gains from trade.

Table 6
Transaction cost scenarios (case A)

Transaction costs (US$/m^3)	Withdrawals (million m^3)	Water traded (million m^3)	Total net benefits (million US$)	'Gains' from trade (million US$)	Shadow price (US$/m^3)
0.00	3119	278	871	122	0.1808
0.04	3108	264	850	101	0.1844
0.10	3075	236	822	73	0.4127
0.20	3051	138	755	6	1.2680

the basin and institutional requirements. Water withdrawals decline substantially in the WR case, relative to BO, when withdrawals are limited to the respective water right and trading is not allowed. 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 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 right to the M&I demand sites, thereby reaping substantial profits. In the dry-year case, a total water volume of 296 million m^3 is traded, about 11% of total dry-year inflows. In the case of normal inflows, 264 million m^3 of water is traded, about 6% of total inflow. M&I areas are the main buyers in both cases, purchasing virtually all the water offered by the irrigation districts. All irrigation districts are net sellers of water over the course of the year. Under the drought-year case, only district A8 purchases 0.2 million m^3 of water to maintain its cropping pattern that features the largest share of higher-valued, perennial crops (grapes, peach, among others, see Table 2). 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 m^3 and 10.8 million m^3, respectively) to supplement their crop production in some months; however, overall both districts are net sellers of water.

As the WR system does not allow the transfer of water to more beneficial uses, benefits from water uses are significantly reduced by locking the resource into relatively low valued uses during 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-valued urban water uses while at the same time benefiting farm incomes. Total benefits in the M&I demand sites almost triple, compared to the WR case, but gains are also significant for the irrigation districts and each district can increase net profits, by between 6 and 62%, depending on their respective physical and other characteristics. Total net profits of the sector increase by about 20%, from US$ 253 million to US$ 301 million. In irrigation districts A1–A5 and A7, total net profits under the WRT scenario are even higher than for the basin-optimizing case. This is due to the higher value of the scarcer water and the resulting benefits from trade and does not occur in case A with normal inflow levels.

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 mt to 1.729 million mt. In addition, the proportion of higher-value perennial crops increases substantially from the WR to the WRT scenarios, from 14 to 19% for grapes and from 13 to 16% for peach, for example. These results not only show the advantages of the water market approach compared to the WR case, but also to the administrative price scenario presented in the sensitivity analysis, in which water is also reallocated from agricultural to non-agricultural 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% of the omniscient decision-maker (BO scenario) to 80%. 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 decision-maker when in fact the cost would likely be very high.

For the water trading scenario, it is currently assumed that both buyer and seller contribute equally to TC (US$ 0.04 per m^3). Three TC scenarios were run in addition to this base trading scenario: zero TC, US$ 0.1 per m^3, and US$ 0.2 per m^3. The results are shown in Table 6. As can be expected, water withdrawals decline with increasing TC, and the volume of water traded plunges by more than half, from 278 million m^3 for the case without TC to 138 million m^3 for the case with TC of US$ 0.2 per m^3. This is due, in part, to the fact that the TC are quite high relative to the shadow prices for water, which range from US$ 0.18 to 1.27 per m^3. Total net benefits decline substantially, from US$ 871 million at zero TC to US$ 755 million at TC of US$ 0.2 per m^3; gains from trade also drop sharply, from US$ 122 million to only US$ 6 million, respectively. Thus, making trading more efficient (reducing TC) has significant benefits, increasing both the volume and the benefits from trade.

5. Conclusions

This paper presents a prototype river basin model that includes essential hydrologic, agronomic and economic relationships, and reflects the interrelationships of water and salinity, food production, economic welfare, and environmental consequences. The model is applied to the Maipo river basin in Chile, but due to its generic form and structure can be applied to other basins.

The model results show the benefits of water rights trading with water moving into higher valued agricultural (and M&I) uses. Net profits in irrigated agriculture increase substantially compared to the case of proportional use rights for demand sites. 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.

Although these preliminary results show the effectiveness of the model for policy analysis and water allocation in the river basin, additional research is needed. During a second research phase, the agricultural production functions will be extended to include inputs in addition to land, water, and irrigation technology, such as agricultural chemicals and labor. In addition, the urban water demand functions will be re-estimated based on empirical data and disaggregated into household and industrial water demands. Moreover, the power generation will be calibrated to local parameters. Based on this extension, more comprehensive policy analysis will be carried out. Existing institutions regarding water rights, priority allocations, and additional institutional realities will be better represented based on local data. Finally, direct cooperation will be established with the relevant government authorities and water user associations in the basin, with the goal of institutionalizing the model as a decision support system for basin water policy.

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