Water pricing options for the Middle Drâa River Basin in Morocco

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Abstract

This paper discusses the possible effects of various ways of charging for water in an integrated modeling framework adapted to the Drâa River Basin in southeastern Morocco. Declining surface water availability in the basin has led to an increase in groundwater use for irrigation in recent decades, even though groundwater extraction is more costly than using surface water. The trade-off between the pricing of ground and surface water is discussed based on recursive-dynamic simulations over a ten-year period. The results identify groundwater pricing as an economically and environmentally favorable option, assuming that revenues from water charges are redistributed to farmers.

Keywords: River basin model; Water pricing; Water management; Conjunctive water use; Morocco

Cet article traite de l'impact des stratégies alternatives de la tarification de l'eau dans le cadre d'une modélisation intégrée, adaptée au bassin du Drâa, dans le sud-est du Maroc. Lors des dernières décennies, une baisse du niveau des eaux de surface a entraîné une augmentation de l'utilisation des eaux souterraines destinée à l'irrigation bien que l'extraction de ces eaux soit plus onéreuse que l'utilisation des eaux de surface. On discute le compromis entre la tarification des eaux de surface et celle des eaux souterraines en se basant sur des simulations dynamiques récursives sur une période de dix ans. Les résultats identifient l'option favorable tant au niveau économique qu'environnemental que représente la tarification des eaux souterraines, à condition de redistribuer aux agriculteurs les revenus issus des tarifs de l'eau.

Mots-clés : *Modèle de bassin versant ; Tarification de l'eau ; Gestion des eaux ; Utilisation conjonctive de l'eau ; Maroc*

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1. Introduction

The Middle Drâa Valley in southeast Morocco is a typical example of an arid river basin where surface water and groundwater resources are hydraulically interconnected. The use of both water resource types by farmers for irrigation purposes is known as a 'conjunctive system' (Gemma & Tsur, 2007: 540), which is typical for river basins in arid regions where groundwater is used as a complementary source during periods when surface water is scarce. The inter-temporal management of conjunctive water resources has been addressed by numerous authors since the 1960s. Buras (1963), Burt (1964) and Bredehoft and Young (1970) were among the first to simulate such systems with dynamic linear programming models that yielded optimal water extraction and allocation plans over multiple locations and periods. The theoretical background of conjunctive water use with a focus on the role of groundwater aquifers as buffers was elaborated by Bear and Levin (1970) and Gisser and Mercado (1973), and later refined by Tsur and Graham-Tomasi (1991) and most recently by Gemma and Tsur (2007).

The authors demonstrate the existence of a steady-state in which groundwater recharge and use are in equilibrium under different assumptions, and identify the stock or buffer value of the groundwater resource. To arrive at optimal water use plans, quantitative restrictions such as quotas or the taxation of groundwater use are suggested (e.g. Noel et al., 1980), with water pricing often oriented at the shadow values of water use. Applying this principle proves difficult when taking the spatial and temporal peculiarities of hydrological flow processes into account in more detail. Pongkijvorasin and Roumasset (2007) arrive at different prices for farmers according to their location along a river when calculating efficiency prices for ground and surface water based on the distance between the demand sites.

It is widely accepted among resource economists that effective pricing of irrigation water supports efficient allocation and conservation of resources (Dinar & Subramanian, 1997). Charging for water is a common practice in most river basins in Morocco, even though price levels are primarily aimed at recovering the costs of water supply, while efficiency or resource preservation considerations are less important (Tsur et al., 2001). In the Drâa Valley, it has so far been possible to avoid charging for either surface or groundwater (Serghini, 2002; Doukkali, 2005), mostly because the region is one of the poorest and most remote in the country. This paper discusses simplified irrigation water pricing strategies for the Drâa Valley in a recursive-dynamic framework. Two key assumptions are that a) farmers can extract water from different but interconnected sources, namely surface water from the Drâa River and groundwater from local aquifers, and that b) neither farmers nor the water management agency take long-term expectations of future water supply into consideration.

As the Drâa Valley is characterized by highly volatile surface water supply conditions, optimal multi-annual water use plans or water charges are difficult to identify. Moreover, given the frequent droughts in the region, 'optimal' use rights or price levels derived from a fully dynamic simulation model would probably seem too restrictive to farming communities to be politically acceptable. Thus, rather than working out an optimal inter-annual water management regime, this paper investigates whether simplified water pricing systems might still be better than the current water management system in the study area over a period of ten years. The study in particular focuses on a comparison between surface and groundwater pricing regimes. Cornish et al. (2004) discuss different experiences of surface and groundwater pricing, and point out that increasing charges for surface water only could lead to groundwater being overexploited. This paper thus tries to answer two questions: is there a trade-off between simplified surface versus groundwater pricing schemes, and what role does the conjunctive nature of the water resources play in this context?

The remainder of the paper is organized as follows: we first describe the study area and its hydrologic and hydro-geologic setting. Then we explain the simulation model used, after which we show the results for different pricing options for the Drâa Valley.

2. Water resources in the Middle Drâa Valley

Most farm production in the Middle Drâa Valley (i.e. downstream from the Mansour Eddahbi reservoir) is found in six oases along the course of the Drâa River (Figure 1). Because of the arid climatic conditions in the area, irrigation water is the most important production resource for cropping and the most limiting factor in most years.

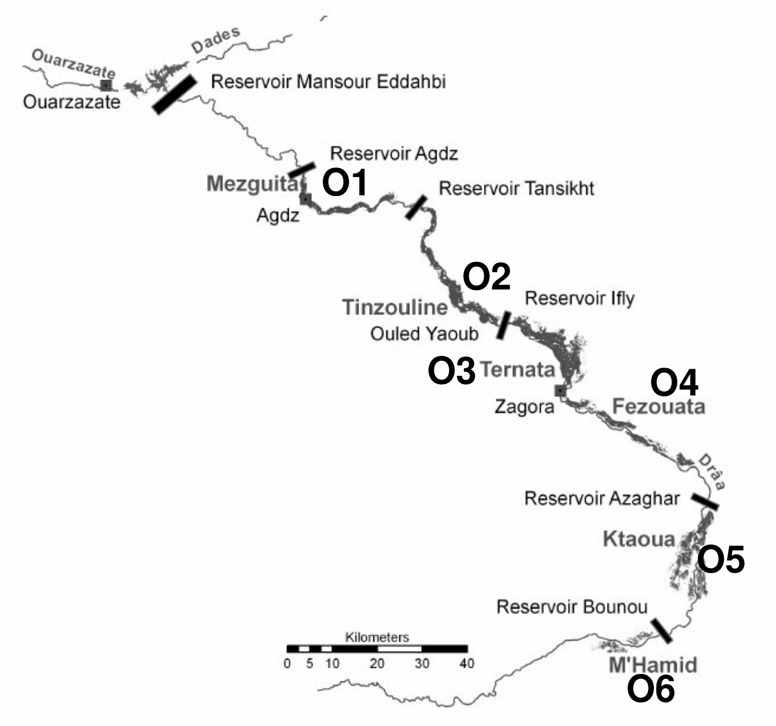
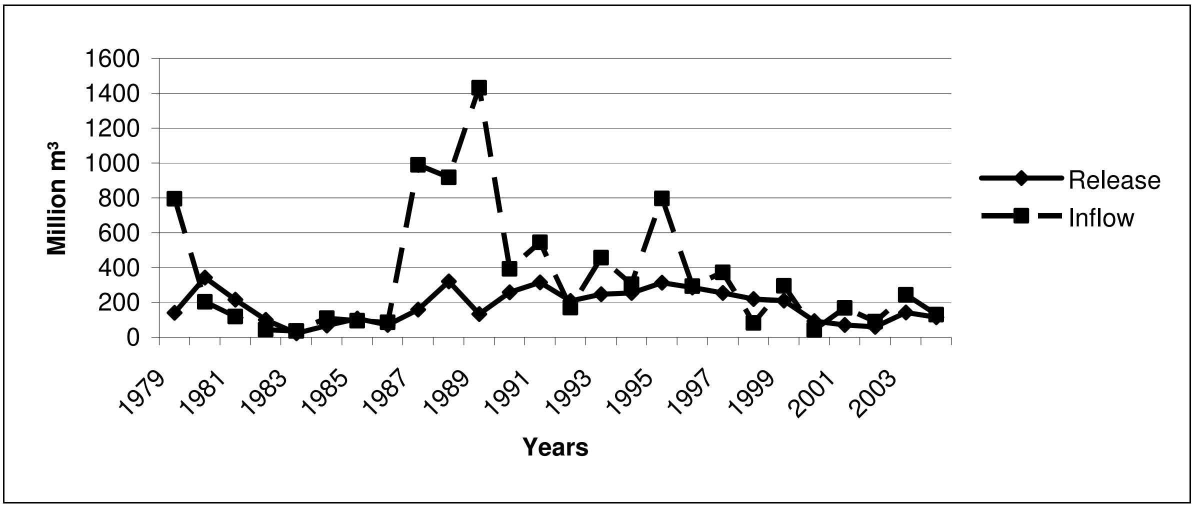


Figure 1: The six oases Mezguita (O1), Tinzouline (O2), Ternata (O3), Fezouata (O4), Ktaoua (O5) and Mhamid (O6) along the Drâa River

Decisions about the distribution of surface water among the six oases are made ex ante at the basin level by a committee at the beginning of the agricultural year (ORMVAO, 1995). Surface water for irrigation is periodically released from the Mansour Eddahbi reservoir to improve the reliability of the water supply. Released water is directed to the southern oases first and then retained in small local reservoirs. From there, water is directed through a traditional channel system onto the fields and distributed according to traditional local water property rights (Ouhajou, 1996).

Because of declining rainfalls in recent years and high evapotranspiration rates, the fill rate of the Mansour Eddahbi reservoir has been decreasing (see Figure 2). The reservoir balance has become increasingly negative, which has led to more and more irregular releases during recent years. Nowadays the releases of the reservoir are sometimes used just to fill up the declining groundwater levels, exploiting the fact that water easily infiltrates into the shallow aquifers below the riverbed.



Source: Direction Générale de l'Hydrologie, Rabat, 2004

Figure 2: Water balance of the Mansour Eddahbi reservoir from 1972/73 to 2002/03

In contrast to decisions about surface water, decisions about groundwater pumping are made by individual farmers who own pumps. It is assumed that each of the six oases has an underlying aquifer with specific hydro-geological characteristics (see Table 1).

Table 1: Total area and natural reserves of the aquifers of the oases

	Mezguita	Tinzouline	Ternata	Fezouata	Ktaoua	M'hamid
Total area of the aquifers (km^2)	45	69	178	196	160	70
Total natural reserves (Mio m³)	22.5	34.5	71.3	127.1	86.4	16.8

Source: Ouhajou, 1996, own calculations

As compared to the total storage volume of the Mansour Eddahbi reservoir (439 million cubic meters in 1998, down from the initial 560 million cubic meters in 1972 due to sedimentation, see Abou-Otmane, 2002), the total natural reserves of groundwater are estimated to represent 359 million cubic meters of water storage capacity (Table 1), meaning that almost half of the total water storage capacity of the Drâa Valley is contained in groundwater aquifers. However, declining rainfall reduces the pluvial aquifer recharge as well as the lateral groundwater afflux (Aoubouazza & Meknassi, 1996; Direction de la Région Hydraulique d'Agadir de Souss-Massa et Drâa, 2001). The general hydrographic trend in fact reveals declining average groundwater levels since 1996. At the same time the number of motor pumps has increased remarkably during the last 30 years (see Table 2). Figures on the number of motor pumps are only available to 1985, which illustrates the problem that groundwater use is insufficiently monitored. Survey data for 2005 suggest that the number of motor pumps has increased tremendously in the last two decades. Basin-wide water management faces a typical conflict between long-term resource conservation goals for the entire basin and short-term income considerations for individual farmers.

Table 2: Development of motor pumps and pumping capacity

	Number of motor pumps			Water pumped in 1985 (Mio cbm)	Pumps per farmer in 1982	Pumps per farmer, estimated for 2005
	1977	1982	1985			
Mezguita	216	260	860	4.64	0.08	1.85
Tinzouline	499	590	1200	6.48	0.17	1.76
Ternata	785	920	1500	8.10	0.22	1.48
Fezouata	383	448	710	3.83	0.16	1.30
Ktaoua	108	130	220	1.19	0.04	0.35
M'hamid	10	15	30	0.16	0.01	0.53

Source: Faouzi, 1986, own estimations from field survey in 2005

3. The MIVAD River Basin model

This study uses a numerical simulation model[1] based on positive mathematical programming (PMP, Howitt, 1995) to compare alternative water pricing options for the Drâa Basin. There are several reasons for this rather normative approach. Most importantly, basin-wide information on water use at the farm level is scarcely available in the case study region. This applies particularly to the use of groundwater. Moreover, the impact of cost changes on water use patterns cannot be estimated ex post as costs of water use are not documented over the years, and because charging for water has not yet been tried in the case study area. Thus, the pricing experiments presented in this study are in effect ex ante evaluations of programming models to decide which ones are suitable for situations where observed data on important variables are scarce or even absent. Finally, programming models allow the derivation of water shadow prices at different locations and periods, thereby delivering a point of reference for administrative water price levels.

Mathematical programming approaches have been widely applied to water resources issues, especially in those cases where the insufficient availability of data means that econometric estimations are not possible. The simulation model MIVAD (Modèle Intégré de la Vallée du Drâa) is designed as a hydrologic-economic optimization model in which spatial relations are represented in a node network representing points of withdrawal along the river, water reservoirs, groundwater bodies and agricultural water demand sites. As such, MIVAD is similar to models that have been recently applied by Cai (1999) to the Syr Darya Basin, by Rosegrant et al. (2000) to the Maipo Basin in Chile, by Ringler (2002) to the Mekong Basin, and by Obeng-Asiedu (2004) to the Volta River Basin. However, these modeling approaches simulate one aquifer per demand site where the aquifers are not interconnected with each other (Cai et al., 2006). In the Drâa Valley the aquifers that are situated below the belt of

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[1] A detailed description of the model is available from the authors on request.

oases are hydraulically interconnected, which has been taken into account in the present modeling approach.

Basically, MIVAD is a planning model that maximizes the net agricultural revenues of the six farming communities (oases) subject to land and water resource constraints. Agriculture is represented by one aggregate farm per oasis, involving the eight most relevant crops in the area: wheat, barley, alfalfa, corn, date palms, henna, pulses and an aggregate of vegetables. All cropping activities are characterized by specific input needs, yield functions, prices and water requirements. The parameters of the PMP-terms in the objective function are calibrated using a priori supply elasticities (Heckelei & Wolff, 2003), which are principally different for annual and perennial crops. Endogenous crop yield functions in the model are designed as non-linear approximations of the ratio between actual and maximum evapotranspiration according to the Modified Penman function (FAO, 1998), making crop yields a function of water application per hectare.

Available cropland is specific to the oasis (farm community) level. Water resources available to the oases, by contrast, are represented by a highly complex hydrological system which is assumed to be governed by a centralized water distribution agency. This ‘virtual planner’ distributes irrigation water to the various oases and municipal users in order to maximize the utility from water use for the entire region.

3.1 The hydrologic framework in MIVAD

The hydrological modeling network of the Drâa River Basin actually starts with the river node that defines the exogenous monthly inflows into the Mansour Eddahbi reservoir from the High Atlas Mountains. From the reservoir, water is released to the Drâa River and flows downstream, partly infiltrating and percolating to the alluvial aquifers subjacent to each oasis. For each of these aquifers a specifically adjusted groundwater balance is part of the model.

In the Drâa Valley, however, aquifers are not closed entities, but interconnected by discharges in the same direction as the river flow. The relatively small flow sections between the aquifers are limited by non-pervious rock formations at the lower end of each oasis. Groundwater discharge is calculated as 1-D flow by the Darcy equation (Darcy, 1856) which depends on the hydraulic conductivity of the alluvial deposits, the flow section and hydraulic gradients between the aquifers. In case of very high groundwater levels, a discharge into the river bed may occur too, but this process is less important under the current dry conditions in the Drâa Valley.

Lateral inflows from rain water infiltrating the catchment area of each aquifer also contribute to groundwater recharge, but have played only a minor role in most years. By contrast, infiltration from the river bed into the aquifers appears to be a decisive factor for the groundwater balance in the case study region. It is also an important element of groundwater management by the authorities, who occasionally use reservoir releases to replenish the groundwater bodies in the river basin. The coefficient for the groundwater recharge by river water infiltration has proved to be a pivotal factor in hydro-geological models (Simmers, 1997). First estimations of the recharge coefficient for the Drâa Valley yield values between 10 and 25% of the river water flow.

The interactions between ground and surface water resources in the model are illustrated in Figure 3. A hydrological balance is formulated for each river node in the model.

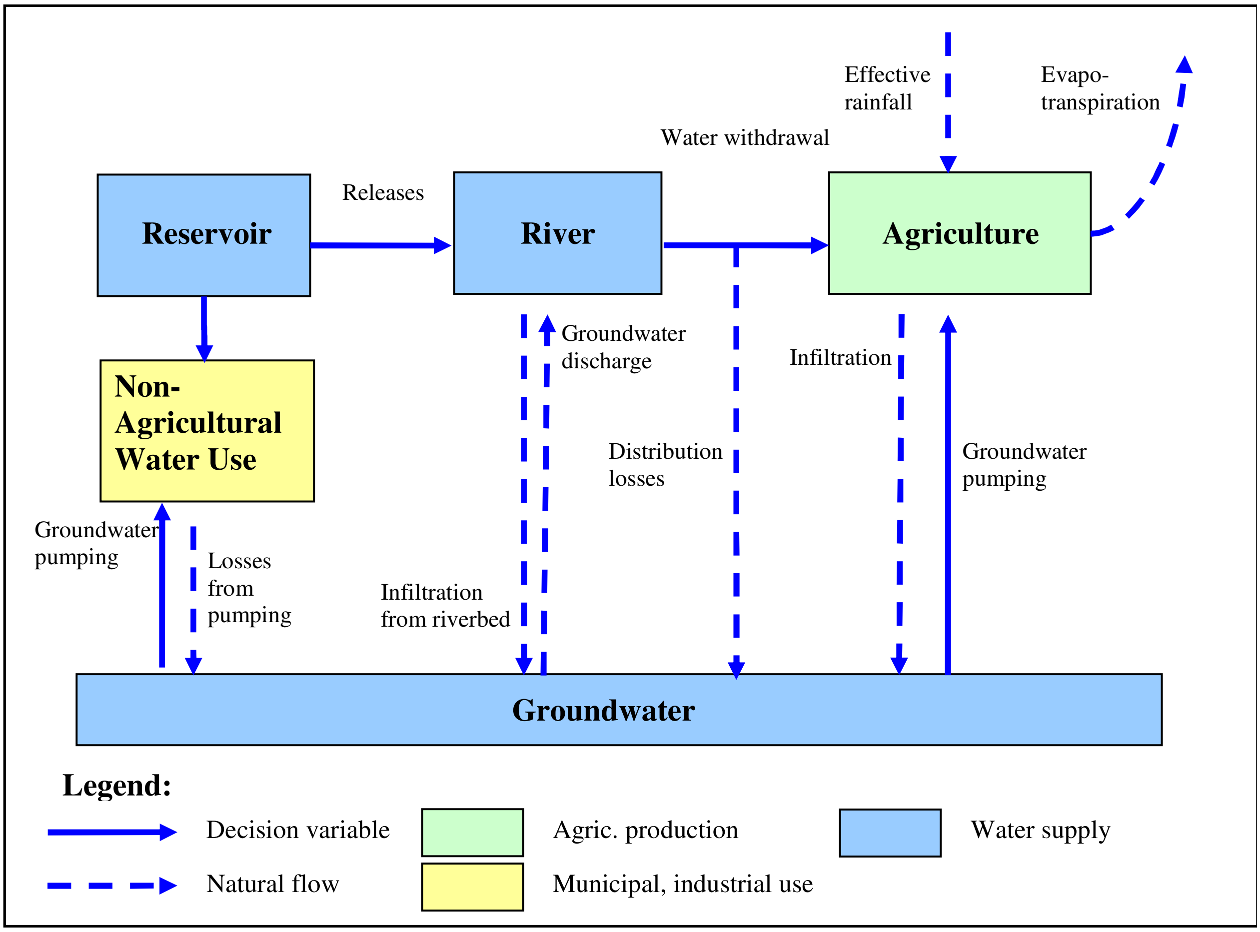

Figure 3: Hydrologic interactions in MIVAD

3.2 Determination of decision variables

There are several levels in MIVAD at which decisions on land and water use are made to arrive at an optimal distributional pattern that maximizes the sum of agricultural gross margins. Decision variables include crop areas in the individual oases (A_i), and various variables related to water use: seasonal water application per crop measured in terms of crop evapotranspiration (ETA_i), water withdrawals by oases from the river (W^S) or the underlying groundwater body (W^G), the fill levels of the groundwater aquifers (R^G), the downstream flows between river nodes (F^S), and fill levels (R^R) and releases (F^R) from the central reservoir. The Kuhn-Tucker conditions for local optima that determine the levels of these decision variables are discussed in the following. Indices denote available cropping activities (i), locations such as river nodes, aquifers and oases (f), and months (t) within a one-year period.

The first-order condition of the objective function with respect to crop area (A_i) is represented by the following non-linear relation between marginal costs (MC_i) and marginal revenues (MR_i) from cropping:

$$MC_i^L\left(\left(\sum_t \lambda_t^A \cdot W_{i,t}^A\right), \lambda^L\right) \geq MR_i^L\left(\overline{P}_i \cdot Y_i, \overline{AC}_i, A_i\right) \qquad \perp \quad A_i \geq 0$$

(W^A = application of irrigation water per hectare; λ^A = shadow price of water for crop irrigation; λ^L = shadow price of cropland; P_i, Y_i, AC_i, = crop prices, yields, and accounting costs, respectively)

The complementarity between the MC-MR-difference and the quantitative decision variable is denoted by the '$\perp$'-sign. Water application per crop (W^A) itself is a function of seasonal evapotranspiration per crop (ETA_i), which ultimately determines crop yields (Y_i), but also of the local irrigation and groundwater shadow prices:

$$MC_i^{irrig}\left(ETA_i^{seas},\overline{ETM_{i,t}^{stage}},A_i,\lambda_t^G,\lambda_t^A\right)\geq MR_i^{irrig}\left(ETA_i^{seas},\overline{ETM_{i,t}^{stage}},\overline{Y_i^{max}},\overline{ky_i^{seas}},A_i,\overline{P_i}\right)\quad\perp\quad ETA_i^{seas}\geq 0$$

(ETM_i^{stage} = yield-max. monthly evapotranspiration; λ^G = shadow price groundwater; Y_i^{max} = maximum crop yield; ky_i^{seas} = seasonal crop water deficit coefficient)

Surface water for irrigation depends on releases from the upstream reservoir. The reservoir has a limited storage capacity and, assuming that the periodic inflows of river water into the reservoir are known ex ante within a one-year horizon, the monthly fill levels (R^R) are chosen such that the shadow prices of reservoir water (λ^R) are equal over all periods t.

$$\lambda_t^R\geq\lambda_{t+1}^R\quad\perp\quad R_t^R\geq 0$$

Releases from the reservoir (F^R) occur when the shadow price in the reservoir (λ^R) is equal to or lower than the shadow price at the adjacent river node (λ^S):

$$\lambda_t^R\geq\lambda_t^S\quad\perp\quad F_t^R\geq 0$$

Similarly, when the shadow price of water at the river node upstream is equal to the river node downstream, a river flow ($F^S_{f,f+1}$) should occur between these nodes. If, however, there are infiltration losses ($infil^{SG}$) of river water into the local aquifers, the decision rule becomes more complex, involving also the shadow price for groundwater in the aquifer belonging to the downstream river node (λ^G). Increasing river-aquifer infiltration will, ceteris paribus, decrease the incentive to let water flow downstream, particularly as long as λ^G is low or zero, i.e. as long as the groundwater aquifer will not be exhausted in any month in the one-year period.

$$\begin{aligned}\lambda_{f,t}^S &\geq \lambda_{f+1,t}^S\cdot\overbrace{\left(1-infil_{f,f+1}^{SG}\right)}^{\text{Share of outflows available at next node}}+\lambda_{f+1,t}^G\cdot\overbrace{infil_{f,f+1}^{SG}}^{\text{Share of outfl. infiltr. into downstr. aquifer}}\\ &\geq \lambda_{f+1,t}^S-\left(\lambda_{f+1,t}^S-\lambda_{f+1,t}^G\right)\cdot infil_{f,f+1}^{SG}\quad\perp\quad F_{f,f+1,t}^S\geq 0\end{aligned}$$

As water for irrigation also infiltrates into the local aquifers, the shadow price relation governing withdrawals by oases from river nodes (W^S) is also quite complex, involving the shadow price at the river node (λ^S), and the shadow price of irrigation water in the oasis (λ^A), but also groundwater shadow prices, the shadow price of the surface water distribution rules (λ^{distr}), and financial costs (including charges) of surface water withdrawals (c^S). Thus, losses within the canal system of the oases mean that water becomes more costly for farmers, an effect that will be dampened, however, as soon as groundwater becomes scarce and its shadow price positive.

$$\lambda_{f,t}^{S} + \overbrace{c_f^S}^{\text{Costs / charges of surface water use}} + \overbrace{\frac{\lambda_f^{distr}}{\sum_t W_{f,t}^S} - \sum_f \left(\frac{\lambda_f^{distr} \cdot \sum_t W_{f,t}^S}{\sum_{f,t} {W_{f,t}^S}^2} \right)}^{\text{Opportunity costs of the distribution rules}} \geq \overbrace{\lambda_{f,t}^A \cdot \left(1 - loss_f^{SG}\right)}^{\text{Marginal value of irrigation water net of losses}} + \overbrace{\lambda_{f,t}^G \cdot loss_f^{SG}}^{\text{Value of infiltration into the groundwater}}$$

$$\geq \lambda_{f,t}^A - \left(\lambda_{f,t}^A - \lambda_{f,t}^G\right) \cdot loss_f^{SG} \qquad \perp \quad W_{f,t}^S \geq 0$$

(with $loss^{SG}$ = coefficient determining the infiltration losses occurring at surface water withdrawals by oases)

Groundwater pumping (W^G) is determined in a simpler way, as groundwater use is not subject to distribution rules or infiltration losses. The local irrigation water shadow price has to be equal to the shadow price of the groundwater aquifer plus the costs (including charges) of groundwater extraction (c^G).

$$\lambda_{f,t}^G + \overbrace{c_f^G}^{\text{Costs / charges of groundwater use}} \geq \lambda_{f,t}^A \quad \perp \quad W_{f,t}^G \geq 0$$

Analogous to water in the reservoir, the fill level of the aquifer is determined by the intertemporal relation between shadow prices of groundwater in the aquifer, but also by the shadow price in the river node (in the case of discharge into the river)[2] and the shadow price in the downstream aquifer (due to inter-aquifer flows as represented by the Darcy equation, which renders the shadow price relation as non-linear in R^G)[3]. Increasing inter-aquifer flows would thus decrease the socially optimal aquifer fill levels and reward more local pumping.

$$\overbrace{\lambda_{f,t}^G - \lambda_{f,t+1}^G}^{\text{Intertemporal difference of GW shadow prices in f}} \overbrace{- \lambda_{f,t}^G \cdot darcy\left[R_{f,t}^G, R_{f+1,t}^G\right]}^{\text{Costs of groundwater outflow to the downstream aquifer}} + \overbrace{\lambda_{f+1,t}^G \cdot darcy\left[R_{f,t}^G - R_{f+1,t}^G \uparrow\right]}^{\text{Value of groundwater outflow to the downstream aquifer}} \geq 0$$

$$\leftrightarrow \lambda_{f,t}^G + \left(\lambda_{f+1,t}^G - \lambda_{f,t}^G\right) \cdot darcy \geq \lambda_{f,t+1}^G \quad \perp \quad \overbrace{R_{f,t}^G}^{\text{Fill level of aquifer}} \geq 0$$

All shadow prices in the model are complementary to the hydrologic balances at certain locations. The entire shadow price system is finally driven by the irrigation water shadow price λ^A, as the use of water for irrigation is the only use component that enters the objective function in the version of MIVAD presented here. λ^A thus represents the opportunity costs of water use for farmers, and is dependent on the marginal value productivity of irrigation water. The opportunity costs of water are also a yardstick for the willingness of farmers to incur costs for obtaining access to irrigation water resources. The complex hydraulic relations between the local water sources, however, can lead to large differences in local irrigation water shadow prices. Water pricing that is oriented at simulated marginal water costs becomes politically delicate under such conditions,[4] particularly when the parameters of hydraulic interactions are uncertain. Moreover, the model assumes that expectations about future water supply – which would be useful for determining optimal inter-annual water price levels – are not taken into account by the water distribution agency. The fact that depleted water buffers in

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[2] This case is omitted as it only happens when there is abundant water in the aquifer.

[3] The 'Darcy factor' increases with the metric difference between the levels of the neighbouring aquifers.

[4] This conclusion has also been drawn by Pongkijvorasin and Roumasset (2007).

reservoirs and aquifers can actually be found in the case study region after a series of dry years supports this assumption. The simulations carried out for this study test to what extent simplified pricing schemes that do not require a multi-annual perspective will nevertheless lead to better results than no charge at all for water.

4. Simulations of pricing options

The following results show scenario calculations for a ten-year period, simulating an increasingly severe drought and farmers' adaptation under different pricing regimes for irrigation water. In the base run (Figure 4) we assume the first year to be a 'normal' year with average rainfall. Surface water availability is simulated to become scarcer each year with a decrease of 6.5% annually, arriving at 12% of the surface water initially available at the end of the ten-year period. Fixed non-irrigation water demand is assumed to increase exogenously at 3.1% annually for urban and 0.8% for rural areas due to population growth. We assume a 15% rate of groundwater recharge by river water infiltration of flows at each river node per month. Calculations based on a farm survey estimate variable costs of pumping groundwater for irrigation purposes at 0.58 Moroccan Dirham (MDH) per cubic meter (cbm) (approximately 7 US cents/cbm in May 2007, see Heidecke & Kuhn, 2006) including fuel as well as operation and maintenance costs. The base run (Figure 4) assumes that neither ground nor surface water is charged for. Nevertheless, groundwater use is less attractive because of the extraction costs, while surface water use is free of costs.

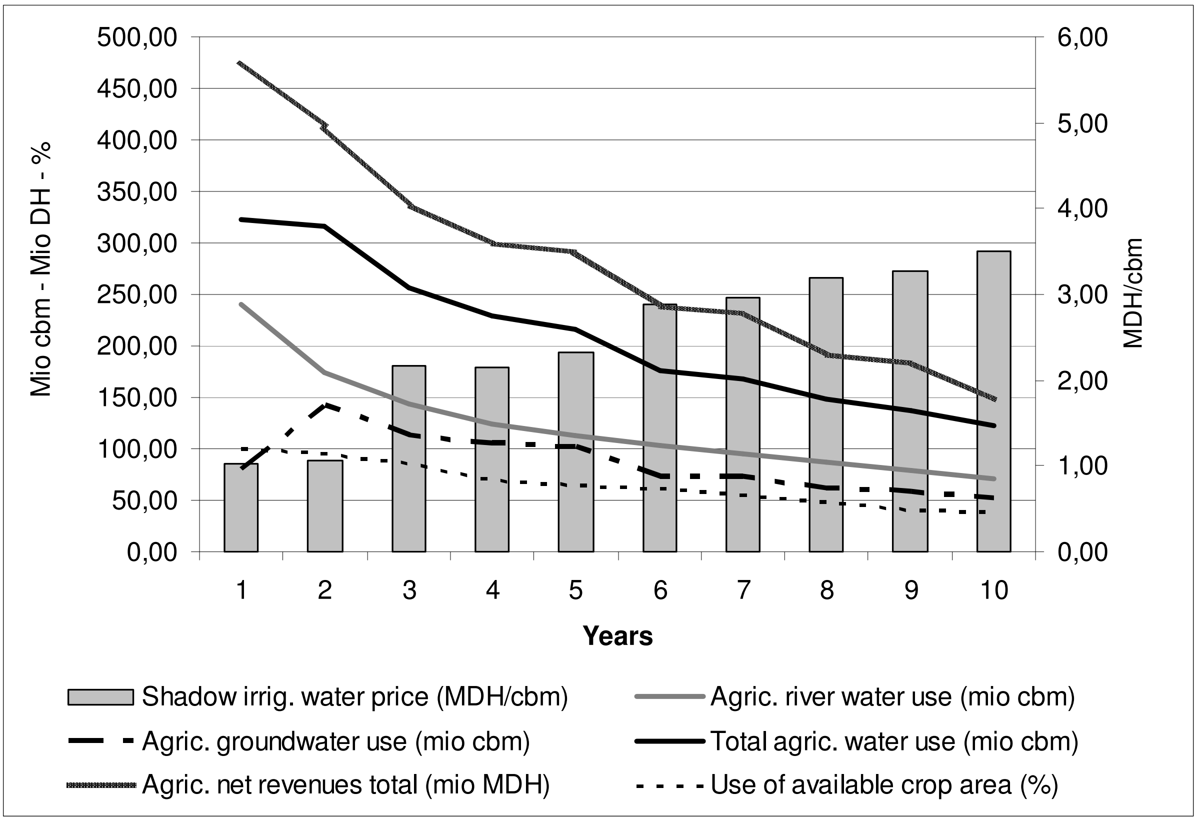

Figure 4: Base run (assuming declining river water availability and variable costs for pumping of 0.58 MDH)

The declining availability of surface water in the base run leads to the use of more groundwater for irrigation. After two years the extraction of groundwater reaches 140 million cubic meters per year and slightly declines afterwards when aquifers are fully exploited and groundwater shadow prices assume non-zero values. The average water shadow price increases with the decreasing availability of surface water from the Drâa River. The fact that these water shadow prices for irrigation by far exceed extraction costs indicates that an effective resource preservation policy would have to consider the pricing of groundwater beyond the extraction costs of 0.58 MDH/cbm. Total net revenues from agricultural production decrease constantly from nearly 500 million MDH to less than 200 million MDH during the ten-year period.

Three counterfactual scenarios are simulated: a charge for surface water only (SWC) of 1.0 MDH/cbm, a charge for groundwater only (GWC) of 1.0 (resulting in groundwater costs of 1.58 MDH/cbm when also considering the extraction costs of 0.58 MDH/cbm), and a 'total water charge' with charges for both water resources (TWC). The TWC scenario simply combines the water charges of the SWC and GWC scenarios, making groundwater still more expensive for farmers than surface water. To evaluate the efficiency of the different pricing regimes, net revenues of agricultural producers are compared to 'total basin revenues'. These 'total basin revenues' contain agricultural revenues plus all revenues from water charges which represent the taxation of farmers, but which are also available for redistribution to the farmers as income transfers. Such transfers are assumed to have no further allocative effects in the model. Total basin revenues are also discounted at 5% and 10% to account for the farmers' preference for short-term incomes (Table 3).

Table 3: Results for the base run, the SWC, GWC, and TWC scenarios for several indicators as averages over ten years

	Base run	SWC	GWC	TWC
Agric. river water use (mio cbm)	123.06	117.07	151.08	137.00
Agric. groundwater use (mio cbm)	86.03	92.91	49.36	66.32
Irrigation water shadow price (MDH/cbm)	2.46	2.46	2.27	2.30
Agric. net revenues total (mio MDH)	279.92	141.25	245.76	61.84
Sum of water charges (mio MDH)	0.00	117.07	49.36	203.31
Total basin revenues (mio MDH)	279.92	258.32	295.12	265.15
Total basin revenues (discounted at 5%)	238.07	218.85	248.54	224.65
Total basin revenues (discounted at 10%)	207.31	189.86	214.58	194.92

The three pricing scenarios yield markedly different results with respect to revenues and resource use. Under surface water pricing, groundwater use becomes more attractive, which leads to higher groundwater use than in the base run, which is likely to be unsustainable. At the same time the basin-wide revenues (including surface water charges) are 8% lower than in the base run. When both water sources are charged for (TWC), groundwater water use decreases, but at the cost of an excessive taxation of farmers. Charging only for groundwater (GWC) yields the most favorable results, both with respect to resource conservation and in terms of total basin income. This seems counterintuitive at first sight, but when looking at the GWC results in more detail over the entire period (Figure 5), the higher income can be explained by the fact that groundwater pricing prevents wasteful groundwater use in the earlier years and thus eases water scarcity in the further course of the scenario. This is also reflected in the fact that average water shadow prices are lowest in the GWC scenario.

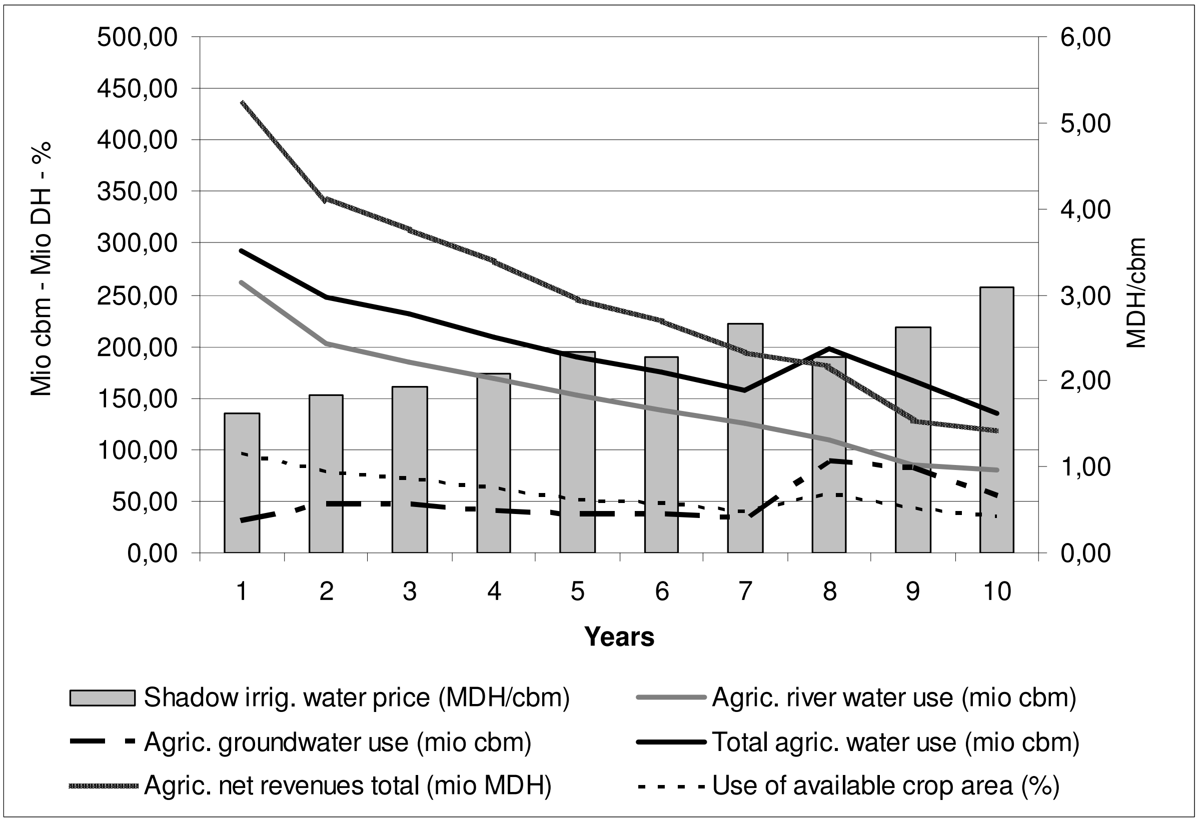

Figure 5: Scenario calculations of charging only for groundwater (GWC)

With a charge for groundwater only, the total agricultural water use is more stable over the entire period than in the base run and in the other scenarios, resulting in a higher stability of farm incomes. When comparing groundwater use over all pricing options (Figure 6), groundwater use is lowest in the GWC scenario, and highest in the base run and SWC scenarios in the first years. This changes when aquifers are depleted in the latter scenarios, while groundwater is still available in the later years of the GWC scenario under severe surface water scarcity.

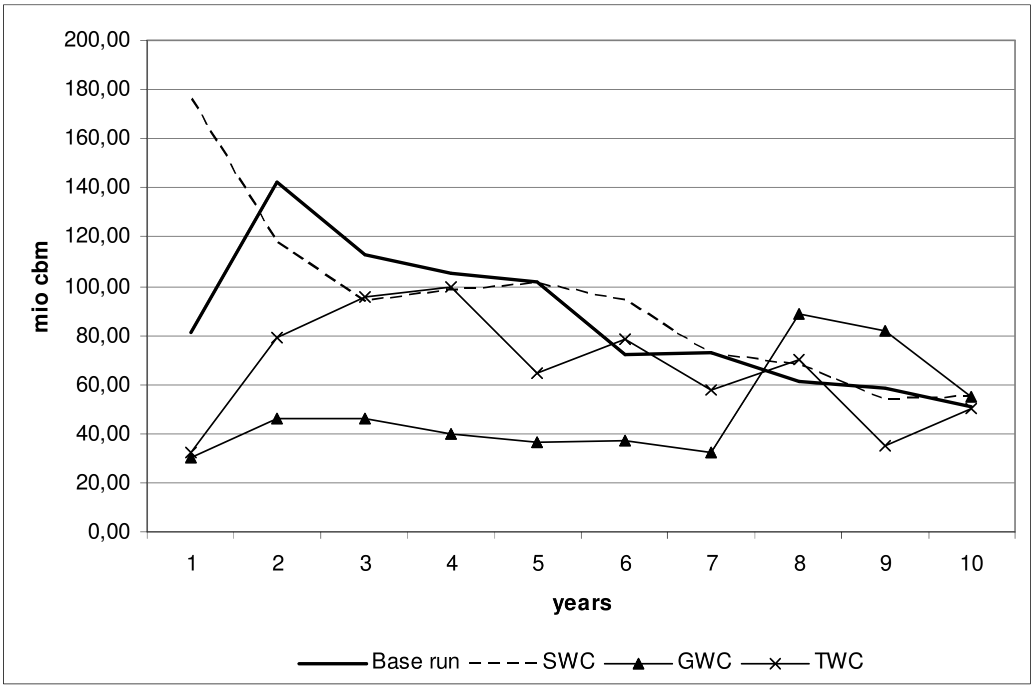

Figure 6: Groundwater use of the six oases over a ten-year period for the base run and for charges for ground and surface water

Regarding farmers' net revenues and the basin-wide income for the scenarios (Figure 7), the advantage of groundwater availability in future years has direct effects on incomes. Naturally, farmers' net revenues are the highest in the base run where farmers are not charged for water at all; however, the GWC scenario only slightly reduces farmers' net revenues and yields even higher basin-wide revenues, especially in the later years. Discounting the basin-wide revenues, revenues at the end of the simulation period are of lower importance; nevertheless the groundwater charge remains the best option (see Table 3).

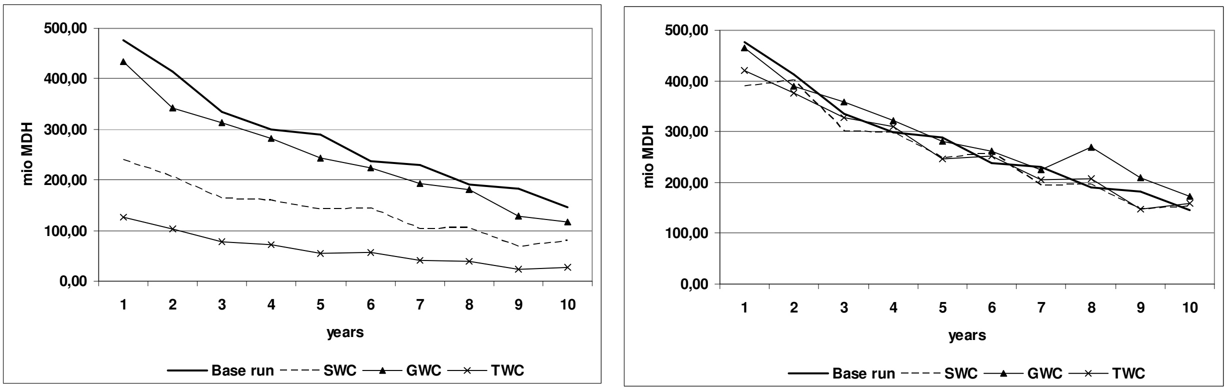

Figure 7: Net revenues and basin-wide revenues

Figure 8 shows the average shadow prices in MDH/cbm for irrigation water, surface water, and groundwater at the level of individual oases across the entire simulation period. In both scenarios the shadow prices of surface water are more or less equal across the oases due to the nature of surface water as a common pool resource. Small variations between the oases can be explained by differences due to infiltration losses and the effects of distribution rules. In the base run, groundwater shadow prices and hence irrigation water shadow prices increase from the northern oases to the southern oases. Broadly speaking, shadow price differences between aquifers can be greater than those for surface water, since groundwater resources are hydrologically more isolated. While the hydraulic connections between aquifers tend to reduce the differences in water scarcity, the dominant infiltration losses from river flows contribute to increasing the inter-aquifer differences in water shadow prices. The groundwater charge obviously reduces the variation of both groundwater and irrigation water shadow prices across oases. Altogether, surface and groundwater shadow prices are smaller when a water charge is applied, since farmers have to pay more for the same marginal value of water.

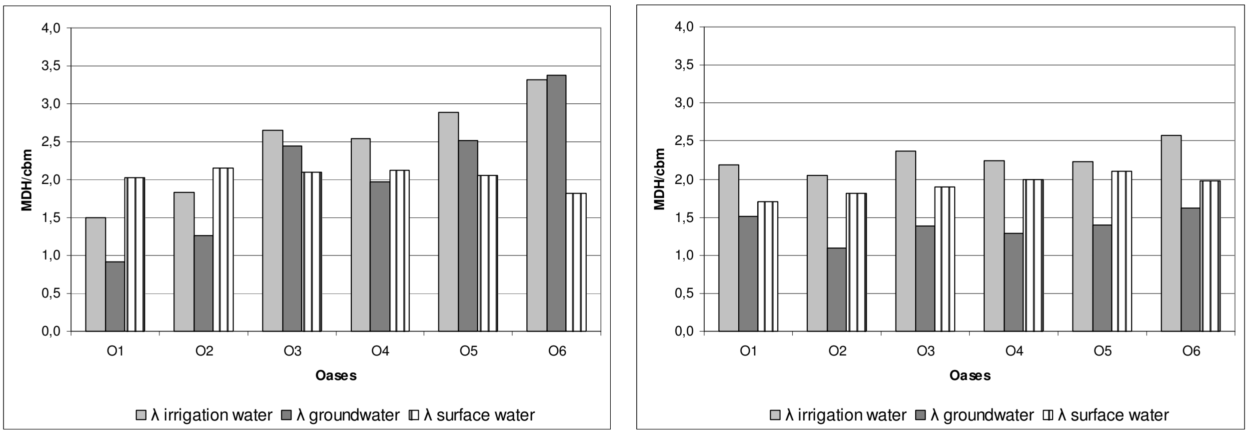

Figure 8: Shadow prices for the six oases for the base run and for GWC (average over a ten-year period)

The scarcity of surface water directly affects the availability of groundwater due to the infiltration into the river bed. To examine the economic effect of this hydrological process more closely, all pricing scenarios are repeated at a groundwater recharge coefficient of 10 and 20%, respectively (Annex 1). Assuming a higher recharge coefficient of 20% instead of 15%, more groundwater is able to infiltrate into the river bed, making surface water even scarcer. The higher the natural infiltration from river to aquifer, the more favorable groundwater pricing appears to be compared with the other options. This also indicates that the suitability of a pricing scheme is sensitive to hydrological parameters and to the availability of ground and surface water.

4. Conclusions

Charging for water has so far been avoided in the Drâa Valley as farmers' incomes were deemed too low to pay for additional water charges. However, the obvious overexploitation of groundwater resources in recent years indicates that the current patterns of water use will not be sustainable in the long run, particularly if the average surface water availability is bound to worsen in the course of population growth and climate change. This paper discusses charges for irrigation water as an option for regional river basin water management, focusing on groundwater conservation and income stabilization as primary goals.

The comparison of water pricing regimes for the Drâa Valley in Morocco shows that groundwater charges, in contrast to surface water charges, lead to the highest basin-wide incomes, and are at the same time more effective in terms of groundwater preservation. This is because the buffer function of groundwater resources, i.e. using groundwater stocks to mitigate water scarcity in future years (Tsur & Graham-Tomasi, 1991), can be better exploited when groundwater overuse in years with less overall water scarcity is avoided through taxation. Charging for groundwater thus emulates the allocative effect of realistic future expectations of water supply and replaces an explicit accounting for the buffer value of groundwater stocks to some degree.

Even though a considerable amount of surface water can also be stored in the reservoir, which thus also functions as a buffer, charging for surface water leads to an overuse of groundwater when surface water is still sufficiently available. When surface water becomes scarce in the later years, groundwater resources are already exploited under the special water availability scenarios used in this study. It is also likely that the existing distribution rules for surface water restrict efficient allocation by the central planner, which increases the value of the locally and temporally more flexible groundwater resources. Enforcing a tax as a replacement for considering a buffer value is thus much less effective in the case of surface water. A sensitivity analysis of the natural rate of surface water infiltration into groundwater aquifers does not alter these conclusions.

A water pricing system should be designed to induce efficient use of irrigation water, to avoid taxing farmers excessively, to be acceptable to farmers with respect to the levels and inter-annual stability of water charges, and to contribute to long-term resource conservation goals, particularly with respect to groundwater. The results of the simulations suggest that a groundwater pricing scheme is the alternative that best meets these requirements, except for the issue of administrative costs, which are probably much higher for groundwater than for surface water. However, the estimated benefits of charging for groundwater might outweigh its higher administrative costs, particularly since a charge for groundwater appears to create much less pressure through taxation of resource use, which could increase its acceptance among water users.

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Annex 1: Sensitivity analysis: recharge coefficient of 10%, 15% and 20% across all pricing scenarios

10% recharge	**Base run**	**SWC**	**GWC**	**TWC**
Agric. river water use (mio cbm)	139.56	135.22	155.54	153.09
Agric. groundwater use (mio cbm)	66.80	71.01	42.35	46.55
Consumption water use (mio cbm)	5.94	5.94	5.94	5.94
Total agric. water use (mio cbm)	206.36	206.23	197.89	199.64
Reservoir fill rate in %	0.31	0.34	0.31	0.31
Agric. net revenues total (mio MDH)	289.74	127.26	252.52	66.28
Basin revenues total (mio MDH)	289.74	262.48	294.86	266.30
Use of available crop area (%)	66.50	68.93	58.50	68.41
Shadow irrig. water price (MDH/cbm)	2.47	2.46	2.34	2.58
Total basin revenues (discounted at 5%)	246.04	222.59	249.37	225.50
Total basin revenues (discounted at 10%)	213.96	193.21	216.03	195.46
15% recharge	**Base run**	**SWC**	**GWC**	**TWC**
Agric. river water use (mio cbm)	123.06	117.07	151.08	137.00
Agric. groundwater use (mio cbm)	86.03	92.91	49.36	66.32
Consumption water use (mio cbm)	5.94	5.94	5.94	5.94
Total agric. water use (mio cbm)	209.09	209.98	200.43	203.31
Reservoir fill rate in %	0.31	0.33	0.31	0.31
Agric. net revenues total (mio MDH)	279.92	141.25	245.76	61.84
Basin revenues total (mio MDH)	279.92	258.32	295.12	265.15
Use of available crop area (%)	65.94	69.69	58.96	60.60
Shadow irrig. water price (MDH/cbm)	2.46	2.46	2.27	2.30
Total basin revenues (discounted at 5%)	238.07	218.85	248.54	224.65
Total basin revenues (discounted at 10%)	207.31	189.86	214.58	194.92
20% recharge	**Base run**	**SWC**	**GWC**	**TWC**
Agric. river water use (mio cbm)	111.82	101.60	147.75	132.93
Agric. groundwater use (mio cbm)	99.07	111.06	51.91	69.48
Consumption water use (mio cbm)	5.94	5.94	5.94	5.94
Total agric. water use (mio cbm)	210.89	212.67	199.66	202.41
Reservoir fill rate in %	0.31	0.33	0.31	0.31
Agric. net revenues total (mio MDH)	271.45	149.84	239.85	60.17
Basin revenues total (mio MDH)	271.45	251.44	291.76	262.58
Use of available crop area (%)	66.62	69.19	57.89	60.39
Shadow irrig. water price (MDH/cbm)	2.52	2.48	2.26	2.33
Total basin revenues (discounted at 5 %)	231.56	213.23	245.98	222.80
Total basin revenues (discounted at 10 %)	202.21	185.16	212.56	193.49