EPTD DISCUSSION PAPER NO. 72

DOES EFFICIENT WATER MANAGEMENT MATTER? PHYSICAL AND ECONOMIC EFFICIENCY OF WATER USE IN THE RIVER BASIN

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ABSTRACT

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, while 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: does enhancement of physical water use efficiency always lead to improved economic water use efficiency? How does the change in responsiveness of water allocation and irrigation technology to economic incentives affect physical and economic irrigation efficiency? What is the impact on physical and economic efficiency of various structural and nonstructural improvements? To explore these issues, an integrated economic-hydrologic river basin model is applied to the Maipo River Basin in Chile. A series of modeling scenarios are defined and policy implications from physical and economic efficiencies for basin-wide irrigation water management are analyzed.

Keywords: Basin water management; Water use efficiency; Irrigation efficiency; Economic efficiency.

CONTENTS

Does Efficient Water Management Matter? Physical and Economic Efficiency of Water Use in the River Basin

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1. INTRODUCTION

Agriculture today accounts for the majority of global water withdrawals, and is often responsible for 80 percent or more of total withdrawals in developing countries. As populations continue to rise, irrigation will be called upon to provide an increasing share of total food production to meet the growing demand (Rosegrant and Ringler 1998). Moreover, water demand for domestic and industrial uses is projected to grow even more rapidly than agricultural water demand, particularly in developing countries (Shiklomanov 1998; Rosegrant, Ringler, and Gerpacio 1999). A portion of the growing demand for water will be met through new investments in irrigation and water supply systems, and some potential exists for the expansion of nontraditional sources of water supply. However, in many arid or semiarid areas—and seasonally in wetter areas—water is no longer abundant, and the high economic and environmental costs of developing new water resources pose limits to supply expansion. Therefore, new supplies will not be sufficient to meet growing demands.

Achieving water savings in existing uses through increases in water use efficiency in agriculture has been suggested as the most readily available path to meet future demands while satisfying both current and future needs. Thus, irrigated agriculture is increasingly feeling the pressure to both demonstrate and improve upon its performance (Burt et al. 1997). According to

Wallace and Batchelor (1997) there is generally considerable scope for improving the efficiency and productivity of water utilization in agriculture, since normally in both rainfed and irrigated agriculture only about one third of the available water (as rainfall, surface or groundwater) is used to grow food. Poor management has been cited as the most frequent cause of inefficient water use in irrigation schemes (Jensen et al. 1990). Moreover, depending on the local conditions in the irrigation system, a series of agronomic, technical, managerial, and institutional improvements can have large positive impacts on water use efficiencies (Batchelor 1999; Wallace and Batchelor 1997).

However, other analysts have argued that the potential gains from improving agricultural water use efficiencies may be minimal. They argue that low values for measured water use efficiencies that imply substantial potential efficiency gains are often derived from individual system evaluations rather than from basin-wide assessments (Seckler 1995). Unmeasured downstream recovery of "waste" drainage water and recharge and extractions of groundwater can result in actual basin-wide efficiencies substantially greater than the nominal values for particular systems. For example, estimates of overall water use efficiencies for individual systems in the Nile Basin in Egypt are as low as 30 percent, but the overall efficiency for the entire Nile system in that country is estimated at 80 percent (Keller 1992). Thus, the increase of classical irrigation efficiency at the system level can have varying impacts on overall basin irrigation efficiencies, depending on the alternative and previous (re)uses of the water ‘saved’ in the irrigation field, on the prevailing water quality levels, and on the location of the irrigated area within the basin.

Water use efficiency in irrigation has various definitions. Whereas physical efficiency compares the volumes of water delivered and consumed, economic efficiency relates the value of output and the opportunity costs of water used in agricultural production to the value of water applied. A further definition compares the water applied to the biomass or yield output. The relationships between these various measures of water use efficiency are not always clear and, although all of these efficiency concepts can be useful for irrigation water management, their perspectives can result in differing policy implications and strategies for investment in water management and irrigation. Open research questions include, for example: Does enhancement of physical water use efficiency always lead to improved economic water use efficiency? How does the change in the responsiveness of water allocation and irrigation technology to economic incentives affect physical and economic irrigation efficiency? What is the impact on physical and economic efficiency of various structural and nonstructural improvements? To examine these issues, an integrated economic-hydrologic river basin model is applied. The model allows the analysis of the relationship between physical and economic water use efficiency under alternative scenarios of water availability and structural and nonstructural improvement measures. In the following, definitions of irrigation efficiency and their policy implications are presented; the modeling framework is described; results from the scenario analysis are presented; and policy implications are explored.

2. DEFINITIONS OF IRRIGATION EFFICIENCY AND POLICY IMPLICATIONS

Wichelns (1999) presents a detailed review of technical and economic efficiency terms, a part of which is drawn upon in the following.

PHYSICAL IRRIGATION EFFICIENCY

Physical irrigation efficiency represents 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):

$$IE_c = \frac{\text{Crop evapotranspiration - Effective rainfall}}{\text{Volume of water delivered - Change of root zone water storage}} \quad (1)$$

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 et al. (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 proposed a new concept, called effective efficiency (IE_e), which takes into account the quantity of the water delivered from and returned to a basin's water supply:

$$IE_e = \frac{\text{Crop evapotranspiration - Effective rainfall}}{\text{Volume of water delivered - Change of root zone water storage - Volume of water returned}} \quad (2)$$

ECONOMIC EFFICIENCY

Economic efficiency of irrigation water use refers to the economic benefits and costs of water use in agricultural production. As such, 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). Economic efficiency can be expressed in various forms, for example, as total net benefit, as net benefit per unit of water, or per unit of crop area and its broader approach compared to physical efficiency allows an analysis of private and social costs and benefits.

Wallace and Batchelor (1997) describe four categories for improving both physical and economic efficiency at the irrigation system level, including:

- agronomic improvements (for example, improved crop husbandry and cropping strategies);
- technical improvements (for example, advanced irrigation system);
- managerial improvements (for example, adoption of demand-based irrigation scheduling systems and improved maintenance of equipment); and
- institutional improvements (for example, introduction of water pricing and improvement in the legal environment);

and Dinar (1993) presents evidence of increased water use efficiency in irrigation through a combination of these improvements for river basins in California and northern Mexico.

PHYSICAL AND ECONOMIC EFFICIENCY AT THE RIVER BASIN SCALE

Water use efficiencies at the river basin scale basically extend the efficiencies at local sites to the basin level. Irrigation efficiency at the basin scale is the ratio of crop water evapotranspiration to total water depletion for irrigation in the basin. The concept takes into account the potential reuse of return flows and the potential decline in the water quality of return flows, and thus follows the concept of effective efficiency suggested by Keller and Keller (1995). However, the concept of basin efficiency and effective efficiency is subject to the following assumptions:

- The amount of return flow is significant relative to water withdrawal;
- The quality of return flow should meet water quality requirements for downstream water uses;
- The return flow can be reused through natural and/or engineering processes, such as withdrawn from rivers and streams, stored in reservoirs or aquifers and could be delivered or pumped, or used for instream committed environment flow, hydropower generation and for ecological preservation; and
- Time lag of flow returning for reuse is neglected. It should be noted that for some basins, there might be a "time lag" for return flows, and that the time lag will affect the reuse of at least part of the return flow by downstream users, which depends on specific hydrologic characteristics in a basin.

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.

Economic efficiency at the basin scale seeks to maximize the net benefits of water uses in the whole basin. The concept can take positive and negative externalities in water use, for example, among upstream and downstream demand sites (irrigation systems), water productivity (output per unit of water consumption), as well as physical efficiencies at the system level into account. In addition, the concept can relate water uses across water-using sectors. However, this issue is not addressed here.

THE RELATIONSHIP BETWEEN PHYSICAL AND ECONOMIC EFFICIENCY

Improvement in the physical efficiency of water use is related to water conservation through increasing the fraction of water beneficially used over water applied, while enhancing economic efficiency is a broader concept seeking the highest economic value of water use through both physical measures and allocation of water to the highest valued uses and users. However, does optimal physical irrigation efficiency correspond to optimal economic efficiency?

Lynne, Anaman, and Kiker (1987) show that the management of soil moisture in the crop root zone differs for the objectives of optimal physical and economic irrigation efficiency. According to the authors, physical efficiency, defined as Eq. (1), is determined by the selection of the depth of irrigation (related to the water source and supply capacity) and the uniformity of water application (related to the irrigation system and field water management). Once optimal physical efficiency is achieved, economic efficiency can be improved based on the selection of the frequency of water applications. The frequency is determined by selecting the optimal Management Allowed Deficit (MAD), which is expressed as a percentage of the available moisture capacity. MAD is the difference between the full water requirement and the amount of water applied that allows for maximum economic efficiency. It should be noted that the authors used a narrow definition of economic efficiency and that a high level of physical efficiency is not necessarily a pre-condition for improved economic efficiency when defined more broadly. For example, reallocating water from lower to higher valued uses will increase economic efficiency, even if physical efficiency remains unchanged.

Sutton and Jones (1994) show, based on an agronomic-economic simulation model for lettuce, that optimal physical efficiency could differ from optimal economic efficiency under various physical conditions and economic incentives. The authors expressed physical efficiency as crop production per unit of water applied, which is identical to classical irrigation efficiency assuming that crop yield is proportional to crop evapotranspiration. Economic efficiency was defined as net profit per unit of area. They find that optimal physical efficiency was achieved at a lower relative water supply than optimal economic efficiency**.**

Both studies analyze efficiency concepts for the crop field scale. At the basin level, the relationship between physical efficiency and economic efficiency can be more complex due to issues such as water allocation among various water users, or the contribution of upstream return flows to downstream water availability, for example. 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 so-called closed or highly developed river basins, where little or no 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 technical limit, and field application efficiencies are 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 an irrigation system, improvements in physical efficiency are only attractive from an economic perspective if the water saved is transferred to higher-valued uses, for example, through changes in the cropping pattern, or through water marketing between systems, or reallocation of water to higher-valued uses, like domestic-industrial uses.

Finally, if improvements in physical efficiency lead to environmental or ecological damage, for example, a reduction in water quality levels, waterlogging and salinization, or other negative externalities and third-party effects, they can actually decrease economic efficiency levels (Wichelns 1999; Dinar 1993).

In the following, these relationships and issues will be empirically examined based on an integrated economic-hydrologic river basin model for the Maipo River Basin in Chile.

3. CASE STUDY – 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 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, particularly in the capital city of Santiago with a population of more than 5 million people. More than 90 percent of the irrigated area in the basin depends on water withdrawals from surface flows. In the mid-1990s, total water withdrawals at the off-take level in the Maipo River Basin were estimated at 2,144 million m^3, about 48 percent of the annual average flow in the basin (4,445 million m^3). Agriculture accounts for 64 percent of total withdrawals, domestic uses for 25 percent and industry for the remaining 11 percent. Total return flows amount to about 20 percent of total inflows. Active reservoir storage amounts to only 130 million m^3—less than 3 percent of average runoff in the basin. Irrigation is of particular importance for perennial crops during the low flow season, like grapes or fruit trees. Benefits from power generation are relatively small in the Maipo Basin; hydropower production is only carried out on run-off-the river power stations.

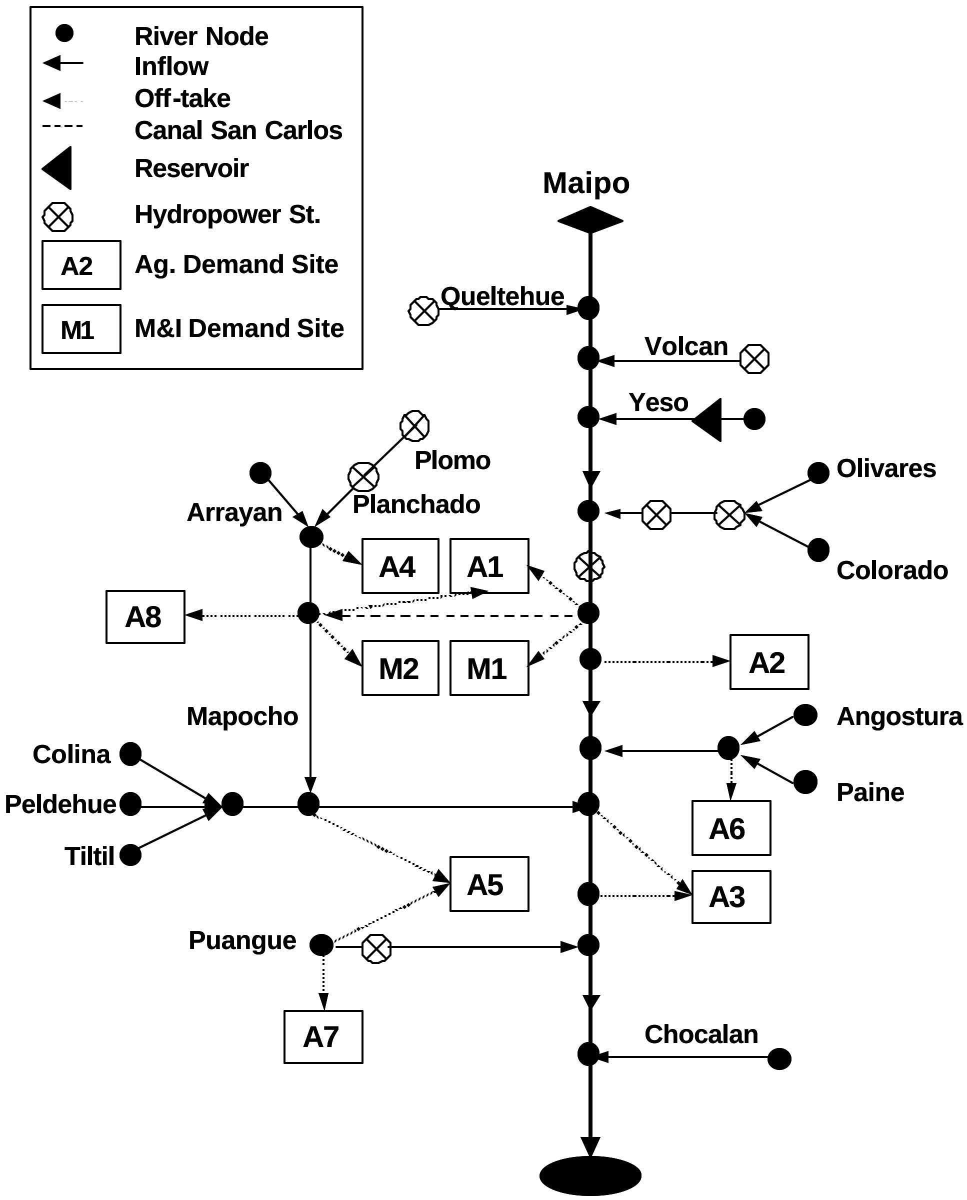
The basin includes 8 large irrigation districts (A1 – A8) with irrigated areas ranging from 1,300-45,000 ha. According to Anton (1993), agricultural areas are mostly flood irrigated, and irrigation efficiencies range from 20 to 60 percent depending on local conditions. The basin average efficiency estimated by local experts is about 45 percent. 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. 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.

Rosegrant et al. (1999, 2000) developed a model for optimal allocation and use of water resources in the Maipo river basin that incorporates the hydrologic, economic, agronomic, and institutional relationships essential for this level of analysis. The basic methodology and structure of the model are described in the following.

Integrated Economic-Hydrologic Model

The river basin modeling system is developed as a node-link network, with nodes representing physical entities and links the connection between these entities (Figure 1).

Figure 1: Node-link network of the Maipo River basin in Chile

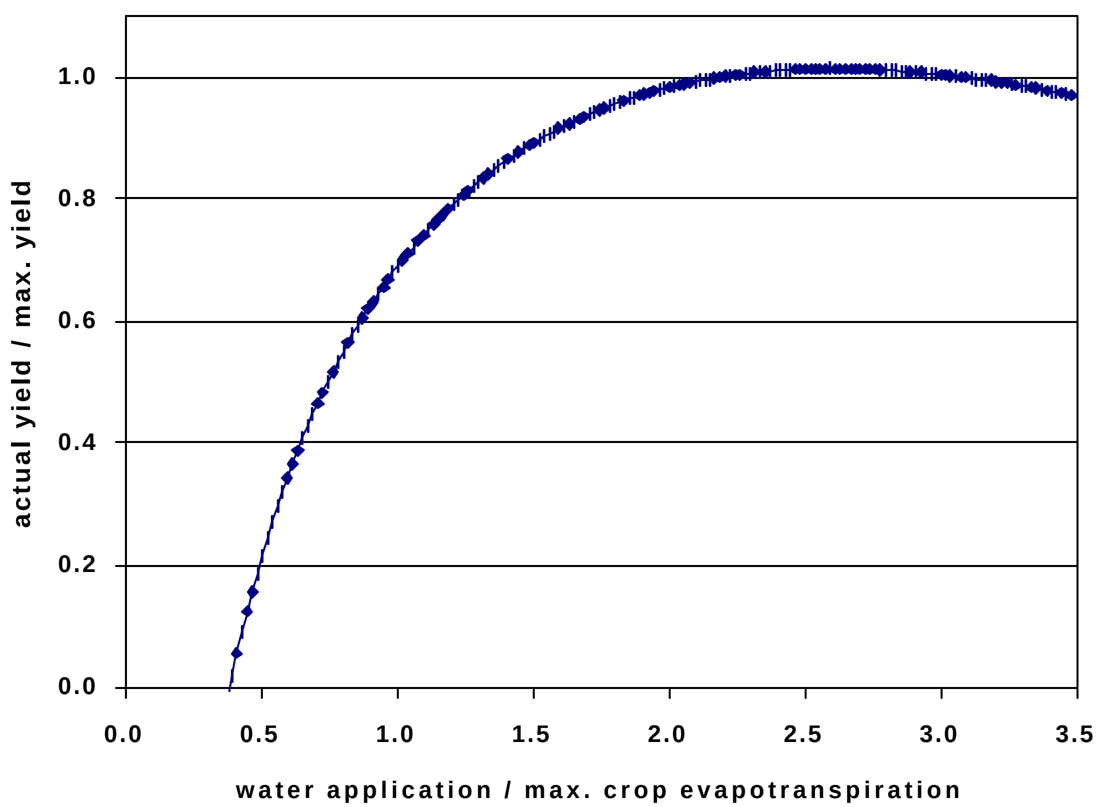


The nodes included in the network are source nodes, such as rivers, reservoirs, and groundwater aquifers and agricultural and municipal and industrial (M&I) demand nodes, which are spatially connected to the basin network. Agricultural demand sites are delineated according to the irrigation districts. At each agricultural demand site, water is allocated to a series of crops, according to their water requirements and economic profitability. In addition to these off-stream uses, instream uses are considered, including minimum flows for environmental uses, flows for waste (salt) dilution, and for hydropower generation. Based on the node-link network, a prototype economic optimization model has been developed with the objective to maximize economic returns to water uses at the basin level. Water demand is determined endogenously based on empirical agronomic production functions for agriculture, and an M&I net benefit 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 supply are then balanced based on the economic objective of maximizing net benefits to water use.

The modeling framework includes hydrologic, agronomic, and economic components. The major hydrologic relations and 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 calculation of the salt concentration allows the endogenous consideration of this externality with respect to upstream and downstream irrigation districts. A one-year time horizon and a monthly time step are applied to the hydrologic processes.

The major agronomic component involved in the model is the crop yield function, which is derived based on a crop-water simulation model (Dinar and Letey 1996). Crop yield is simulated under given water application, irrigation technology (the Christiensen Uniformity Coefficient or CUC), and irrigation water salinity. 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 an explicit representation of technology, the choice of water application technology can be determined endogenously. Based on the simulation results, a regression function for crop yield is derived based on the water application, irrigation uniformity, and salinity concentration of the irrigation water for each crop in the model. Figure 2 shows an example of a crop yield function for wheat.

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



The objective function in the optimization model calculates total net benefits/profits to water use *(PT)* from irrigation *(PA)*, municipal and industrial areas *(PMI)*, and hydropower production *(PHP)* over the corresponding water demand sites (*dm*) and hydropower stations (*st*).

$$PT = \sum_{dm \in Agr.} PA(dm) + \sum_{dm \in M\&I} PMI(dm) + \sum_{st} PHP(st) \tag{3}$$

The seasonal function for net profits from irrigation (*PA*) at demand site *dm* is specified as follows:

$$\begin{aligned} PA(dm) = & \sum_{cp} A(dm,cp)\, Y_a(dm,cp)\; p(dm,cp) - \sum_{cp} A(dm,cp)\big(fc(dm,cp) + tc(dm,cp)\big) - \\ & \sum_{t} w(dm,t) \cdot wp(dm) \end{aligned} \tag{4}$$

in which:

t	=	monthly time period
cp	=	crop type
A	=	harvested area (ha), determined in the model
Y_a	=	actual crop yield (mt/ha)
p	=	crop price (US$/mt)
fc	=	fixed crop cost (US$/ha)
$tc\,(= k_o \cdot 10^{(-k_1 \cdot u)})$	=	technology cost (US$/ha); formulation following Dinar and Letey (1996), in which u is the Christiensen Uniformity Coefficient (CUC); k_0 is the intercept of technology cost function; and k_1 is the cost coefficient per unit of u
w	=	water delivered to demand sites (m^3)
wp	=	water price (US$/$m^3$)

The net benefit for M&I water use is calculated as water use benefit minus water supply cost. The net profit from power generation is equal to gross profit from power sale minus the cost of hydropower generation.

Assuming no change for the seasonal crop root zone water storage, following Eq. (1), the classical irrigation efficiency at a specific irrigation demand site (farm) level is calculated as:

$$IE(dm) = \frac{\sum_{t}\sum_{cp}\left(eta(dm,cp,t) - er(dm,cp,t)\right)\cdot A(dm,cp)}{\sum_{t} WD(dm,t)} \quad (5)$$

Considering the return flows that can be reused downstream, effective efficiency (Eq. 2) at irrigation demand sites, *EIE(dm)* is determined as:

$$EIE(dm) = \frac{\sum_{t}\sum_{cp}\left(eta(dm,cp,t) - er(dm,cp,t)\right)\cdot A(dm,cp)}{\sum_{t}\left(WD(dm,t) - RF(dm,t)\right)} \quad (6)$$

where:

eta (dm,cp,t)	=	Actual evapotranspiration
er (dm,cp,t)	=	Effective rainfall
WD(dm, t)	=	Water withdrawals including surface and groundwater
RF (dm,t)	=	Return flows from demand sites to the water supply system,

and all other terms as defined before.

The basin (effective) irrigation efficiency is calculated as:

$$IE_b = \frac{ETC}{WDP} = \frac{\sum_{dm}\sum_{t}\sum_{cp}\left(eta(dm,cp,t) - er(dm,cp,t)\right)\cdot A(dm,cp)}{\sum_{t}\left(Inflow(t) - Outflow(t) - \Delta S(t)\right)} \quad (7)$$

in which

ETC	=	Actual crop evapotranspiration in the basin
WDP	=	Total irrigation water depletion from the basin
Inflow	=	Inflow including surface drainage and groundwater recharge
Outflow	=	Outflow flow out of the basin
ÄS	=	Change of surface and groundwater storage

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

Economic efficiency in this modeling framework is expressed as total water use profit (PT, Eq. 3). In addition, profit per unit of water consumed *(PUW)* is calculated for each irrigation demand site.

$$PUW(dm) = \frac{PA(dm)}{\sum_t \left(WD(dm,t) - RF(dm,t)\right)} \tag{8}$$

in which PA is net profit from irrigation (Eq. 3). PUW at the basin level is

$$PUW_b = \frac{\sum_{dm} PA(dm)}{WDP} \tag{9}$$

The advantages for using this modeling framework to analyze irrigation efficiency at the basin level lie in 1) realistic water accounting, based on both spatially and temporally distributed water demand and supply; 2) adequate depiction of infrastructure conditions that characterize the water distribution and use systems; 3) endogenous determination of water demands; 4) endogenous consideration of institutions and policy constraints; 5) empirical estimation of economic returns to water use; and 6) analysis of the impact of changes in both physical and managerial measures on the basin water economy.

RESULTS

Analytical Scenarios

The first set of scenarios explores the outcome for physical and economic irrigation efficiency of changes in the responsiveness of water allocation and irrigation technology to economic incentives. The second set of scenarios examines the relationship between economic efficiency and physical efficiency under different distribution and conveyance efficiencies and water prices—a combination of structural and nonstructural measures influencing efficiency. All scenarios are run for a drought-year case (inflows at 60 percent of average flows) to simulate conditions of water scarcity.

Alternative Scenario: Changes in the Responsiveness of Water Allocation and Irrigation Technology to Economic Incentives

The Baseline Scenario (BAS), a full optimization scenario, assumes an omniscient decision-maker allocating water to the most profitable uses. Irrigated crop area is determined within a range of current crop acreage (60 – 150 percent) in the model; and irrigation technology (CUC) is determined within a range of 70 - 95. The irrigation water price is US$0.015/$m^3$; and the water distribution and conveyance loss rate is 0.20 - 0.25. The Fixed Water Rights Scenario (FWR) is defined equally, but in addition defines fixed water rights for the various irrigation demand sites. Water rights are allocated proportionally to total inflows based on historical withdrawals for M&I demand sites and on the harvested (irrigated) area for irrigation 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.

In the Fixed Irrigation Technology Scenario (FIT) the CUC is fixed at the lower bound; all other parameters and assumptions are defined as in BAS. Finally, the Tradable Water Rights Scenario (TRD) assigns the initial water rights of the FWR scenario to the agricultural and non-agricultural demand sites, but permits full trading of water across demand sites. The transaction cost under TRD is US$0.04/$m^3$.

Table 1a shows the results of these four scenarios for total and M&I water withdrawals, total profits and net benefits from M&I water use, and total profit per unit of water at the basin level.

Table 1a: Selected results for baseline *(BAS)*, fixed water rights *(FWR)*, fixed irrigation technology *(FIT)*, and tradable water rights *(TRD)* scenarios, basin-level aggregation

	Total water withdrawal	**M&I water withdrawal**	**Total profit**	**M&I benefit**	**Profit per unit water**
	(million m^3)	***(million m^3)***	***(million US$)***	***(million US$)***	***(US$/$m^3$)***
BAS	3,182	1,457	918	605	0.291
FWR	2,297	758	423	136	0.184
TRD	2,435	1,050	717	392	0.295
FIT	3,067	1,428	874	605	0.282

Table 1b presents results for the individual irrigation demand sites for classical irrigation efficiency *(EI)* and effective efficiency *(EIE)* and for economic efficiency—represented by profit from irrigation per unit of water *(PUW)* and total irrigation profit from water use *(PT)*.

Table 1b: Selected results for baseline *(BAS)*, fixed water rights *(FWR)*, fixed irrigation technology *(FIT)*, and tradable water rights *(TRD)* scenarios, by irrigation demand sites

	Demand Sites	A1	A2	A3	A4	A5	A6	A7	A8	Basin (Irrigation)
Classical Irrigation	BAS	0.424	0.436	0.435	0.436	0.443	0.409	0.534	0.410	0.431
Efficiency *(EI)*	FIT	0.424	0.444	0.413	0.475	0.428	0.397	0.508	0.415	0.426
(Ratio)	FWR	0.478	0.473	0.416	0.421	0.417	0.482	0.538	0.519	0.457
	TRD	0.511	0.514	0.463	0.493	0.474	0.507	0.571	0.547	0.498
Effective Efficiency *(EIE)*	BAS	0.536	0.571	0.569	0.576	0.466	0.520	0.625	0.543	0.530
(Ratio)	FIT	0.527	0.560	0.524	0.586	0.429	0.511	0.590	0.556	0.506
	FWR	0.597	0.598	0.558	0.568	0.446	0.605	0.619	0.630	0.550
	TRD	0.623	0.629	0.592	0.612	0.488	0.620	0.648	0.651	0.583
Irrigation Profit per	BAS	0.266	0.269	0.200	0.247	0.177	0.244	0.142	0.274	0.227
Unit Water *(PUW)*	FIT	0.246	0.250	0.192	0.213	0.160	0.254	0.136	0.263	0.214
(US\$/m^3)	FWR	0.287	0.288	0.203	0.246	0.172	0.280	0.141	0.272	0.236
	TRD	0.338	0.317	0.240	0.397	0.225	0.296	0.282	0.384	0.310
Irrigation Profit *(PT)*	BAS	114.6	44.0	47.1	2.2	57.8	8.9	1.4	36.5	312.6
(million US$)	FIT	97.8	39.3	41.3	1.2	57.8	6.0	1.1	24.6	269.2
	FWR	105.4	40.8	43.9	2.1	59.3	7.6	1.4	26.1	286.6
	TRD	116.7	41.7	48.2	3.1	69.7	7.7	2.7	35.0	324.8
Irrigation Withdrawals	BAS	561.1	223.9	323.5	12.4	365.1	48.4	12.5	179.0	1,726.0
(million m^3)	FIT	513.7	222.4	304.7	7.5	395.3	42.8	11.2	141.8	1,639.5
	FWR	478.7	188.1	303.1	11.9	388.8	35.3	12.7	119.9	1,538.4
	TRD	432.0	166.6	278.6	10.0	342.8	33.1	11.4	110.0	1,384.4

Note: Irrigated harvested area is the weighted area over all demand sites.

As expected, the basin-optimizing baseline scenario generates the highest total profit from water usage in the river basin. At the other end of the spectrum, the fixed water rights regime causes significant losses in basin income. Compared to BAS, FWR has slightly lower irrigation water withdrawals (89 percent of those under BAS), and much lower M&I water withdrawals (52 percent of those under BAS); correspondingly, the M&I net benefit under the FWR scenario falls sharply to only 23 percent of that under BAS, and profit per unit of water withdrawn is 0.107US$/$m^3$ less than under BAS (Table 1a). There are also significant changes in water withdrawals among irrigation demand sites. Under FWR, water withdrawals for upstream and midstream demand sites (A1, A2, A4, A6, and A8) decrease, on average, by 19 percent relative to those under BAS; while water withdrawals for downstream demand sites decrease less (A3) or even slightly increase (A5 and A7). Tables 2a and 2b show selected results for relatively low-valued wheat and high-valued grapes.

Table 2a: Comparison of selected results for wheat under the *BAS* and *FWR* scenarios

Demand Sites	BAS Area	BAS Relative yield	BAS Water application	BAS Field application efficiency*	FWR Area	FWR Relative yield	FWR Water application	FWR Field application efficiency*
	(ha)		*(m³/ha)*		*(ha)*		*(m³/ha)*	
A1	4,100	0.83	8,170	0.68	4,100	0.82	7,923	0.70
A2	3,415	0.83	8,174	0.68	3,773	0.81	7,658	0.71
A3	5,568	0.86	8,406	0.64	2,625	0.91	9,512	0.58
A4	135	0.83	8,135	0.68	135	0.81	7,723	0.70
A5	2,978	0.8	7,815	0.72	2,978	0.78	7,394	0.75
A6	666	0.86	8,925	0.64	302	0.90	10,010	0.59
A7	193	0.78	7,435	0.74	326	0.76	7,137	0.77
A8	1,783	0.83	8,679	0.69	1,783	0.81	8,295	0.71
Basin Tot/Ave	18,839	0.83	8,251	0.67	16,022	0.82	8,086	0.69

*

Table 2b: Comparison of selected results for grapes under *BAS* and *FWR* scenarios

Demand Sites	BAS Area	BAS Relative yield	BAS Water application	BAS Field application efficiency*	FWR Area	FWR Relative yield	FWR Water application	FWR Field application efficiency*
	(ha)		*(m³/ha)*		*(ha)*		*(m³/ha)*	
A1	9,264	1.00	17,655	0.51	6,515	0.99	17,249	0.52
A2	3,798	1.00	17,950	0.49	3,427	0.99	16,982	0.52
A3	1,064	1.00	16,907	0.50	1,064	1.00	16,907	0.50
A4	52	1.00	17,754	0.50	52	0.99	17,174	0.51
A5	1,916	0.99	17,426	0.51	1,916	0.98	16,351	0.53
A6	753	1.00	18,772	0.47	753	0.99	18,167	0.49
A7	2	1.00	17,385	0.50	2	1.00	17,309	0.50
A8	2,562	1.00	18,248	0.51	1,652	0.99	17,660	0.52
Basin Tot/Ave	19,412	1.00	17,771	0.50	15,381	0.99	17,143	0.52

* In this model, field application efficiency is a function of irrigation technology variable (CUC) which is crop-wise.

Under the FWR scenario, irrigation water applied at the field level declines for both wheat and grape, albeit by small amounts, 2 and 4 percent, respectively. Wheat area decreases by 15 percent in the basin with a major reduction in A3 (53 percent); while grape area decreases by 20 percent with major reductions in A1 (30 percent) and A8 (36 percent). This result is due to the fact that under fixed water rights, not all crop water demands can be met during the low flow season of February-March—which is crucial for the maintenance of grape and other perennial crop areas, but not for wheat, which is already harvested. As a result, area planted to grape 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. This frees up water for downstream irrigation districts, helping those districts to maintain their grape areas. Thus, the fixed water rights regime locks water into less productive uses both within and among irrigation districts.

Allowing water trading corrects many of the distortions from fixed water rights. By permitting trading under the TRD scenario, water moves from lower valued crops into higher-valued, perennial crops, and particularly into higher-valued urban water uses while at the same time benefiting farm incomes. Under the TRD scenario, total profits in M&I demand sites increase three-fold compared to the FWR case, but gains in profits are also significant for irrigation districts with profits, including gains from water trading, increasing by 13 percent, from US$287 million to US$325 million (Table 1b). 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/m^3 under the FWR scenario to US$0.310/m^3 under the TRD scenario. At the same time, water withdrawals for agricultural uses decline across irrigation districts, on average, by 10 percent compared to the FWR scenario. This is in part due to 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 irrigation efficiency and effective basin efficiency increase as it becomes profitable for farmers to invest in improved irrigation technologies and to sell the surplus water to urban areas (Table 1b). Profits from agricultural production alone decline from US$287 million under the FWR scenario to US$267 million under the TRD scenario. 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 due to the price of purchased water and the transaction costs incurred during the purchase of water rights (Table 1a).

Choice of irrigation technology proves to be even more important for farmer incomes under the model specifications. When irrigation technology is fixed, profits from irrigated agriculture decline by 14 percent compared to the basin-optimizing level that allows for endogeneity in technology choice based on the economic profitability of the various crops in the model. Net benefits in M&I areas, on the other hand, remain unaffected. Irrigation withdrawals decline, but only by 5 percent compared to the BAS scenario, as both local and effective irrigation efficiencies decline, on average, by 1.2 and 4.5 percent, respectively, due to the lack of responsiveness of technology to the variation in water values across irrigated crops, and water productivity is reduced.

With the possibility of endogenous adjustment of the CUC value, the BAS scenario 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 like 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. For these crops, a reduction in the cost of more efficient irrigation technology could boost both physical and economic efficiency in the basin.

A comparison across the 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 1b). The TRD scenario also results in the highest economic efficiency levels for irrigation alone, both at the per unit and total profit level. Total profits from water use, on the other hand, are largest under the BAS scenario. 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 usage 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 1b). 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 will be further explored in the following section.

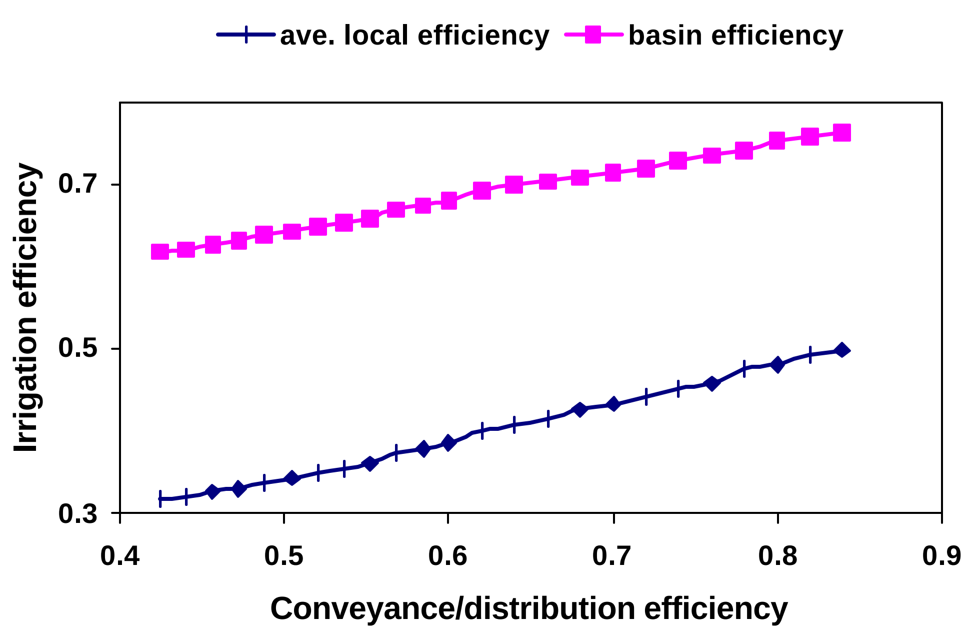
The results also show a tradeoff between optimal off-stream profits from water usage and resource conservation in the absence of an explicit valuation of instream flows. Overall water withdrawals are largest under the BAS scenario, followed by the FIT scenario, as water can move without restrictions to the most profitable uses. As a result, the instream flows left in the Maipo River under these scenarios are near the minimum flow requirements included into 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, on the one hand, water in excess of (off-stream) water rights is left instream, particularly during the high-flow season and, on the other hand, (perennial) crop water demands cannot be fully met during the low-flow season due to the water right 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 m^3 under the BAS scenario and 648 m^3 under the FIT scenario, but are much larger at 1,153 million m^3 and 1,037 million m^3 under the FWR and TRD scenarios, respectively. To the extent that instream flows in excess of minimum flow constraints have value for environmental uses, like conservation of the river habitat, water quality improvement through waste dilution, and for the general aesthetics 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.

Alternative Scenario: Changes in Water Distribution/Conveyance Efficiency and Water Prices

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 efficiency and economic efficiency under alternative irrigation water loss rates and water prices, a series of scenarios are defined for a range of combined water distribution and conveyance efficiency levels from 42-85 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 non-beneficial 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 1b. The effects of changes in the distribution/conveyance efficiency on economic and physical efficiency are analyzed for the baseline water price in irrigation of US$0.015/m^3 and an alternative water price of US$0.05/m^3, respectively.

The physical (effective) basin efficiency (defined by Eq. 7) and the average local or classic irrigation efficiency levels are plotted in Figure 3 for various conveyance/distribution efficiencies.

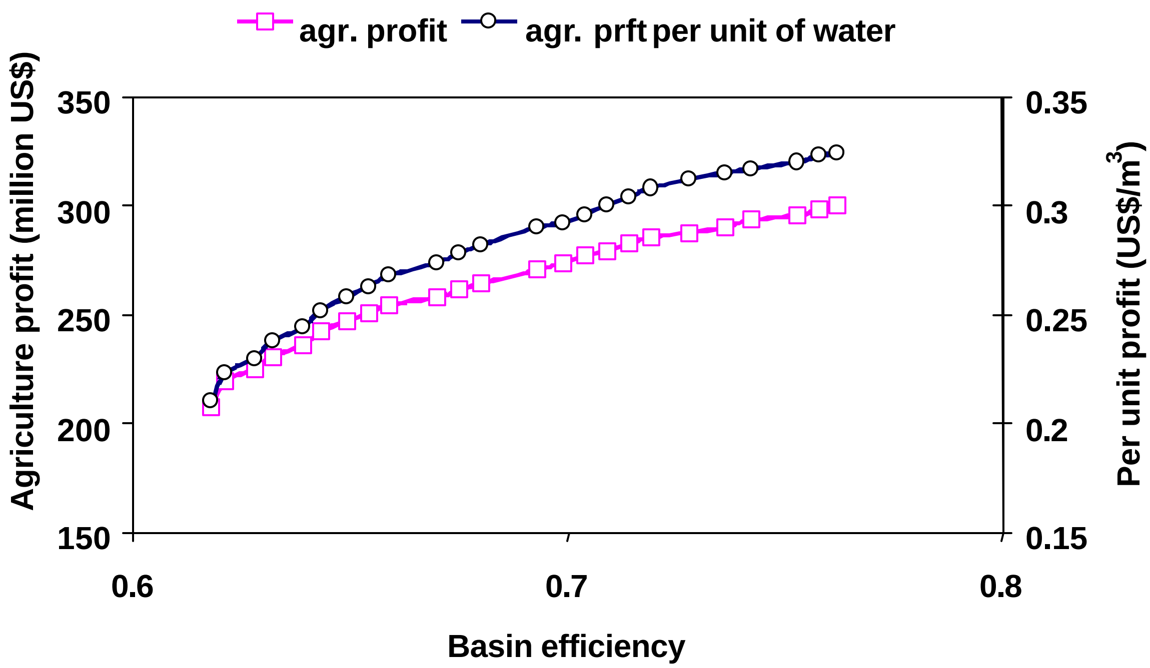
Figure 3: Basin irrigation efficiency and average local irrigation efficiency at various levels of water distribution efficiency



The figure shows that both measures of physical efficiency increase over the range of increasing conveyance/distribution efficiency levels, by 24 percent for basin efficiency and 58 percent for local (classical) efficiency. As 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 local irrigation efficiency.

Figures 4a and 4b show the relationship between economic and physical efficiency under various conveyance/distribution efficiencies for a water price of US$0.015 per m^3. Figure 4a plots the relationship between total agricultural profit and profit per unit of water withdrawn and basin irrigation efficiency.

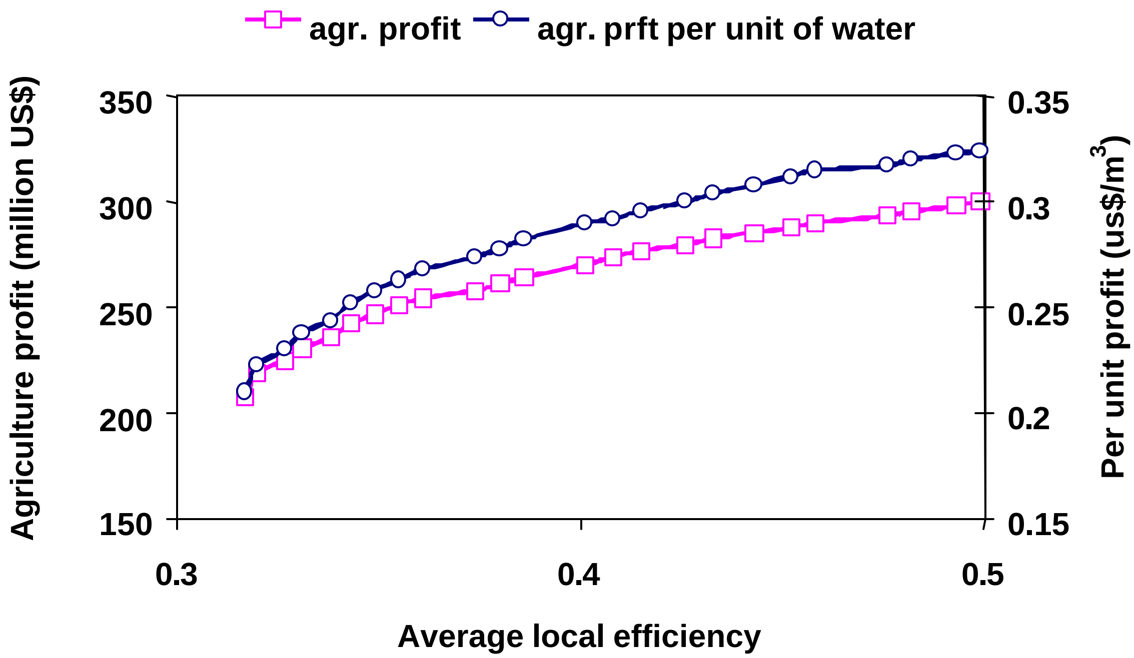
Figure 4a: Relationship between economic and physical efficiency – basin efficiency at various loss rates (water price=US$0.015/$m^3$)



Both total profits from irrigated agriculture and profits per unit of water increase at a declining rate with increasing basin irrigation efficiency. However, due to 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 a point where the marginal benefits of improved physical infrastructure equal the marginal costs of improvement and decline thereafter. 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 4b plots the relationship between total irrigation profits and per unit profits and average local irrigation efficiency.

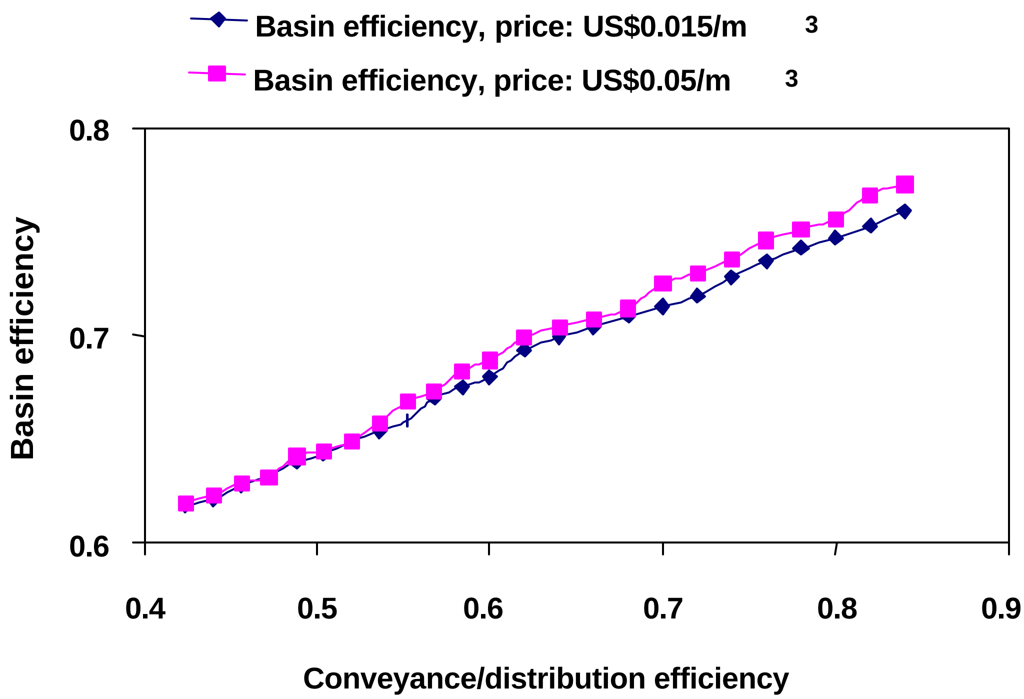
Figure 4b: Relationship between economic and physical efficiency – average local (classical) efficiency at various loss rates (water price=US$0.015/m^3)



Compared to the curves shown in Figure 4a, economic efficiency levels increase more slowly with respect to changing levels of local irrigation efficiency. This result confirms that increasing the classical irrigation efficiency will not have as large an impact as an equal percentage increase in basin efficiency, because the computation of classical efficiency treats return flows as non-beneficial 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—further improvements in agricultural profits are minimal. However, the increase in average local efficiency from 0.32 to 0.50 results in an increase in basin agricultural profits of US$93 million (from US$207 to US$300 million). Increased local (classical) efficiency increases the beneficial evapotranspiration in the crop field, reduces local water losses to deep percolation and non-beneficial evapotranspiration, and decreases the return flows to the river system. The contribution of improvements in local (classical) efficiency to overall basin profits depends on various factors. Contrary to the 'only-basin-efficiency-counts'-school, at low levels of local efficiency, improvements in efficiency levels can and do generate significant basin-wide profits.

In order to study the impacts of non-structural 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 prices. As can be seen in Figure 5, the higher water price results in 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.

Figure 5: **Relationship between physical irrigation efficiency (IE) and conveyance/ distribution efficiency under alternative water prices**



The effect of the higher water price 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.

Figures 6a and 6b show the total profit for all sectors and for irrigated agriculture at different conveyance/distribution efficiencies under the two irrigation water prices. The higher water price results in a decline in both total and irrigation profits. Although farmers adjust to the change in incentive structure from alternative irrigation water prices by reducing water withdrawals through changes in irrigation technology and shifts of water uses to higher-valued crops, the increase in water price results in an overall decline in agricultural 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 prices at these high levels of water losses.

The drop in total profits is smaller than the drop in agricultural profits, because the water prices induce a small increase in non-agricultural water withdrawals and profits (Figure 6a).

Figure 6a: Relationship between total profit (water charge subtracted) and conveyance/distribution efficiency under alternative water prices

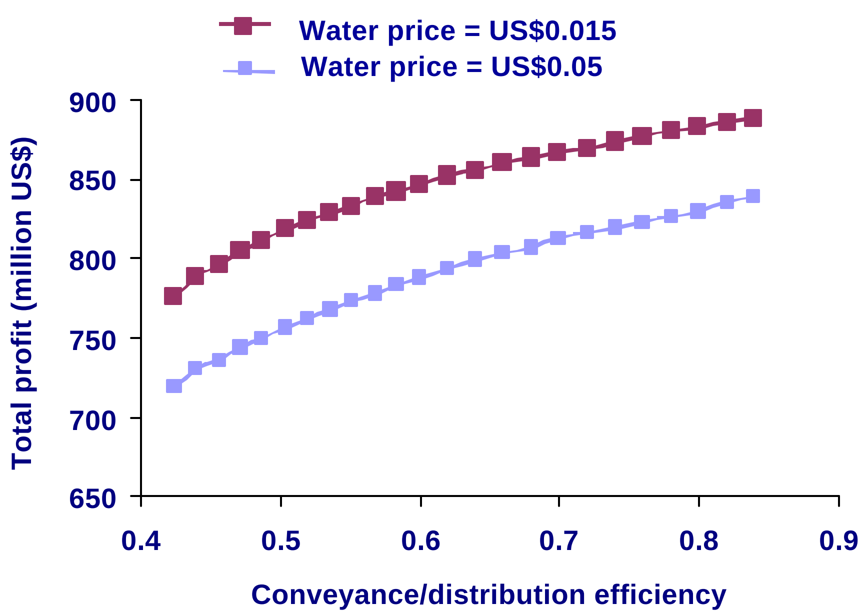
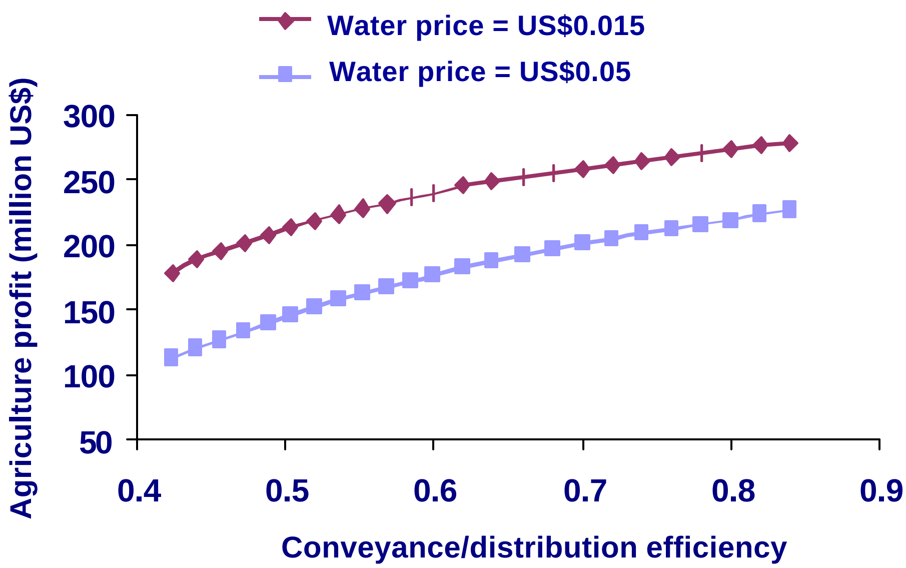


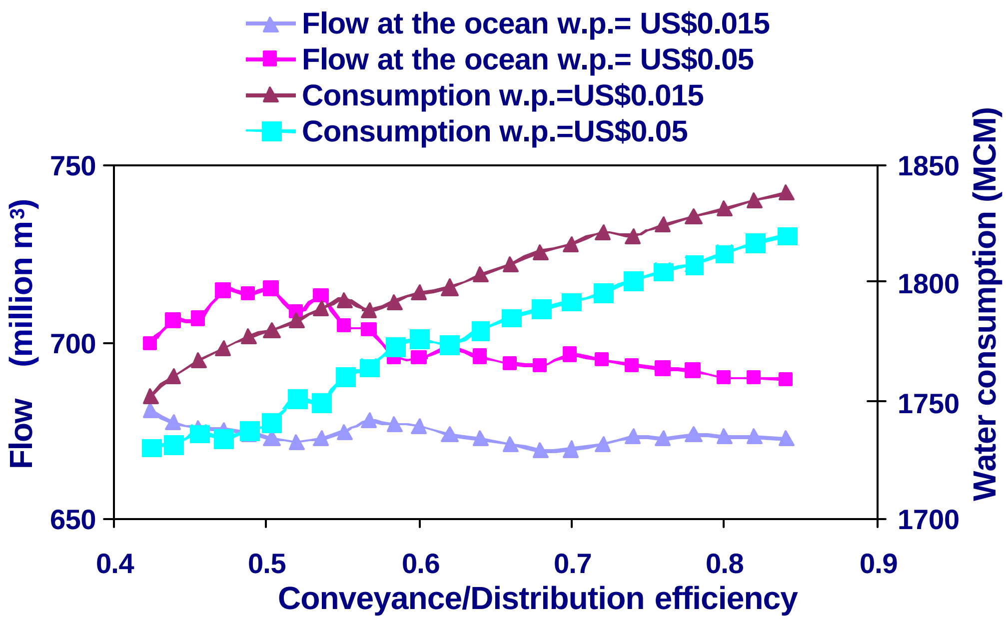
Figure 6b: **Relationship between agricultural profit (water charge subtracted) and conveyance/ distribution efficiency under alternative water prices**



Why do overall profits from basin water use decline despite the (small) reallocation of water to M&I areas? The marginal value of water in non-agriculture is virtually identical to the marginal value of water in agriculture, since an optimal solution is already achieved under the lower water price. Therefore, the induced increase in non-agricultural water use is small, and the marginal profits from use of that water are also small.

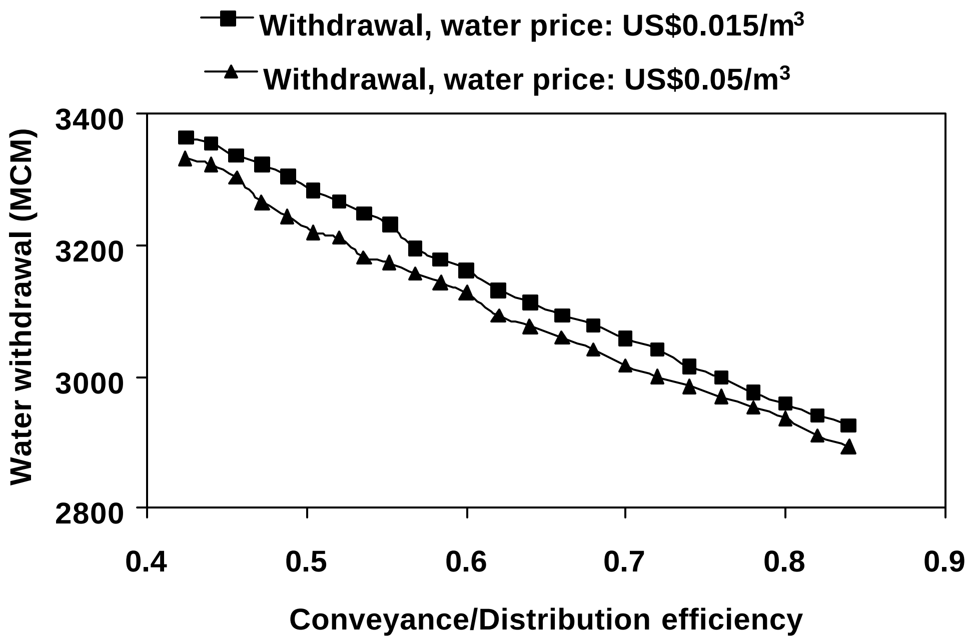
In addition to reducing agricultural incomes, increased irrigation water prices change the level of instream flows available for environmental uses. Under the higher water price, more water remains instream (see Figure 7, outflow to the sea). If environmental uses of instream flows would be explicitly valued, the higher water price could result in a higher social benefit.

Figure 7: **Relationship between water consumption and outflow to the sea and conveyance/distribution efficiency under alternative water prices**



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 from the modeling framework show that increases in irrigation efficiency in fact do lead to increased water consumption. Figure 7 shows that water consumption increases, and outflows to the sea decline with increasing physical efficiency levels. However, water withdrawals decline (Figure 8).

Figure 8: Water withdrawal vs. conveyance/distribution efficiency under alternative water prices



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 non-beneficial evaporation losses decline. Moreover, economic efficiency increases and can induce additional water consumption, as more water can be beneficially used at the same water price.

4. CONCLUSIONS

In this paper, the relationship between basin physical and economic efficiencies of irrigation water management is analyzed based on an integrated economic-hydrologic model for the Maipo River basin in Chile. The model allows for a simultaneous, endogenous consideration of these efficiency concepts in an integrated economic-hydrologic framework.

The alternative scenarios for changes in the flexibility of water allocation through shifting from fixed to tradable water rights show that substantial gains in economic efficiency can be obtained without prior changes in physical efficiency levels. Thus, for a given infrastructure, physical efficiency is not a strong predictor of overall economic efficiency. Moreover, tradable water rights induce improvements in physical efficiency as it becomes profitable for farmers to invest in improved irrigation technologies and to sell the surplus water to urban areas.

Although increased water prices significantly increase instream flows, increased irrigation efficiency can negatively affect instream flows as water consumption increases, even though actual water withdrawals may decline. Moreover, although restricted water allocation rules can help protect instream flow uses as the economic efficiency principle cannot be fully realized for off-stream uses, the ideal strategy would be to determine the value of these uses and to reflect these values in marketable water rights, and thus to take these uses explicitly into account in the determination of optimal water allocation strategies.

The analysis of endogenous as compared to fixed irrigation technologies shows that technology choice can generate large economic gains in irrigated agriculture, and simultaneously increase physical efficiency levels. Technical improvements in both the conveyance system and on-farm irrigation technology can increase physical efficiency up to some technical maximum, this is only efficient from an economic point of view as long as the marginal benefits of additional water use are larger than the marginal costs of additional improvements.

Higher (irrigation) water prices result in 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. Moreover, the improvement of physical structures can strengthen the effectiveness of water prices, but incentive prices have little impact on physical efficiency at low levels of infrastructure development. Farmer incomes (and total basin profits) decline with increased water prices, when water cannot be allocated or sold to higher-valued uses, an outcome reflected in the model results.

There are large gains to be made through increasing both local efficiency and overall river basin efficiency. However, effective efficiency is higher than classical irrigation efficiency at the system level, and overall basin efficiency is higher than efficiency 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, contrary to analysts who have said the improving classical efficiency simply reduces beneficial return flows without benefiting total basin income, within a significant range, classical efficiency improvement does improve basin-wide economic efficiency substantially. Only once local efficiency reaches a fairly high level, will the contribution to basin profits from further improvements in local efficiency be minimal. 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 technical improvements are very large, meeting future water demands will require a shift towards nonstructural measures that enhance both economic and physical water use efficiencies.

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