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Summary

A great challenge facing future agricultural water policy is to explore the potential for transition from the current myopic competitive (common) exploitation of groundwater resources to a long-term efficient and sustainable allocation. A number of economic and/or command and control instruments can be used by the relevant water authority in order to deal with the economic and environmental problems generated by competitive exploitation. However, according to previous experience in both developed and developing countries, tradable permits seem as one of the most effective and efficient instruments, especially under conditions of limited water availability. On this account, the aim of the current study is to explore the feasibility and implementation of a tradable permit system in irrigated agriculture. To this end, two distinct optimization models are applied and compared: (a) an individual farmer's model (representing the myopic non-cooperative exploitation of groundwater) and (b) a social planner's model (representing the cooperative and sustainable allocation). The deviation of their results shows the rationale for using a tradable permit system, while the final allocation of the social planner's model, solved as an optimal control problem that maximizes the social welfare under specific water policy objectives, denotes the equilibrium state of this system. The two models are then applied in a typical rural area of Greece where groundwater is the only source of irrigated agriculture. The derived time paths for water consumption and water availability illustrate the significant environmental benefits from the future implementation of a tradable permit system.

Keywords: Tradable Water Permits, Sustainable Water Use, Irrigated Agriculture

JEL Classification: Q15, Q25, Q28

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OPTIMAL EXPLOITATION OF GROUNDWATER AND THE POTENTIAL FOR A TRADABLE PERMIT SYSTEM IN IRRIGATED AGRICULTURE*

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Abstract

A great challenge facing future agricultural water policy is to explore the potential for transition from the current myopic competitive (common) exploitation of groundwater resources to a long-term efficient and sustainable allocation. A number of economic and/or command and control instruments can be used by the relevant water authority in order to deal with the economic and environmental problems generated by competitive exploitation. However, according to previous experience in both developed and developing countries, tradable permits seem as one of the most effective and efficient instruments, especially under conditions of limited water availability. On this account, the aim of the current study is to explore the feasibility and implementation of a tradable permit system in irrigated agriculture. To this end, two distinct optimization models are applied and compared: (a) an individual farmer's model (representing the myopic non-cooperative exploitation of groundwater) and (b) a social planner's model (representing the cooperative and sustainable allocation). The deviation of their results shows the rationale for using a tradable permit system, while the final allocation of the social planner's model, solved as an optimal control problem that maximizes the social welfare under specific water policy objectives, denotes the equilibrium state of this system. The two models are then applied in a typical rural area of Greece where groundwater is the only source of irrigated agriculture. The derived time paths for water consumption and water availability illustrate the significant environmental benefits from the future implementation of a tradable permit system.

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1. Introduction

Water has traditionally been regarded as a free-access public good. That was true for all water uses including agriculture. However, changes in technology, tastes, organization and scale proved that the systems built to provide water for irrigation and domestic uses free of charge or at heavily subsidized rates, cannot support anymore the increasing demands and degraded (polluted and depleted) supplies. The problem is most pressing in irrigated agriculture which accounts for more than two-thirds of water use. Water cannot be regarded anymore as a true free-access public good, since it is not abundant and has to be allocated among users by some type of mechanism. The economic literature suggests that allocation mechanisms that use markets and prices (water charges or tradable water permits) could help to ensure sustainable water use efficient allocation, and provide incentives for the development of water-efficient technologies in the long-run.

Tradable permits are commonly considered as one of the most efficient market-based instruments for groundwater allocation. Water permit markets could yield the right price and lead to the efficient allocation without the need for overall planning and management. In a perfectly competitive setting, a permit market would ensure that water goes to the higher value use. They are also consistent with the latest EU guidelines for water policy that promote the use of economic instruments providing water use efficiency and financial incentives.

The present paper examines the use of tradable permits in managing water use in irrigated agriculture. We develop a model in which there are two groups of farmers, producing each a high water demanding crop. All farmers share the same aquifer and thus, the rate of change in the eater table is a function of the total water used for irrigation. We assume that all farmers in both groups have the same marginal cost of pumping water. However, the crop-water production function differs between the two crops which also yield different prices in the market. Within this framework we examine two types of aquifer management; one based on a quota system and another on tradable water permits. The complexity of the analytical solutions does not permit meaningful comparisons, so we resort to an empirical application, using actual data from an agricultural region in Northern Greece. We first confirm that both systems yield significant improvements over the benchmark case, in which individual farmers are allowed to pump water at rates that maximize their annual income, ignoring the future impact of their action on the groundwater levels and consequently on other farmers' as well as their own future pumping costs. Furthermore, the results of the empirical application show that the implementation of a tradable water permit system yields not very significant benefits relative to a quota system. Although these results seem to question the use of water permits systems, they are specific to the characteristics of the area examined, which imply very similar marginal benefits for the two crops examined. Given that in addition, the two crops share the same marginal costs of pumping water, the small difference in the two systems' benefits is not surprising at all. Augmenting the difference between the two crops, either by widening the spread between their prices or their marginal water productivity, or imposing a stricter water constraint, yields very significant benefits from the transfer to a tradable permit system.

The present paper verifies both theoretically and empirically the urgent need for water management in irrigated agriculture. In the absence of any water management system, individual farmers could very fast deplete the available water resources. Both tradable and non-tradable water permit systems, if well-designed, provide the basic mechanism for sustainable water use. However, a tradable water permit system provides always higher economic benefits. The economic improvement is positively related to the existing differences among the technologies used in the production of different crops and their market prices. The more diverse are the crops sharing the same aquifer, the higher are the benefits from using a tradable water permit system.

A number of studies have evaluated various water market approaches to improve both water quality and quantity management.[1] Although most of the literature focuses on the use of water charges, there is some work highlighting the reasoning and the importance of using tradable water permit systems. For example, Ballestero et al. (2002) suggest that tradable permits may significantly improve water use efficiency, while they can also help to confront water scarcity and groundwater depletion. Hadjigeorgalis (2009) states also that their use in smallholder agriculture, a typical situation in most agricultural areas around the world, is likely to reduce the risk on

[1] See for example, Vaux and Howitt (1984), Howe et al. (1986) and Weinberg et al. (1993).

farmers' income. Tradable permits are often considered as the most appropriate water policy measure to cope with problems such as the continuous decline of groundwater levels and/or the heavy discount on future benefits (Griffin, 2006). Besides, their proper use may also enable water planners to approximate the optimal allocation of a theoretical dynamic model, recovering thus the potential gains from groundwater management (Provencher, 1993).

The main common issue addressed in these studies is the use (or the specification) of annual market models for surface water resources, usually without considering the long-term evolution (depletion) of groundwater resources. On the other hand, extensive research has been conducted during the past 30 years in order to estimate the optimal allocation of groundwater over time.[2] Nevertheless, there are no studies attempting to combine the above two methods, that is, the use of water markets as a tool for optimal groundwater allocation, highlighting thus the need for further research on this topic. The present paper attempts to cover this void, by developing a model that combines a dynamic optimal groundwater allocation problem with one of implementing a tradable water permit system. Both problems are applied exclusively to irrigated agriculture in order to determine the optimal time path for groundwater use in both economic and environmental terms. Making a step forward from previous studies that implied a single homogenous group of farmers, the present paper assumes that farmers are divided into two groups according to their main agricultural product and their crop-water production function. Farmers' decisions concerning water abstraction and use are supposed to be made annually, based on the current pumping costs. Hence, the proposed tradable permit system adopts such an empirical strategy by using an annual system of permits, which are granted at the beginning of each irrigation period and are valid only during this specific year.

2. The model

In the following sections two distinct optimization models are analyzed. The first one aims to solve the problem of an individual (non-cooperative) water user, by simulating farmers' annual pumping decisions and estimating the associated long-term economic and environmental impacts. Farmers' decisions are supposed to be

[2] Gisser και Sanchez, 1980; Feinerman and Knapp,1983; Burness and Brill, 2001; Koundouri, 2004.

made within a short-time period (every year), without considering at all the negative externalities of their actions (i.e. higher pumping cost to other irrigators due to lowering of the groundwater level).

On the other hand, the second model attempts to solve the same problem under the perspective of a social planner, who aims to maximize the aggregate long-term net benefits of groundwater use (during the same time period as in individual farmer's problem). The basic assumption made in this approach is that the social planer is well informed about the current and future state of the aquifer (i.e. the groundwater resource), as well as of the agricultural markets. The results of this model will be next used as a starting point for designing the appropriate economic instruments (tradable water permits or non-transferable quotas) in order to achieve the optimal aggregate groundwater extraction.

We assume two groups of farmers, each cultivating an area of equal size to produce a homogenous product. We further assume that all pumped water is used in agricultural activities and particularly to irrigate the two high water demanding crops. Furthermore, in order to focus on the relationship between crop yield and water use, we assume a simple crop-water production function which takes the following quadratic form:[3]

$$f(q_{r,t}) = a_r q_{r,t} - b_r q_{r,t}^2 + g_r \qquad (1)$$

where q_t is the per hectare annual consumption of irrigation water (m^3/ha). *a*,*b* and *g* are the fitting coefficients, determined for each type of crop ($r=1,2$) and depending on climate conditions and soil properties, as well as on irrigation and agronomic management practices in the reference area. These coefficients are assumed to be constant in our analysis. Farm revenues are then expressed solely as a function of the marginal product of water, even though other variable inputs are utilized (Burness and Brill, 2001).

All farmers pump water from a single-cell unconfined aquifer (Figure 1), where the groundwater resource is determined by a single variable such as the volume of water

[3] Similar crop – water production functions have been used extensively, see for example Helweg (1991).

remaining in the aquifer or the height of the aquifer (water table). Throughout this type of aquifer – which is often called "bathtub" – the water table and its fluctuation are both considered as uniform (Brozovic et al., 2006). For simplicity we do not take into account the drawdown within the well, because it is considered to have a constant and small effect on the pumping level during each irrigation period.

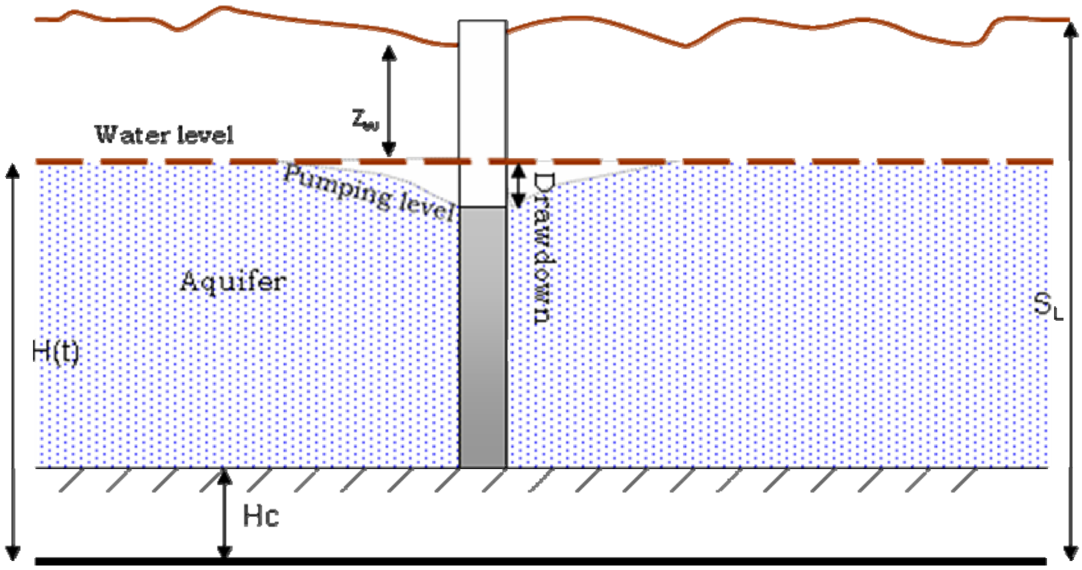

Figure 1: Water level changes associated with groundwater pumping

Within this framework, the pumping level (z_w) in a well is given by the following equation:

$$z_w = S_L - H(t) \tag{2}$$

where S_L is the height of the ground surface level and *H(t)* is the height of water table at time *t*.

Following Gisser and Sanchez (1980), we assume that the rate of change in the water table, $\dot{H}(t)$ is a function of the total volume of water used in irrigated agriculture (total water pumped), as well as of certain hydrological conditions in the reference area. In particular we assume that,

$$\dot{H}(t) = \frac{1}{AS}\left[N + (\alpha - 1)Q_t\right] \quad , \quad H(0) = H_0 \quad , \quad H(T) \geq H_c \tag{3}$$

where *N* is the natural recharge of the aquifer, α is the constant return flow coefficient ($0 < \alpha < 1$), Q_t is the total volume of water pumped and used at time t, *A* is the surface area of the groundwater reservoir, considered uniform in depth, S is the storativity coefficient, H_c is the height of the bottom of the aquifer and H_0 is the initial (current) height of the water table.

We assume that the marginal cost of pumping (MC_t), depends only on the pumping level, $z_w = S_L - H(t)$. Since we neglect drawdown within the well, the pumping level is the same as the water level of the aquifer, which implies zero marginal cost of the drawdown.[4] Furthermore, we assume a simple linear marginal cost function (Brill and Burness, 1994):

$$MC_t = c_0(S_L - H(t)) \tag{4}$$

where c_0 is the marginal cost per cubic meter of water pumped, per meter of lift.

3. Individual farmer's optimization model

The basic principles of groundwater aquifer exploitation in a typical common pool model have been discussed thoroughly in the literature.[5] One of the main results is that in the absence of institutional rules (such as water pricing, water quotas, etc.) individual farmers' decisions concerning water pumping ignore the consequences of their actions to other water users. Especially when there are many users, each abstracting a small quantity as compared to the resource volume, the effect of individuals' current decisions on the future status of the regional groundwater stock is considered negligible (Knapp et al, 2003). Therefore, individual farmers pump water at rates that maximize their annual income, ignoring the future impact of their action on the groundwater levels and consequently on other farmers' as well as their own future pumping costs.

The model used herein assumes that every irrigator in the study area tends to maximize his annual income by using a semi-empirical approach to estimate his pumping costs. This approach is based on farmers' ability to assess their marginal pumping costs (Eq.4) at the beginning of each irrigation period, just after the first water abstractions. In addition, this model assumes that farmers are facing high

[4] This is a simplifying assumption. In the more general case, the marginal cost of the drawdown is incorporated in the marginal cost. See for example, Martin and Archer (1971) and Gisser and Sanchez (1980).
[5] See for example, Gisser and Sanchez (1980), Negri (1989) and Provencher and Burt (1993).

investment costs and significant agricultural market constraints that affect their ability to deal with higher water costs. Namely, under these assumptions, crop changes are not considered as an economically viable solution and farmers are only left with the possibility to adjust their water application levels.

Since we assume a uniform water table and a negligible drawdown within the wells, marginal cost of pumping water is the same for both groups of farmers. Therefore, their final decisions on water consumption vary only because of their different net benefit functions (due to the diverse crop-water production function and the different market price of each product). Thus, the annual net benefit (*NB*) for each group of farmers is,

$$NB_{r,t} = p_r \cdot f(q_{r,t}) - MC_t \cdot q_{r,t} - Cnw_r \quad (5)$$

where p_r is the market price of each group's crop and Cnw_r is the cost of all other inputs, assumed constant and independent of the total water use.

For simplicity, it is also assumed that the two groups of farmers irrigate a total land of equal size, *M* hectares each. The allocation of land among farmers within each group is not considered. Therefore, total annual water consumption is $Q_t=M(q_{1,t}+q_{2,t})$. Substituting this into equation 3, yields the following discrete-time equation,

$$H_{t+1} - H_t = \frac{1}{AS}\left[N + (\alpha - 1)M(q_{1,t} + q_{2,t})\right] \quad (6)$$

As already mentioned, farmers' decisions on water consumption neglect the long-term effects on the water table. Thus, each individual farmer selects to pump and use an annual volume of groundwater that equates his marginal benefits of irrigation to his marginal pumping costs.

$$MNB_{r,t} = 0 \;\; \Rightarrow \;\; p_r \cdot f'(q_{r,t}) = MC_t \quad (7)$$

Assuming linear marginal benefits, Figure 2 illustrates the effect of the increase in marginal cost on q_t. Over time, water consumption reduces as a result of the continuous increase of pumping costs.

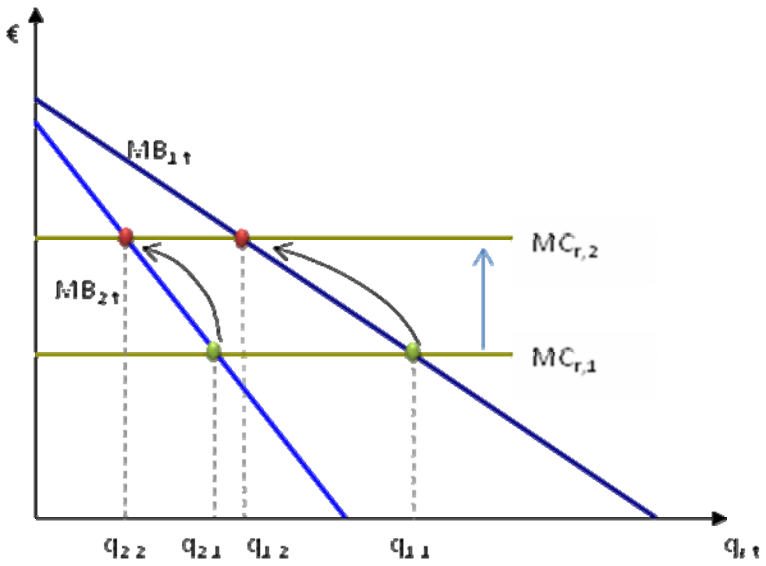

Figure 2: Optimal groundwater use for each group of farmers during two different time periods (years)

Substituting $f(q_{r,t})$ and MC_t from equations (1) and (4) respectively into equation (7) and solving for $q_{r,t}$, yields equation (8a). Given that total annual water consumption is $Q_t=M(q_{1,t}+q_{2,t})$, we also derive equation (8b).

$$q_{r,t}= \frac{a_r}{2b_r}-\frac{c_0}{2b_r p_r}\left[S_L-H_t\right] \tag{8a}$$

$$Q_t=M\cdot\left[\sum_r\frac{a_r}{2b_r}-\frac{c_0}{2}\left[S_L-H_t\right]\cdot\sum_r\frac{1}{b_r p_r}\right] \tag{8b}$$

We derive water consumption for the next time period, $q_{r,t+1}$, by substituting the corresponding height of the water table, H_{t+1}, from equation (6), into the time-adjusted equation (8a).

$$q_{r,t+1}= \frac{a_r}{2b_r}-\frac{c_0}{2b_r p_r}\left[S_L-H_t-\frac{1}{AS}\left[N+(\alpha-1)M(q_{1,t}+q_{2,t})\right]\right] \tag{9}$$

It should be noted that the optimum individual annual consumption of irrigation water at $t+1$, $q_{r,t+1}$, is negatively related to the total volume of water used during the previous time period, Q_t.

Substituting $q_{r,t}$ from equation (8a) into (9), yields $q_{r,t+1}$ as a function of $q_{r,t}$.

$$q_{r,t+1}= q_{r,t}+\frac{c_0}{2b_r p_r AS}\left[N+(\alpha-1)M(q_{1,t}+q_{2,t})\right] \tag{10}$$

Although the parameter H_t does not appear in equation (10), it is still indirectly incorporated into the water use levels. Summing up both farmers' groups annual water consumption, and multiplying with the total cultivated area *M* yields the total water consumption (abstraction) in the study area,

$$Q_{t+1} = Q_t\left(1+\frac{M\cdot c_0\cdot\Omega\cdot(\alpha-1)}{2\cdot AS}\right)+\left(\frac{M\cdot c_0\cdot\Omega\cdot N}{2\cdot AS}\right) \tag{11}$$

where: $\Omega=\left(\frac{1}{b_1p_1}+\frac{1}{b_2p_2}\right)$

Equations (10) and (11) express the time path for both the individual and the total groundwater use in irrigated agriculture as discrete-time functions.

Utilizing the initial condition $H(0) = H_0$, equations (8a) and (8b) yield the initial individual and total pumping water volumes.

$$q_{r,0} = \frac{a_r}{2b_r}-\frac{c_0}{2b_rp_r}(S_L-H_0) \tag{12a}$$

$$Q_0 = M\cdot\left[\frac{a_1}{2b_1}+\frac{a_2}{2b_2}\right]-\frac{M\cdot c_0\cdot\Omega}{2}\left[S_L-H_0\right] \tag{12b}$$

The initial conditions allow us to formulate a first-order difference equation for the total groundwater use $Q_{t+\Delta\tau}=f(Q_t)$. This equation fits well with the semi-empirical estimation of farmers concerning their marginal pumping costs. The difference equation can be written as:

$$Q_{t+1} = \Delta\cdot Q_t+K \tag{13}$$

where $\Delta=\left(1+\frac{M\cdot c_0\cdot\Omega\cdot(\alpha-1)}{2\cdot AS}\right)$ and $K=\left(\frac{M\cdot c_0\cdot\Omega\cdot N}{2\cdot AS}\right)$

The first step in solving equation (13) is to find a particular solution, denoted as Q_s, which is actually any solution to the above first order difference equation. A constant over time variable is applied in equation (13) (Pemberton and Rau, 2001), giving the following particular solution:

$$Qs = -\frac{N}{\alpha-1} \tag{14}$$

The associated homogenous equation of equation (13) is $Z_{t+1} = \Delta \cdot Z_t$; hence the complementary solution is $\Phi \cdot \Delta^t$, where Φ is an arbitrary constant. The general solution to the difference equation is therefore:

$$Q_t = \Phi \cdot \left(1 + \frac{M \cdot c_0 \cdot \Omega \cdot (\alpha - 1)}{2 \cdot AS}\right)^t - \frac{N}{\alpha - 1} \quad (15)$$

The value of the constant Φ is next found by using the boundary condition (equation (12b)) and thus the final solution concerning the time path of the aggregate groundwater consumption reads:

$$Q_t = \left(\frac{N}{\alpha - 1} + Q_0\right) \cdot \left(1 + \frac{M \cdot c_0 \cdot \Omega \cdot (\alpha - 1)}{2 \cdot AS}\right)^t - \frac{N}{\alpha - 1} \qquad t = 1, 2, ...T \quad (16)$$

Substituting Q_t from equation (16) into (8b), yields the time-path of the water table level,

$$\begin{aligned} H_t = S_L &- \frac{a_1/b_1 + a_2/b_2}{c_0 \cdot \Omega} - \frac{2N}{(\alpha - 1) \cdot M \cdot c_0 \cdot \Omega} + \\ &+ \left(\frac{2}{M \cdot c_0 \cdot \Omega}\right) \cdot \left(\frac{N}{\alpha - 1} + Q_0\right) \cdot \left(1 + \frac{M \cdot c_0 \cdot \Omega \cdot (\alpha - 1)}{2 \cdot AS}\right)^t \qquad t = 1, 2, ...T \end{aligned} \quad (17)$$

4. Social planner's optimization model

Contrary to the myopic and competitive behavior of individual farmers concerning the use of groundwater, the social planner's objective is to choose a groundwater resource allocation that maximizes the aggregate long-term net benefit. Moreover, this allocation should guarantee a minimum stock of groundwater at the end of the planning period. We assume that the social planner has full information regarding the hydrological[6] and the agro-economic[7] conditions along the reference area. The model used in this section is based on previous studies examining the optimization of the inter-temporal groundwater allocation.[8]

The main objective of the social planner is to determine the optimal aggregate yearly quota $\overline{Q}_t$ and then to allocate the volume of water per hectare $\overline{q}_{r,t}$ to each farmer in

[6] The hydrological conditions include the current groundwater level, the return flow coefficient and the natural recharge of the aquifer.

[7] The agro-economic conditions include the market value of agricultural products, the crop-water production functions and the marginal pumping cost.

[8] Among them, the most characteristic of these studies are: Gisser and Sanchez (1980), Feinerman and Knapp (1983), Laukkanen and Koundouri (2006) and Pitafi and Roumasset (2009).

group r ($r=1,2$) for the year t. In order to achieve this objective, the social planner may implement either a tradable water permit or a non-transferable quota system. Both systems are analyzed in detail in the rest of this section.

4.1. Tradable water permits system

Under the tradable permits system, each farmer is allowed to trade part of, or even the whole of, his water entitlement with other farmers during the year of issue. For the specific case of an annual tradable permit system with two equal-size groups, the total water volume used by all irrigators during a typical year t is:

$$\bar{Q}_t = M(\bar{q}_{1,t} + \bar{q}_{2,t}) = M(q_{1,t} + q_{2,t}) \tag{18}$$

After receiving its water entitlement, each farmer chooses her water use in each particular time period. Assuming a perfectly competitive market for water quotas and zero transaction costs, efficiency requires that at the equilibrium the marginal net benefits are equalized among the two farmers' groups.[9]

$$MNB_{1,t} = MNB_{2,t} \tag{19}$$

Equations (18) and (19) describe the equilibrium state of the system at time t. The solution of this system yields the water volume used by each group of farmers at t, as a function of the aggregate water quota in the reference area:

$$\begin{aligned} q_{1,t} &= \frac{1}{p_1 b_1 + p_2 b_2}\left(\frac{a_1 p_1 - a_2 p_2}{2} + p_2 b_2 \frac{\bar{Q}_t}{M}\right) \\ q_{2,t} &= \frac{1}{p_1 b_1 + p_2 b_2}\left(\frac{a_2 p_2 - a_1 p_1}{2} + p_1 b_1 \frac{\bar{Q}_t}{M}\right) \end{aligned} \tag{20}$$

The social planner's objective is to determine the optimal path of aggregate water use over the planning period, taking into account the optimal choice of farmers at each time period given by equation (20). To obtain this, the regulator maximizes the sum of the flow of individual farmers' net benefits over a fixed time horizon $t \in [0, T]$ subject to the transition equation on the water level of the aquifer (equation (3)). A fixed time horizon is used instead of the infinite horizon, since this concept better fits the planning process of a regulating agency (Xepapadeas, 1996). Additionally, the social planner has to guarantee that at T, a minimum level of water table H_{min} should be preserved. Therefore, the social planner solves,

[9] See among others Griffin (2006).

$$\max_{\bar{Q}(t)} \int_0^T e^{-\delta t} \left[\sum_r \left(p_r \cdot f(q_{r,t}) - C_t(H_t) \cdot q_{r,t} \right) \right] dt$$

subject to: (21)

$$\dot{H}(t) = \frac{1}{AS}\left[N + (\alpha - 1) \cdot \bar{Q}_t \right], \quad H(0) = H_0 \quad , \quad H(T) = H_{min}$$

where δ is the discount rate. [10]

This is a formal optimal control problem. The current value Hamiltonian is,

$$\tilde{H} = \left[\sum_r \left(p_r \cdot f(q_{r,t}) - C_t(H_t) \cdot q_{r,t} \right) \right] + \mu \left[\frac{1}{AS} \left(N + (\alpha - 1) \cdot \bar{Q}_t \right) \right] \quad (22)$$

where μ represents the shadow value of groundwater (i.e. the change in the marginal use cost of groundwater as the water table changes over time). This parameter differentiates the social from the private optimal solution. Given the current value Hamiltonian and assuming an interior solution, the necessary conditions for optimization (optimality condition and adjoint equation respectively) are the following:

$$\partial \tilde{H} / \partial \bar{Q}_t = 0 \quad (23a)$$

$$\dot{\mu} = \delta\mu - \left(\partial \tilde{H} / \partial H(t) \right) \Rightarrow \dot{\mu} = \delta\mu - c_0 \bar{Q}_t \quad (23b)$$

Equation (23a) implies that the total marginal net benefits from water use are equal to the shadow value of the actual volume of water pumped from the aquifer. To solve this equation for μ an initial condition should be specified for the shadow value of groundwater. In order to reduce the number of unknown variables in this condition (there are two unknown variables, $\bar{Q}_t$ and H_t), the state equation (3) is used once again and solved for $\bar{Q}_t$. Following this, the shadow value of groundwater is determined as,

$$\mu = \frac{AS}{(1-\alpha)} \cdot \left[\Pi - \Theta \cdot \frac{AS\dot{H}_t - N}{\alpha - 1} - c_0 (S_L - H_t) \right] \quad (24)$$

where:

[10] For simplicity we choose to express the terminal condition as an equality instead of an inequality. In the case examined, this simplification is close to reality since total water consumption will always tend to reach the maximum allowable volume and water table will subsequently always approximate the lower limit.

$$\Theta = \frac{2p_1b_1p_2b_2}{M\left(p_1b_1 + p_2b_2\right)} \quad , \quad \Pi = \frac{p_1p_2(a_1b_2 + a_2b_1)}{\left(p_1b_1 + p_2b_2\right)} \tag{25}$$

Differentiating equation (24) with respect to time and equating to the right hand side of (23b) yields,

$$\delta\mu - c_0\bar{Q}_t = \frac{AS}{(1-\alpha)} \cdot \left[\Theta \frac{AS\ddot{H}_t}{1-\alpha} + c_0\dot{H}_t \right] \tag{26}$$

Substituting μ from (24) and $\bar{Q}_t$ from the state equation and rearranging terms gives the following second order differential equation,

$$\ddot{H}_t - \delta\dot{H}_t - \left(\frac{\delta c_0(1-\alpha)}{AS\Theta} \right) H_t - \frac{1-\alpha}{AS\Theta} \left[\delta\Pi - \delta c_0 S_L - \frac{c_0 N}{AS} - \frac{\delta\Theta N}{1-\alpha} \right] = 0 \tag{27}$$

The general solution of the above differential equation can be estimated by reducing it to a first order equation after factorization,

$$H_t = X_1 e^{\rho_1 \cdot t} + X_2 e^{\rho_2 \cdot t} + \left[\frac{N}{\delta AS} + S_L - \frac{\Pi}{c_0} - \frac{\Theta N}{c_0(\alpha-1)} \right] \tag{28}$$

where, X_1 and X_2 are arbitrary constants, while ρ_1 and ρ_2 are the roots of the polynomial function, after the factorization of differential operators. These roots are equal to,

$$\rho_1 = \frac{\delta}{2} - \sqrt{\frac{\delta^2}{4} - \frac{\delta c_0(\alpha-1)}{AS\Theta}}, \quad \rho_2 = \frac{\delta}{2} + \sqrt{\frac{\delta^2}{4} - \frac{\delta c_0(\alpha-1)}{AS\Theta}} \tag{29}$$

Applying the boundary conditions $H(0)=H_0$ and $H(T)=H_{min}$ to (28), yields X_1 and X_2,

$$\begin{aligned} X_1 &= \frac{H_0 \cdot e^{\rho_2 \cdot T} - H_{min} - \left(e^{\rho_2 \cdot T} - 1\right) \cdot \left[\frac{N}{\delta AS} + S_L - \frac{\Pi}{c_0} - \frac{\Theta N}{c_0(\alpha-1)} \right]}{\left(e^{\rho_2 \cdot T} - e^{\rho_1 \cdot T}\right)} \\ X_2 &= \frac{H_{min} - H_0 \cdot e^{\rho_1 \cdot T} + \left(e^{\rho_1 \cdot T} - 1\right) \cdot \left[\frac{N}{\delta AS} + S_L - \frac{\Pi}{c_0} - \frac{\Theta N}{c_0(\alpha-1)} \right]}{\left(e^{\rho_2 \cdot T} - e^{\rho_1 \cdot T}\right)} \end{aligned} \tag{30}$$

Then, the aggregate annual allowable consumption of groundwater resources is,

$$\bar{Q}_t = \frac{AS \cdot \left[\rho_1 X_1 e^{\rho_1 \cdot t} + \rho_2 X_2 e^{\rho_2 \cdot t} \right] - N}{\alpha - 1} \tag{31}$$

Recalling now the allocation of water permits, according to the equilibrium state of Eq.20, it is also possible to estimate the annual volume of water used by each farmer when a tradable permit system is in place.

$$q_{1,t} = \frac{1}{p_1 b_1 + p_2 b_2}\left(\frac{a_1 p_1 - a_2 p_2}{2} + p_2 b_2 \frac{AS\cdot\left[\rho_1 X_1 e^{\rho_1\cdot t} + \rho_2 X_2 e^{\rho_2\cdot t}\right] - N}{M\cdot(\alpha-1)}\right)$$
$$q_{2,t} = \frac{1}{p_1 b_1 + p_2 b_2}\left(\frac{a_2 p_2 - a_1 p_1}{2} + p_1 b_1 \frac{AS\cdot\left[\rho_1 X_1 e^{\rho_1\cdot t} + \rho_2 X_2 e^{\rho_2\cdot t}\right] - N}{M\cdot(\alpha-1)}\right) \quad (32)$$

4.2. Non-tradable quota system

Contrary to the above mentioned market approach, under the non-tradable quota system farmers cannot sell their water shares to others. Annual water rights are granted free of charge and are allocated based on the historical use of irrigation water. Specifically, the maximum volume of water per hectare that each farmer in group *r* (*r=1,2*) is permitted to use during the year *t* is

$$\overline{q}_{r,t} = v_t \cdot q_{r,0} \quad (33)$$

where, $q_{r,0}$ is the initial individual pumping water volume, from equation (12a), and v_t is the water use reduction rate over time (as compared to the initial volumes). This rate is the same for both groups of farmers.

Following this allocation rule, the total water volume used by all irrigators during a typical year t is now determined as,

$$\overline{Q}_{t}= M(\overline{q}_{1,t} + \overline{q}_{2,t}) = M\cdot v_t (q_{1,0} + q_{2,0}) \quad (34)$$

Using equations (33) and (34) instead of the market equilibrium state (20) and solving once again the former optimal control problem (21) yields the time-path of the aggregate annual allowable consumption of groundwater resources under the water quota system. The general form of this function is identical to equation (31). However, the time-path differs: (a) in the values of the polynomial function's roots (ρ'_1, ρ'_2),

$$\rho'_1 = \frac{\delta}{2} - \sqrt{\frac{\delta^2}{4} - \frac{\delta c_0(\alpha-1)(q_{1,0}+q_{2,0})}{AS\Theta'}}, \quad \rho'_2 = \frac{\delta}{2} + \sqrt{\frac{\delta^2}{4} - \frac{\delta c_0(\alpha-1)(q_{1,0}+q_{2,0})}{AS\Theta'}} \quad (35)$$

as well as, (b), in the values of the arbitrary constraints (X'_1, X'_2),

$$
\begin{aligned}
X_1' &= \frac{H_0 \cdot e^{\rho_2' \cdot T} - H_{min} - \left(e^{\rho_2' \cdot T} - 1\right) \cdot \left[\dfrac{N}{\delta AS} + S_L - \dfrac{\Pi'}{c_0(q_{1,0} + q_{2,0})} - \dfrac{\Theta' N}{c_0(\alpha - 1)(q_{1,0} + q_{2,0})} \right]}{\left(e^{\rho_2' \cdot T} - e^{\rho_1' \cdot T}\right)} \\
X_2' &= \frac{H_{min} - H_0 \cdot e^{\rho_1' \cdot T} + \left(e^{\rho_1' \cdot T} - 1\right) \cdot \left[\dfrac{N}{\delta AS} + S_L - \dfrac{\Pi'}{c_0(q_{1,0} + q_{2,0})} - \dfrac{\Theta' N}{c_0(\alpha - 1)(q_{1,0} + q_{2,0})} \right]}{\left(e^{\rho_2' \cdot T} - e^{\rho_1' \cdot T}\right)}
\end{aligned}
\tag{36}
$$

where,

$$
\Theta' = \frac{\left(2p_1 b_1 q_{1,0}^2\right) + \left(2p_2 b_2 q_{2,0}^2\right)}{M\left(q_{1,0} + q_{2,0}\right)} \quad , \quad \Pi' = q_{1,0} a_1 p_1 + q_{2,0} a_2 p_2 \tag{37}
$$

The decision about the implementation or not of a regulated system of water allocation is mainly influenced by the divergence on water table levels between the individual and the social planner's model. The final outcome of the social planner's optimization model, no-matter the allocation mechanism, seems to depend largely on the initial water table level and on the environmental (hydrological) targets. Specifically, the annual volume of water granted to farmers is mainly determined by the desired stock of water resources when $t=T$.

On the other hand, the decision between tradable water permits and non-tradable quotas depends on the additional net benefits (water use efficiency) provided by the market approach. Tradable permits are expected to increase efficiency if the two groups of farmers have substantially different marginal benefit functions[11]. Dissimilar crop prices and diverse production functions (mainly in terms of the coefficient a) may lead to this condition. Furthermore, when strict hydrological constraints (targets) are applied, tradable permits seem to generate higher net benefits as compared to the non-transferable quotas.

It should be also noted that the market system offers flexibility, as it allows each farmer to make periodical (annual) adjustments to the use of his water shares, in order to adapt to potential variations in environmental or economic factors that are considered, so far, to be constant in time. This flexibility can also be interpreted in economic terms (e.g. higher net benefits of tradable permits during dry years).

[11] Marginal cost functions are assumed to be equal in both groups of farmers.

5. Empirical Application

5.1. Study area and data

The theoretical model developed in the previous sections is applied to the case of groundwater management in the Moudania agricultural region, in Northern Greece. The basic criteria for selecting this particular region are the following: (a) agriculture is one of the main activities in the area, (b) groundwater is intensively used for irrigation and (c) there is a deficit in the water balance of the river basin. It should be also noted that the water used for local agricultural activities derives solely from pumping numerous wells (more than 800 wells in the study area), the majority of which are located in the southern part of the basin (Figure 3).

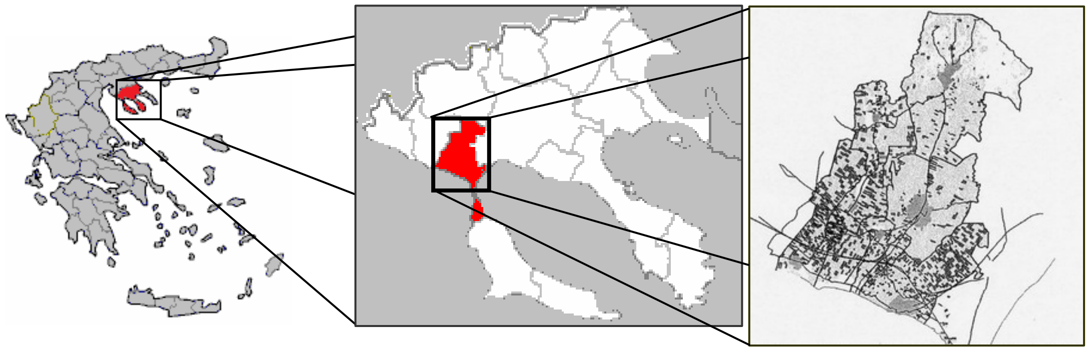

Figure 3: Study area map

Current agricultural patterns and practices are extremely dependent on water resources, leading thus to a severe over-pumping of the aquifer. According to a local water management plan, the annual demand for water outweighs the annual supply by 5.5 millions m^3/year, causing a steady decline in the aquifer's water level equal to 0.6m/year (Latinopoulos, 2003). Table 1 summarizes the main hydrological data for the study area.

Source: (Latinopoulos, 2003)

Table 1: Hydrological data in the study area

The most needed agro-economic data were collected from the databases of Hellenic Statistical Authority, as well as from a questionnaire survey in the area (Pagidis and Latinopoulos, 2008). As far as the crop share is concerned, almost 50% of the irrigated area is cultivated with olive trees. In the remaining area, the prevailing crops are: orchard trees (30% of the total area), vegetables, cotton and corn. In order to feed the data into our theoretical model, we assume that there are only two crops, olive and orchard trees, each of which occupies half of the total irrigated area (M=1300 ha).

The restructuring of the area's cropping plans seems to be an economically inefficient solution due to the high percentage of permanent crops (crops that are actually associated with high investment costs). For this reason, the potential increase of the marginal pumping (use) cost of water is not going to alter the crop-mix of the area. Consequently, the irrigation water demand function should be derived from yield reductions (i.e. income losses) of the existing crops due to deficit irrigation practices. In other words, the water demand functions for both groups of farmers are equivalent to the crop-water production functions (equation (1)).

The coefficients a_r, b_r and g_r of these functions are estimated according to the local climate, soil and crop characteristics, as well as, to water application efficiency and irrigation scheduling. They are in fact the result of a regression analysis (linear OLS regression) on crop responses to the corresponding sequential reductions of water consumption. Crop responses on different water use levels are estimated by means of specific computer software, called CROPWAT and provided by FAO (Smith, 1992). The resulting equations are presented in Table 2, along with other relevant agro-economic data. Substituting these data in (5) gives the net benefit functions for both groups of farmers. It is worth mentioning that the first group: (a) is currently associated with higher economic output (net benefits per hectare of cultivated land), due to the higher market price of olives, and (b) maximizes its yield at lower water use levels than the second group, due to its water-yield function (i.e. a less-water demanding crop).

Parameter	Description	Value
C_o	Pumping cost per cubic meter of water pumped per meter of lift	0.0004 €/m^3
M	Total cultivated area by each group of farmers	1300 ha
$f(q_{1,t})$	Production function for the 1st group of farmers	$0.778q_t - 0.000058q_t^2 + 1440$

	(crop: olive tree) – kg/ha	
$f(q_{2,t})$	Production function for the 2nd group of farmers (crop: orchards) – kg/ha	$1.501q_t – 0.000094q_t^2 + 4910$
$p(q_{1,t})$	Current price of the crop of group1	1.20 €/kg
$p(q_{2,t})$	Current price of the crop of group1	0.42 €/kg
Cnw_1	Cost of the other crop inputs (apart from water) for the 1st group of farmers	2700 €/ha
Cnw_2	Cost of the other crop inputs (apart from water) for the 2nd group of farmers	3150 €/ha

Table 2: Agro-economic data in the study area

5.2 Results of the optimization model

A time horizon (planning period) of 40 years ($t \in [0,T],\ T = 40$) is chosen and used in both models; the individual and the social planner one. As already mentioned, the individual farmer's model is based on the hypothesis that each farmer maximizes his net benefit for given pumping decisions of other farmers, taking under consideration an empirical pumping cost estimation (at the beginning of the irrigation period). Substituting thus the data from Tables 1 and 2 into (16), the resulting time path for the aggregate water use is,

$$Q_t = 11{,}620{,}647 + 5{,}922{,}472 \cdot (0.9989)^t \qquad t = 1,2,...40 \tag{38}$$

Likewise, from (17), the time path for the water table height is,

$$H_t = -513.81 + 573.81 \cdot (0.9989)^t \qquad t = 1,2,...40 \tag{39}$$

From the above equations it becomes evident that there is only a very small decline in the long term use of groundwater resources, indicating the limited effect of water pumping costs to current and future decisions of farmers. Namely, the annual reduction of water consumption in the next 20 and 40 years is estimated to be equal to 0.7% and 1.4% of the current usage, respectively. Hence, given the current deficit water balance, a substantial drawdown of the water table (i.e. a decline of water stock) is expected. From (17) the average annual drop of the water table level is found equal to 0.59 m (the range of this measure varies from 0.58m/year to 0.61m/year), confirming the outcome of the local water management plan (Latinopoulos, 2003) and resulting in a total drawdown of 23.8m, at the end of the planning period (t=40).

In order to implement the social planner's model in the study area, we need to determine the appropriate discount rate and to set the environmental target of the water policy, that is, the terminal value of the water table level. A generally accepted social discount rate for this kind of problems usually varies from 2% to 4% (Pearce and Ulph, 1995; Spackman, 2006). On this account, a discount rate equal to 3% was selected. Concerning the terminal value of the water table, a value equal to 50m was chosen ($H_T=50$) to safeguard the minimum impact of the drawdown to the coastal areas (i.e. to minimize seawater intrusion into coastal wells). Combining these values with the hydrologic and socioeconomic data of Tables 1 and 2, the following time-paths for the water table height and aggregate water use are obtained:

Tradable water permit system

$$H_t = 529.57e^{-0.001\cdot t} + 4.56e^{0.031\cdot t} - 474.14 \quad (40)$$

$$\bar{Q}_t = 11,620,647 + 5,285,723e^{-0.001\cdot t} - 1,382,069e^{0.031\cdot t} \quad (41)$$

Non-tradable quota system

$$H_t = 555.94e^{-0.001\cdot t} + 4.63e^{0.031\cdot t} - 500.56 \quad (42)$$

$$\bar{Q}_t = 11,620,647 + 5,312,043e^{-0.001\cdot t} - 1,398,829e^{0.031\cdot t} \quad (43)$$

It is worth-mentioning that, contrary to the individual farmer's optimization model, both approaches followed here by the social planner result in a large variation of the annual drawdown (from 0.04m/year to 0.40m/year). This variation is mainly due to the discount effect, which leads to higher values at the first planning years and lower values at the end of the time horizon. It is also apparent from the equations (40-43) that there are no significant deviations in the time-paths generated by the tradable and non-tradable permit systems.

Comparing the results of the aggregate water consumption in both models (Figure 4)[12] confirms the expectation that when decisions are made by individual farmers, irrigated agriculture is usually leading to overconsumption of groundwater resources. In particular, the excessive water consumption is growing over time, starting from an initial (t=1) value of 2.02 millions m^3 (13% more than the corresponding estimate of the tradable permit model) and finally (t=40) reaching the value of 5.38 millions m^3

[12] The social planner's model is represented only by the tradable permit system. The reason is that the time path of both permit systems are almost identical (their annual variation is less than 0.15%), and hence appear as a single curve in Figures 4 and 5.

(45% more than the corresponding estimates of the tradable permit model). This divergence is partly due to the fact that farmers do not consider the scarcity cost of groundwater resources. However, the main cause of this divergence is the social planner's sustainable water management policy, as expressed by means of the terminal value of the water table level (H_{min}). It should be also mentioned that

The overconsumption of water resources under the individual farmer's model is indirectly presented in Figure 5, where the time path for the height of the water table is shown. According to this figure, individual farmer's model results to an almost linear negative slopped function, leading to a water table height equal to 36.2m. On the other hand, social planner's time-path for the stock availability is an exponential function leading by definition to the pre-selected water table level (H_T=50).

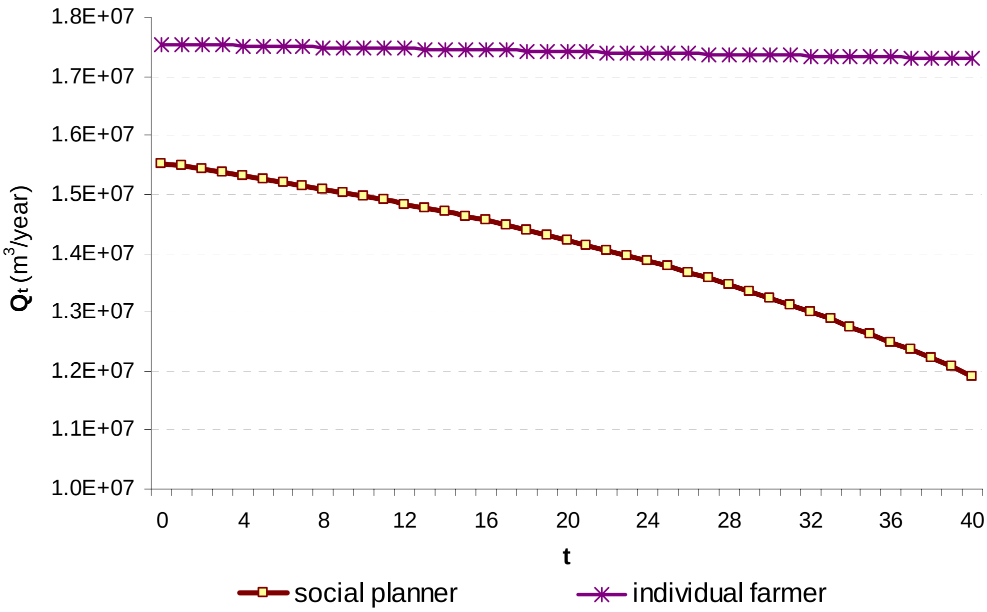

Figure 4: Time path for aggregate water consumption at the individual farmer's and the social planner's optimum

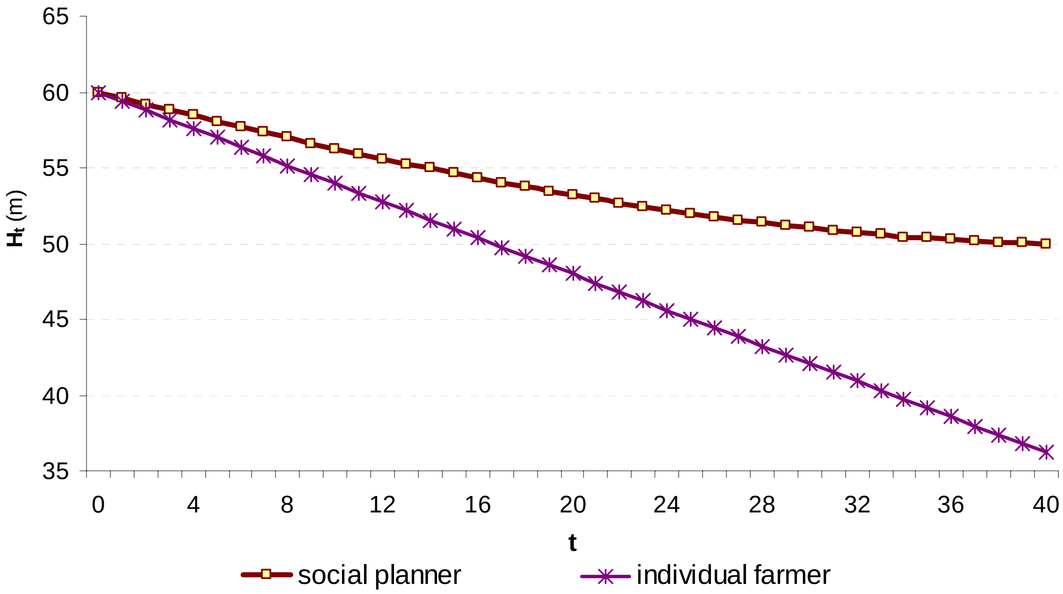

Figure 5: Time path for the water table height at the individual farmer's and the social planner's optimum

As expected, the dissimilar patterns of water consumption between the two models induce significant differences in their economic results, which are illustrated in Figure 6. Namely, the application of the social planer's model and the attainment of the associated environmental targets may cause a notable decrease in farmers' income. The additional total annual cost (loss of net benefits) of the tradable permit approach ranges from € 81,000 (t=1), up to € 496,000 (t=40). These costs estimates are equivalent to the 2.3% and 14.6%, respectively, of the aggregate annual net benefits in the study area, as calculated in the individual farmer's model.

In order to examine the efficiency of tradable permits, as compared to the non-tradable quotas it is worthwhile to compare the aggregate net benefits generated by these two approaches during the planning period T. As shown in Figure 6, there is a little additional benefit from the implementation of the market system (0.4% of the aggregate net benefits). This outcome is not surprising, considering the similarity between the marginal benefits in the two groups of farmers. However, this is not a general rule concerning the efficiency of tradable permits in irrigated agriculture. To support the latter argument, the model was tested under various scenarios of data modification (i.e. different crop prices, production functions and water constraints), which result to a range of additional net benefits from 0 up to 15%[13].

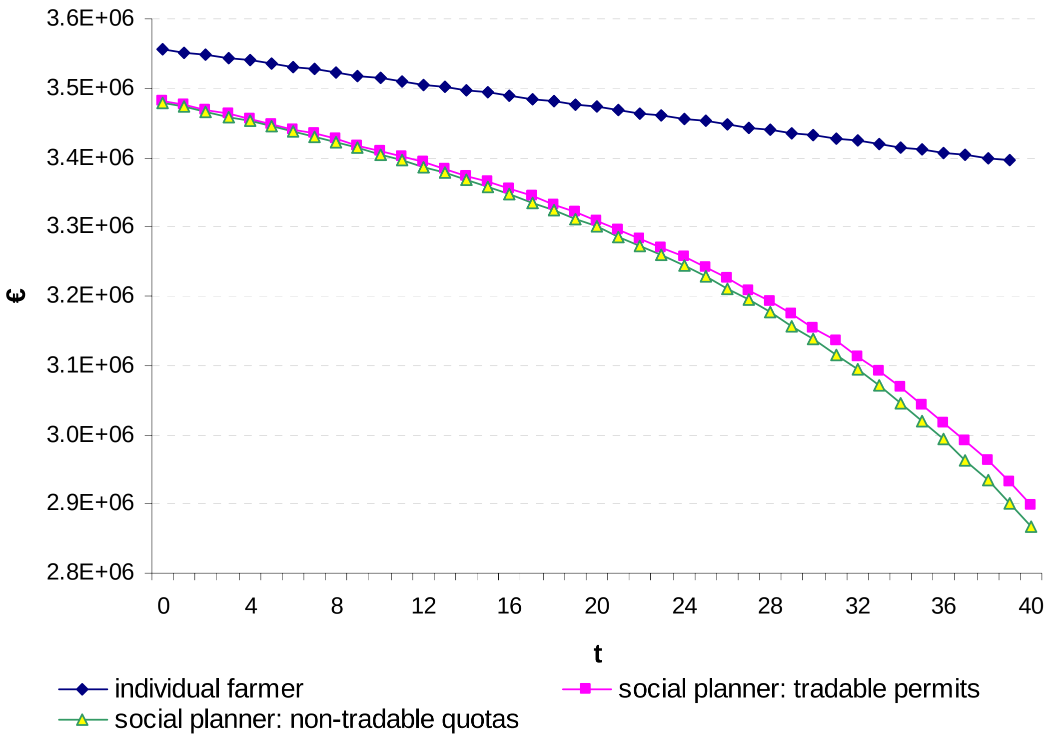

Figure 6: Time path for the aggregate net benefits in all three models

Finally, in order to find the time path for the price of water permits, a simple expression, recommended by Griffin (2006), is adopted:

$$P_t^z = MNB_{1,t} = MNB_{2,t} \tag{44}$$

According to Griffin (2006), when many agents (e.g. farmers) are present, the market price of water permits is likely to be equal to individual farmers' net benefit, at the equilibrium state. Marginal net benefits can be easily estimated according to the social planner's model (i.e. the tradable permit approach), by making use of the optimum individual water consumption ($q_{r,t}$). In this framework, the time path for the market price of water permits is determined as:

$$P_t^z = 0.0156 + 0.007 \cdot e^{-0.001t} + 0.055 \cdot e^{0.031t} \tag{45}$$

[13] For example: (a) a stricter water constraint: H(T)=60 leads to additional net benefits equal to 1.3%, (b) a double price on the crop of group 1 leads to additional net benefits equal to 5%, (c) an alternative crop for the 1st group (with higher marginal productivity) may lead to additional net benefits up to 10%.

Figure 7 illustrates the graphical representation of Eq.39. The market price of tradable water permits seems to increase in a slightly exponential way through time. Specifically, the initial price is found equal to 0.079 €/m^3, while the final price is equal to 0.210 €/m^3 (t=40). This price increase is mainly due to the decreasing (in time) optimal level of individual water consumption.

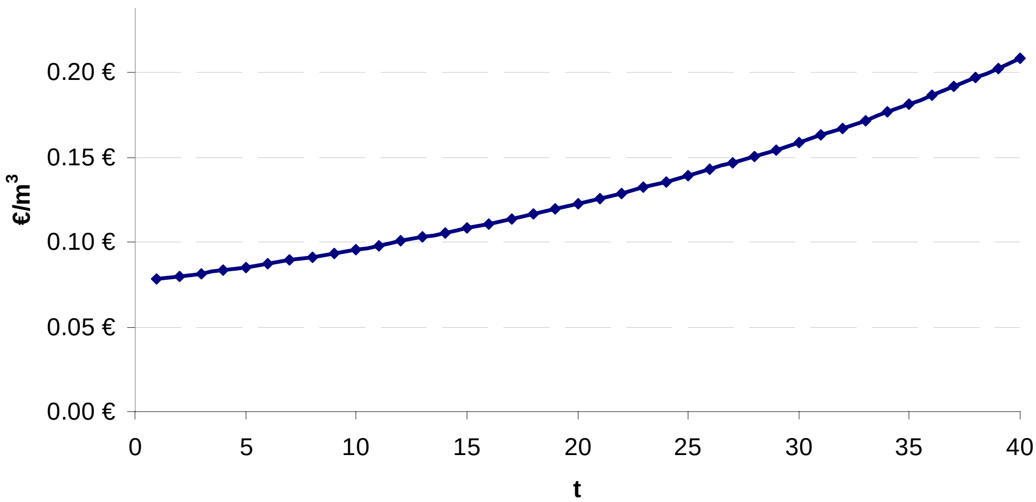

Figure 7: Time path for the price of water permits

4. Conclusions

The present paper analyzed a problem of groundwater allocation in irrigated agriculture. On this purpose two different models are analyzed and then compared. The first model examined the long-term results of a free access system to groundwater resources, under the assumption that farmers act myopically and take short-term (annual) decisions concerning water abstractions (use). On the other hand, the optimal allocation from the social planner's point of view was estimated by means of an optimal control approach, under the assumption that the final resolution (allocation) will provide a feedback to a tradable permit system. Comparing thus the outcomes of these two models can help in identifying the potential for a future tradable water permit system.

The analysis of the individual farmer's model showed that the depletion of groundwater resources is a very likely scenario when: (a) decisions concerning individual water abstractions don't take under consideration the possible externalities of their action, b) the pumping costs do not constitute a significant component of production costs, which is a common phenomenon in Greek agriculture. The depletion time depends on the current water balance of the aquifer, as well as, on its initial stock (water table) level.

On the other hand, the analysis of the social planner's model showed that the time path of water availability (e.g. the time path for the water table level of the aquifer) is determined by the long-term net benefits of farmers, as well as by the desired water table level (as defined by the river basin water authority) at the end of the planning horizon. A sensitivity analysis on the final water table level can actually act as a multicriteria problem with two objective functions: maximum income versus minimum depletion. The efficient solution set for this problem can form the basis for future groundwater resource management.

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However, numerous externalities associated with common property groundwater extraction and the myopic behaviour of water users, impede market operation and hinder the efficiency of the permit market system. Furthermore, a number of problems, affecting the system's effectiveness, may arise during implementation and are due to: the existing institutional framework,[14] the lack of information from the relevant water authorities[15] and the excessive transaction and monitoring costs of these systems. Addressing these problems, so as to achieve the efficiency potential of tradable permit systems for groundwater resources, poses a great challenge for water managers and scientists alike.

[14] For example, free access to groundwater, water rights strictly related to the land ownership, etc.
[15] For example, information concerning water demand, the current water balance in the reference basin, the current stock of groundwater resources, etc.

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