The Effect of Discounting on the Formulation of an Aquifer Management Policy Based on Groundwater Trading

Athanasios Tsiarapas[1] · Zisis Mallios[1]

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Abstract

Optimal groundwater management is a necessary condition for achieving the objective of sustainable development, which is directly linked to issues of intergenerational equity. Thus, groundwater management policy shaping has to consider such issues, in particular through the implementation of appropriate discounting methods. The existing literature in the field of groundwater management focuses on a single discount function (DF), the exponential one, without considering the impact of different DFs on the results obtained. At the same time, tradable water rights (TWR) systems have been suggested as policy instruments for more efficient and sustainable water use. This paper focuses on the impact that different DFs have on the formulation of groundwater management policies based on TWR. To this end, a dynamic model is formulated, which concerns groundwater pumping from an aquifer by two groups of users participating in a TWR system and four different DFs are considered to calculate the present value of social welfare: no discounting, exponential, hyperbolic and Gamma discounting. The results of simulations based on data for an aquifer in Northern Greece show that there is a high sensitivity of the results to the DF, which has a direct effect on social welfare from groundwater consumption, aquifer's hydrological behavior and TWR system intertemporal economic efficiency.

Keywords Groundwater management · Discounting · Tradable water rights · Optimization

1 Introduction

The United Nations 2030 Agenda for Sustainable Development includes sustainable water management as one of its 17 goals (Goal 6) (UN 2015). The concept of sustainable water management is inherently linked to the concept of intergenerational equity, which refers to equitable use of a renewable or non-renewable natural resource over time by different generations (Harpman 2014).

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Based on the principle of intergenerational equity, a long-standing debate has emerged in the scientific community on the choice of the DF when economically evaluating projects and policies that are considered to have a direct impact on future generations (Arvaniti et al. 2018). Therefore, understanding how people discount, i.e. evaluate future costs and benefits, is crucial for effective environmental policies and consequently groundwater resource management policies formulation (Green and Richards 2018).

According to Green and Richards (2018), one of the key questions that an environmental policy maker is required to answer concerns the form of discounting to use in order to evaluate different policies. In the international environmental economics literature, exponential discounting, i.e. discounting using a fixed discount rate, has attracted interest with many studies using it (see Gollier and Hammitt 2014). However, using a fixed discount rate when formulating environmental policies raises two important concerns: first, optimal policy is highly sensitive to the discount rate and second, the use of a high discount rate makes the present value of economic benefits or costs arising in the future negligible (Karp 2005; Anari et al. 2023). Thus, new approaches to discounting environmental policies have been proposed, which are considered to address more effectively intergenerational equity and sustainability issues discussed earlier (Harpman 2014). One of these approaches is the use of non-fixed discount rates known as Declining Discount Rates (DDR), i.e. discount rates that vary over time, which are considered more appropriate for evaluating policies or projects with an intergenerational character (Anari et al. 2023). The use of non-fixed discount rates is not as widespread when addressing environmental problems (Arvaniti et al. 2018).

In terms of water resources management, with the exception of Duarte (1995), who considers different DFs, literature focuses on only one form of discounting, exponential (Gisser and Sanchez 1980; Esteban and Albiac 2011, 2012; Biancardi et al. 2022) without going deeper into the impact that this choice has on the results obtained. Consequently, water management policies' evaluation based on DFs different from exponential such as those including non-constant discount rates is a subject that, to the best of authors' knowledge, has not been adequately studied.

This paper attempts to fill this gap in literature on the effect of DF form on the formulation of the optimal aquifer management policy. Given the strong research interest in groundwater management by implementing economic instruments such as TWR systems (Zhang et al. 2012; Fu et al. 2016) the impact of the DF form on the formulation of a management policy of an aquifer from which two groups of users extract groundwater based on a corresponding system is going to be evaluated. Thus, a time-dynamic optimization problem is to be formulated with the objective of maximizing the social welfare resulting from groundwater consumption during a given planning period. This problem is to be solved for different DFs to be considered and corresponding conclusions are to be drawn. The different DFs to be considered are as follows: no discounting, exponential discounting, hyperbolic discounting and Gamma discounting, i.e. discounting considering uncertainty.

The novelty of the paper lies in the identification of the impact of using different DFs when evaluating a groundwater management policy based on TWR. Previous studies (see for example Koundouri et al. (2017)) suggest conducting sensitivity analysis for the discount rate when evaluating groundwater management policies using exponential discounting. Therefore, the impact of DF form on policy shaping is acknowledged. However, as noted above, none of previous studies focuses on identifying the impact of the DF form on groundwater management policy shaping based on TWR.

A social planner considering the effect of different forms of DF on groundwater management policy shaping and particularly the effect of time-varying discount rates on it, actually considers uncertainty of the future. The use of a fixed discount rate does not

introduce the uncertainty factor into the problem under consideration. For a social planner to consider uncertainty by using a fixed discount rate, they have to perform sensitivity analysis on the discount rate and then calculate the Expected Value of the present value of the policy under consideration and finally determine the certainty equivalent discount rate, which is time-varying (Broughel 2020). In this case, the social planner has no insight into aquifer's hydrological behavior, total groundwater consumption and TWR price under uncertainty about the future. The insight they do have relates only to the present value of the policy under consideration, in this case the TWR system. Hence, the analysis performed in this paper provides additional information to the policy maker regarding the influence of uncertainty in groundwater management policy shaping based on TWR.

2 Methodology

2.1 The Model

In order to formulate the model on the basis of which the subsequent analysis will be carried out, a typical groundwater pumping problem is considered. Thus, a social planner (for example a water agency) is considered, who is responsible for managing an aquifer from which two groups of users extract water. The social planner manages aquifer by implementing a system of TWR aimed at maximizing social welfare resulting from groundwater consumption over a planning period of T years. Thus, what social planner is essentially doing is maximizing the present value of cash flow resulting from total benefits SW_t in each year t during the planning period. For discounting, social planner uses a DF $D(t)$, which is given by the following equation (Hepburn et al. 2010):

$$D(t) = e^{-\int_0^t r(\tau)d\tau} \tag{1}$$

where $r(t)$ is the discount rate, which is either time-dependent or not, depending on the DF used, as it will be shown below.

Total benefit SW_t in each year t is obtained as the sum of users' individual benefits. For group of users i, the net benefit $W_{i,t}$ derived from groundwater consumption in each year t is obtained from the following equation:

$$W_{i,t} = f(Q_{i,t}, H_t) = \frac{1}{2k_i}Q_{i,t}^2 - \frac{g_i}{k_i}Q_{i,t} - c_0(s_L - H_t)Q_{i,t} - C_{i,other,t} \tag{2}$$

where $Q_{i,t}$ is groundwater quantity consumed by group of users i in year t, g_i and k_i are coefficients of groundwater demand function, constant over the period of T years, c_0 is marginal pumping cost per cubic meter of water and per meter of pumping level, s_L is average ground elevation, H_t is groundwater table level (GTL henceforward) in year t and $C_{i,other,t}$ various costs per year, constant during the planning period, which are not related to groundwater consumption.

In Eq. (2) the term $\frac{1}{2k_i}Q_{i,t}^2 - \frac{g_i}{k_i}Q_{i,t}$ shows the benefit resulting from groundwater consumption during year t, which equals the area under inverse demand function corresponding to the demand function with coefficients g_i and k_i ($Q_{i,t} = g_i + k_i p_t$, where p_t is groundwater price). The term $c_0(s_L - H_t)Q_{i,t}$, where $(s_L - H_t)$ is pumping level,

indicates groundwater pumping cost for group of users i in year t and it can be obtained by assuming a linear cost function such as that of Brill and Burness (1994).

In order to model TWR system, what is reported by Latinopoulos and Sartzetakis (2014) is adopted, who formulate a corresponding model assuming an initial allocation of TWR in each year and that first, perfect competition prevails in TWR market, second, that transaction costs are zero and third, that no borrowing or saving of TWR is allowed. Hence, the necessary condition that introduces TWR system into the model developed is the following (Latinopoulos and Sartzetakis 2014):

$$\frac{\partial W_{1,t}}{\partial Q_{1,t}} = \frac{\partial W_{2,t}}{\partial Q_{2,t}} = P_t \tag{3}$$

The condition described by Eq. (3) means that at equilibrium (demand for TWR equals supply for TWR, under conditions of perfect competition) marginal benefit of one group of users is equal to marginal benefit of the other group of users and both are equal to TWR price. Exploiting this condition and assuming that no borrowing and saving of TWR is allowed, so in each year what is marketed by social planner through initial allocation is consumed, i.e., $Q_{tot,t} = \sum_{i=1}^{2} Q_{i,t}$, the amount of groundwater $Q_{i,t}$ consumed by each group of users can be expressed as a linear combination of the total amount of groundwater pumped per year $Q_{tot,t}$. This implies that:

$$Q_{i,t} = u_i Q_{tot,t} + v_i, \forall i \tag{4}$$

where $u_i = \frac{\frac{1}{k_j}}{\frac{1}{k_i} + \frac{1}{k_j}}$ and $v_i = \frac{\frac{g_i}{k_i} - \frac{g_j}{k_j}}{\frac{1}{k_i} + \frac{1}{k_j}}$, $i, j = 1, 2$, so finally it is $W_{i,t} = f(Q_{tot,t}, H_t)$.

Aquifer's GTL rate of change is described by the following differential equation (Gisser and Mercado 1973):

$$\dot{H} = \frac{1}{AS}[R - (1 - a)Q_{tot,t}] \tag{5}$$

where A is aquifer's total area, S is aquifer's storativity coefficient, R is annual natural recharge of aquifer, $\alpha < 1$ is return flow coefficient and $Q_{tot,t}$ as mentioned above is total amount of groundwater pumped during year t.

Consequently, the optimization problem that social planner has to solve in order to maximize social welfare resulting from groundwater consumption during the planning period is the following:

$$maxV = \left\{ \int_0^T D(t)SW_t(Q_{tot}, H_t, t)dt \right\} \tag{6}$$

subject to:

$$\begin{aligned} \dot{H} &= \frac{1}{AS}[R - (1 - a)Q_{tot,t}] \\ H(0) &= H_0 \\ H(T) &= H_{min} \end{aligned} \tag{7}$$

In expression (7) H_0 is aquifer's GTL at the beginning of the planning period. The constraint $H(T) = H_{min}$ is set by social planner, as one of his objectives is to protect aquifer from depletion.

Assuming that:

$$F(Q_{tot,t}, H_t, t) = D(t)SW_t(Q_{tot,t}, H_t, t) \tag{8}$$

and substituting $Q_{tot,t}$ based on Eq. (5), the optimization problem that social planner has to solve is finally the following:

$$maxV = \left\{ \int_0^T F(\dot{H}_t, H_t, t)dt \right\} \tag{9}$$

subject to:

$$\begin{aligned} H(0) &= H_0 \\ H(T) &= H_{min} \end{aligned} \tag{10}$$

The optimization problem described by Eq. (9) and expression (10) can be solved using the Euler–Lagrange equation according to which the trajectory H_t that maximizes the integral of Eq. (9) can be obtained from the following equation (Hamill 2014):

$$\frac{\partial F}{\partial H_t} - \frac{d}{dt}\left(\frac{\partial F}{\partial \dot{H}_t}\right) = 0 \tag{11}$$

Equation (11) is sufficient for an absolute maximum of V only if function $F(\dot{H}_t, H_t, t)$ is jointly concave in $\dot{H}_t$ and H_t (Chiang 1999). In Appendix a proof for the concavity of function F is provided.

Applying the condition described by Eq. (11) and a little algebra, the following second-order differential equation can be obtained:

$$\ddot{H}_t + \frac{\dot{D}(t)}{D(t)}\dot{H}_t + \frac{m_2}{m_1}\frac{\dot{D}(t)}{D(t)}H_t = \frac{m_4}{m_1} - \frac{m_3}{m_1}\frac{\dot{D}(t)}{D(t)} \tag{12}$$

where $m_1 = \left[\frac{AS}{(1-a)}\right]^2\left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right), m_2 = -\frac{c_0 AS}{(1-a)}, m_3 = -\frac{AS}{(1-a)}\left[\left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)\frac{R}{(1-a)} + \frac{u_1}{k_1}(v_1 - g_1) + \frac{u_2}{k_2}(v_2 - g_2) - c_0 s_L\right]$ and $m_4 = \frac{c_0 R}{(1-a)}$.

In differential Eq. (12) it is $\frac{\dot{D}(t)}{D(t)} = -r(t)$ according to Eq. (6), where $r(t)$ is discount rate. It has to be noted that based on the solution of differential Eq. (12) optimal trajectories for the variables $Q_{tot}(t)$, $SW(t)$ and $P(t)$ can be also obtained.

2.2 No Discounting

When a social planner evaluates environmental policies using no discounting, i.e. a zero- discount rate (see Fig. 1), it firstly shows that they are equally concerned about someone who is living today and someone who is going to live in both near and distant future and secondly it shows that they are indirectly imposing an income reduction on current generation in order to benefit future generations, i.e. leading current generation to a kind of impoverishment (Pearce et al. 2003; Harpman 2014). Consequently, discounting with a zero-discount rate raises issues of intergenerational equity.
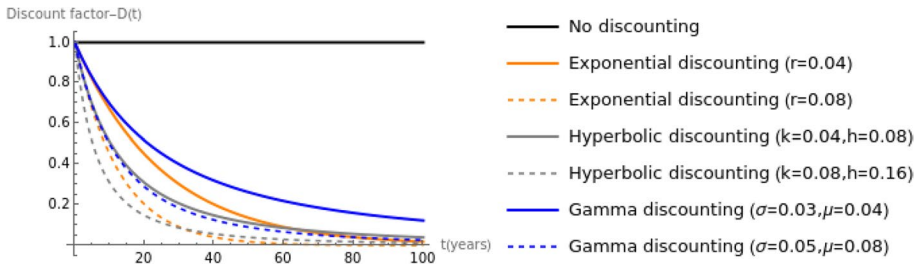
Fig. 1 DFs for a period of 100 years

Thus, assuming a zero-discount rate, differential Eq. (12) is reduced to a simple differential equation with constant coefficients (since $\frac{\dot{D}(t)}{D(t)} = -r(t) = 0$), the analytical solution of which is a second-degree polynomial function.

2.3 Exponential Discounting

In this case the discount rate is fixed in time. As reported by Winkler (2009) and Hepburn et al. (2010) it is an approach presented by Samuelson (1937), who claimed that the use of a constant discount rate is a working hypothesis that is contradicted by scientific observations.

Nevertheless, exponential DF is widely used, as mentioned above, because of a key advantage it has over other approaches that will be presented below, which is time consistency. Time consistency, which is considered a necessary condition for rational decision making, refers to the effect that decision's timing has on the decision that is ultimately taken. In the case of exponential DF there is no such problem, since optimal solution choice does not depend on the time point of alternatives' evaluation (Farmer and Geanakoplos 2009; Winkler 2009).

In the case of exponential discounting, DF is as follows (Mazur 1987; Green and Myerson 1996):

$$D(t) = e^{-rt} \tag{13}$$

where r is discount rate, which is independent of time and expresses the rate at which the value of a future cost or benefit decreases in proportion to the time lag over which it arises. A high value for r indicates that the discounting is steep, which means that a high weight is given to rewards that arise in immediate future and a low weight to rewards that arise in distant future. In contrast, a small value for r indicates that discounting is relatively mild, assigning sufficient weight to both rewards that arise in near future and rewards that arise in distant future (see Fig. 1) (Green and Myerson 1996).

Thus, assuming an exponential DF, differential Eq. (12) is reduced to an ordinary second-order differential equation with constant coefficients (since $\frac{\dot{D}(t)}{D(t)} = -r(t) = -r$), the analytical solution of which is an exponential function of time that can be easily determined.

2.4 Hyperbolic Discounting

Hyperbolic discounting is based on the belief that in reality people attach more weight to rewards that occur either in very near or in very distant future and little weight to rewards that occur at intermediate time points, so exponential discounting does not capture their way of thinking (Farmer and Geanakoplos 2009; Sargisson and Schöner 2020). Consequently, since there is evidence that people behave 'hyperbolically' rather than 'exponentially' a social planner should in his analysis explore the possibility of using a hyperbolic DF (Duarte 1995).

Hyperbolic DFs appear in literature in two different forms: one-parameter functions and two-parameter functions, which are also known as hyperboloid functions (Sargisson and Schöner 2020). In this paper a hyperbolic two-parameter DF such as that of Loewenstein and Prelec (1992) is going to be used, which is as follows:

$$D(t) = \left(\frac{1}{1 + kt} \right)^{h/k} \tag{14}$$

where h and k are parameters. Parameter k expresses the extent to which hyperbolic DF differs from the corresponding exponential one. Consequently, as k approaches zero the closer the hyperbolic DF is to the exponential one. Parameter h expresses the perception of time, which means that when it approaches zero time passes very quickly while when it approaches infinity time passes extremely slowly (Harpman 2014). The time-varying discount rate in this case is $r(t) = \frac{h}{1+kt}$.

As mentioned in previous subsection, the main advantage of exponential discounting is time consistency. In the case of hyperbolic discounting, however, time consistency is not a fact, since as mentioned by Strotz (1956) the evaluation of alternative policies at different points in time leads to different conclusions (Winkler 2009). Therefore, it is understandable that the use of a hyperbolic DF creates the problem of time inconsistency, although in this paper the evaluation of groundwater management policy is carried out only at time $t = 0$, when decisions are to be made.

Thus, considering a hyperbolic DF, differential Eq. (12) is reduced to a second-order differential equation with variable coefficients (since $\frac{\dot{D}(t)}{D(t)} = -r(t) = -\frac{h}{1+kt}$), the analytical solution of which is difficult to determine, so the best approach is to solve it numerically.

2.5 Gamma Discounting

As stated by Duarte (1995) and Strulik (2021) an important problem when using exponential DF is the choice of discount rate value and most importantly the introduction of general uncertainty present in discount DF. Uncertainty is mainly associated with the possibility that one may not perceive the reward at the right time and thus future rewards have to be discounted in such a way that this possibility is considered (Sozou 1998). Thus, related approaches have been developed that address this issue of uncertainty, most notably that of Weitzman (2001), who showed that when there is uncertainty about time-constant discount rate, the DF that has to be used is a two parameters hyperboloid function of the form (Weitzman 2001):

Table 1 Hydro-economic data (Sources: Amir and Fisher 1999; Weitzman 2001; Latinopoulos 2003; Spackman 2006; Latinopoulos and Sartzetakis 2014; Tsiarapas and Mallios 2023)

Parameter	Description	Value	Units
g_1	Water demand function coefficient (domestic use)	2790114.112	$m^3/year$
k_1	Water demand function coefficient (domestic use)	−1073120.812	$m^6/€•year$
g_2	Water demand function coefficient (agricultural use)	17387066.667	$m^3/year$
k_2	Water demand function coefficient (agricultural use)	−16189333.333	$m^6/€•year$
$C_{1,other,t}$	Various costs (domestic use)	0	-
$C_{2,other,t}$	Various costs (agricultural use)	2700	$€/ha/year$
c_0	Marginal pumping cost	0.0004	$€/m^3/m$
α	Return flow coefficient	0.166	-
R	Annual natural recharge	9691620	m^3
A	Aquifer's total area	12700	ha
S	Aquifer's storativity coefficient	0.064	-
S_L	Average ground elevation	210	m
H_0	Initial GTL	60	m
H_{min}	Desired GTL for the end of the planning period	50	m
T	Planning period	50	$years$
r	Exponential discount rate	0.04	-
k	Hyperboloid DF parameter	0.04	-
h	Hyperboloid DF parameter	0.08	-
σ	Gamma DF parameter	0.03	-
μ	Gamma DF parameter	0.04	-

$$D(t) = \frac{1}{\left(1 + \frac{\sigma^2}{\mu}t\right)^{\frac{\mu^2}{\sigma^2}}}$$

(15)

where σ is standard deviation of Gamma distribution, μ is mean of Gamma distribution and $r(t) = \frac{\mu}{1 + \frac{\sigma^2}{\mu}t}$ is time-varying discount rate which is equivalent to the discount rate of a hyperboloid DF with $h = \mu$ and $k = \frac{\sigma^2}{\mu}$.

In this case, as shown in Fig. 1, great weight is given to rewards that arise in distant future. Obviously, in this case there is also the problem of time inconsistency, although, as mentioned above, the formulation of the problem under study is such that it is not based on future reassessment but on a binding decision in present.

Considering, therefore, a DF based on Gamma distribution, differential Eq. (12) is degraded, as in the case of hyperbolic DF, to a second-order differential equation with variable coefficients (since $\frac{\dot{D}(t)}{D(t)} = -r(t) = -\frac{h}{1+kt}$), the analytical solution of which, as mentioned above, is difficult to determine, so the best approach in this case too is to solve it numerically.
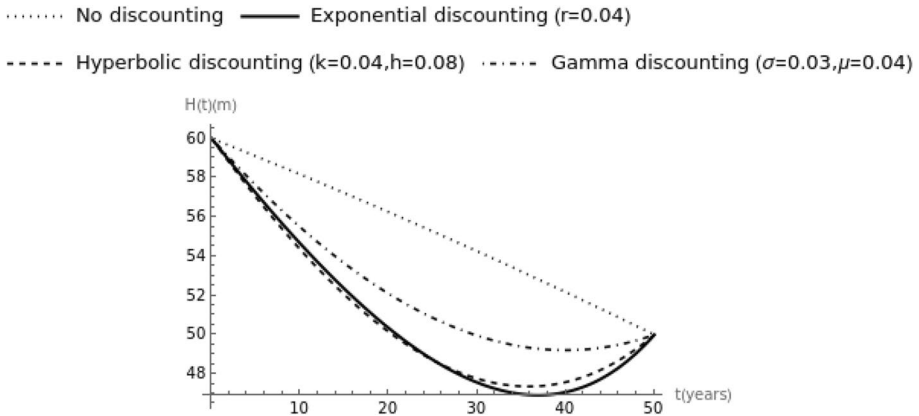
Fig. 2 Optimal trajectories for GTL under different DFs

3 Case Study

3.1 Case Study Area

The case study area selected for the implementation of the methodology presented in Section 2 is the area of Nea Moudania in the peninsula of Chalkidiki in Northern Greece. The predominant water uses in the area are domestic and agricultural, so these are the two uses that are to be considered. Table 1 presents hydro-economic data to be used for the simulations.

This case study area is an ideal one for implementing the proposed methodology, since it is an area where groundwater is the only reliable source of water. This fact combined with high water demand, create problems related to aquifer's sustainability. As reported by Theodossiou (2016) the aquifer has an annual deficit in its water balance equal to $3.29 \cdot 10^6 m^3/year$, which is expected to increase by 32% by 2100 reaching $4.34 \cdot 10^6 m^3/year$.

3.2 Simulations Results and Discussion

The analysis of the results focuses on key variables that a social planner should consider when formulating a groundwater management policy. These variables in the case of aquifer management by implementing a TWR system are aquifer's GTL, quantity of groundwater extracted by users, TWR price and social welfare resulting from groundwater consumption.

Figure 2 shows optimal trajectories for aquifer's GTL for each DF considered. The difference between the case where no discounting is implemented and the cases where discounting is implemented regardless of the form is evident. When no discounting is used optimal trajectory corresponds to a second degree convex curve, whereas when discounting of any form is used the optimal trajectory corresponds to a concave curve.

The implications behind each different DF seem to be fully reflected in the optimal trajectories for aquifer's GTL. Thus, as noted above, when there is no discounting, this implies an indirect impoverishment of current generation to the benefit of future generations. This belief is confirmed by Fig. 2, since when there is no discounting there is conservative
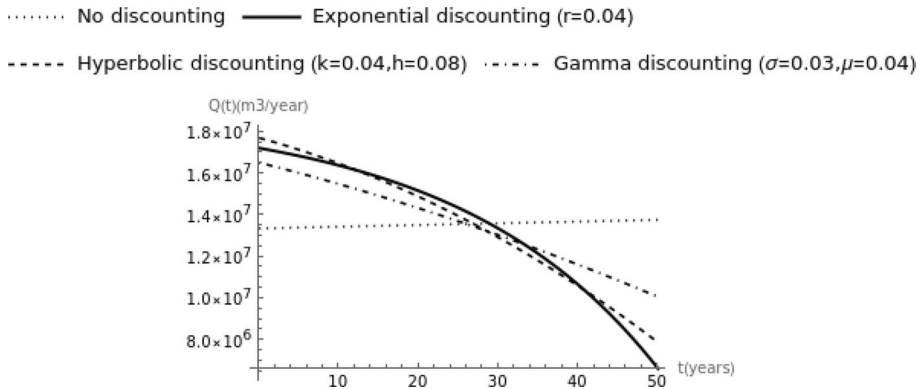
······· No discounting ———— Exponential discounting (r=0.04)

- - - - Hyperbolic discounting (k=0.04,h=0.08)   ·-·-·- Gamma discounting (σ=0.03,μ=0.04)

Fig. 3 Optimal trajectories for pumping rates under different DFs

aquifer management as opposed to other cases of discounting. Conservative management is based on the apparently small and stable GTL drop, i.e. limited groundwater pumping in first years of planning period (see also Fig. 3). In contrast, where there is discounting, the preference for consumption in immediate future is clearly evident. When hyperbolic discounting is implemented, it appears that social planner gives more weight to immediate and distant benefits and less weight to intermediate benefits than when using exponential discounting, and this is precisely the reason for slightly larger drop in GTL (which implies higher groundwater consumption, as shown in Fig. 3) observed in hyperbolic discounting in early years and slightly smaller drop also observed in it in intermediate years. In the case of Gamma discounting, a preference for benefits accruing in distant future is evident, leading to a relatively conservative management (less conservative than in the case of no discounting but more conservative than both exponential and hyperbolic discounting). This conservative management is justified by milder fall in GTL (Fig. 2), which is due to lower consumption (Fig. 3).

An important difference between different DFs, especially with regard to the trajectory of aquifer's GTL, is that when social planner implements some form of discounting, it is not the case that $H(t) \geq H_{min}$ over time. This is only true in the case where there is no discounting. This difference is particularly important, since maintaining GTL above a minimum value is not only related to aquifer reserves but also to in situ services provided by groundwater, one of which is to avoid seawater intrusion into coastal aquifers such as the one in the case study area (Kemper et al. 2003). Seawater intrusion into a coastal aquifer is directly related to the quality of water consumed by users and, in the case of water used for irrigation, to the reduction of agricultural production. Therefore, groundwater salinization has an impact on benefits users derive from groundwater. However, in this paper the effect of salinity on user benefits has not been considered, since the aim of the paper is not to quantify benefits from groundwater consumption but to compare different DFs. Thus, in the case of exponential and hyperbolic discounting from year $t = 21$ onwards it is expected that $H(t) < H_{min}$. In the case of Gamma discounting this is expected to be the case from year $t = 29$.

In terms of optimal trajectories for social welfare (Fig. 4), these seem to follow the corresponding trajectories for GTL and quantity of groundwater pumped. In the case of no discounting, social welfare is increasing over time which is due to aquifer's conservative
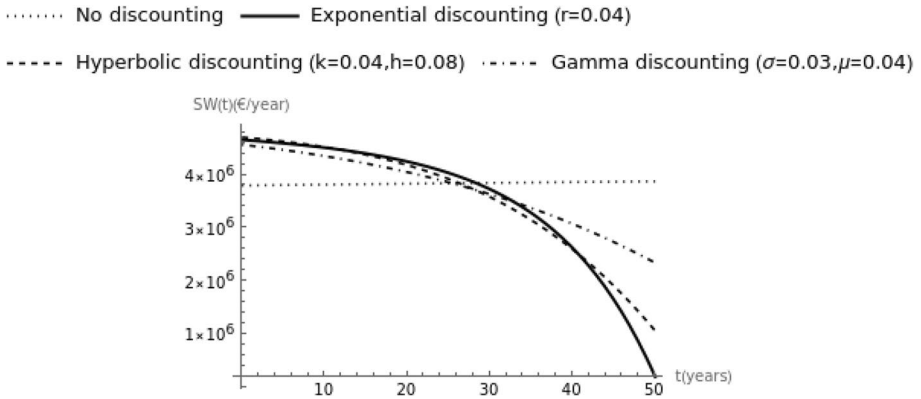
.... No discounting ———— Exponential discounting (r=0.04)

- - - - Hyperbolic discounting (k=0.04,h=0.08) ·-·-·- Gamma discounting (σ=0.03,μ=0.04)

Fig. 4 Optimal trajectories for social welfare under different DFs

.... No discounting ———— Exponential discounting (r=0.04)

- - - - Hyperbolic discounting (k=0.04,h=0.08) ·-·-·- Gamma discounting (σ=0.03,μ=0.04)
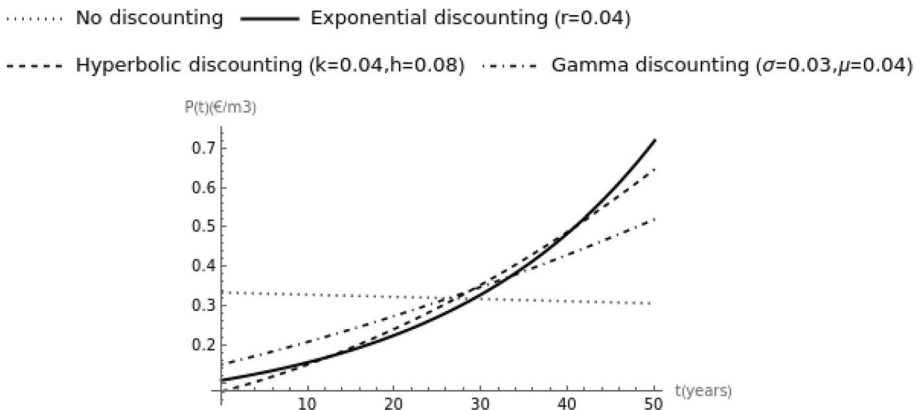
Fig. 5 Optimal trajectories for TWR price under different DFs

treatment leading to a small benefit from groundwater consumption but at the same time to small pumping costs. That is why from year $t = 29$ onwards social welfare with no discounting exceeds social welfare in every other case. In the other discounting cases benefits are diminishing and in the case of hyperbolic discounting and Gamma discounting it appears that at the end of the planning period social welfare outperforms social welfare obtained using exponential discounting indicating the preference in these cases for rewards arising in distant future.

As expected when discounting is not implemented the present value of social welfare calculated by a social planner over the planning period is larger than any other case reaching 196 million €. This amount of money has actually no value, since the time preference of people for immediate benefits is not considered. In the case of exponential discounting the present value is estimated at around €90 million, in the case of hyperbolic discounting at around €70 million and in the case of Gamma discounting at around €100 million. The large difference in present value calculation between exponential and hyperbolic discounting is due to the use of a time-varying discount rate in the latter case, which leads to a low preference for benefits accruing at intermediate points in time.
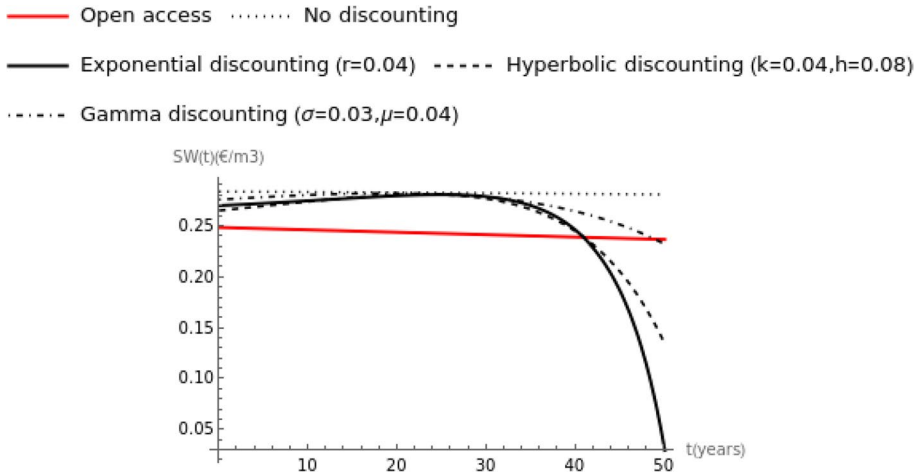
Fig. 6 Optimal trajectories for social welfare per unit of groundwater extracted under different DFs

Figure 5 depicts optimal trajectories for TWR price. The key observation here is that when there is no discounting, price follows a decreasing path over time while when there is discounting, price follows an upward path as expected, since water scarcity increases over time. The decreasing trajectory of TWR price when no discounting is implemented is attributed to the increase in the quantity of groundwater pumped from the aquifer over time (see Fig. 3), i.e. the increase in supply. What the declining trend in TWR price shows is that users have to pay for water at a high price in near future in order to ensure cheap water for distant future.

Comparing optimal trajectories for TWR price in Fig. 5 corresponding to three cases where a DF is used clearly shows the implication of each of them in terms of people's time preference. In hyperbolic discounting, the preference for rewards arising in immediate or distant future is proved, which translates into a lower price compared to exponential discounting in early years of the planning period and a higher price compared to it in later years. In Gamma discounting, a preference for rewards arising in distant future is evident, which means that TWR price in early years is expected to be higher than price resulting from exponential or hyperbolic discounting, while in later years this is expected to be lower than price resulting from both exponential and hyperbolic discounting.

A final point, which is worth commenting on, is the effect of the DF form on the assessment of TWR system economic efficiency. Given that the main argument in favor of such systems is that they lead to more efficient use of water than an open access regime, it is considered appropriate to devote a few lines to this claim. Therefore, an open access[1] regime is considered, which corresponds to a non-intervention regime regarding aquifer management. Economic efficiency is defined as social welfare resulting from each unit of groundwater extracted from aquifer.

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[1] Under an open access regime each user seeks to maximize their private benefit from groundwater consumption, so trajectories for key variables used in this application are easily derived by setting $\frac{\partial W_{1,t}}{\partial Q_{1,t}} = \frac{\partial W_{2,t}}{\partial Q_{2,t}} = 0$.

Figure 6 shows optimal trajectories for groundwater economic efficiency corresponding to different DFs. The attractiveness of a TWR system cannot in general be questioned, since groundwater economic efficiency under such a system is higher than the economic efficiency under an open access regime either during the entire planning period (no discounting) or during most of the planning period (exponential, hyperbolic and Gamma discounting).

The difference among DFs mainly concerns the point in time after which TWR system economic efficiency is lower than that of an open access regime. In the case without discounting this point obviously does not exist, since a TWR system is more efficient throughout the planning period. In the case of exponential and hyperbolic discounting this point in time is expected to be in year $t = 41$ while in the case of Gamma discounting, where uncertainty is considered, it is expected to be in year $t = 49$. Thus the use of either exponential or hyperbolic DF, which do not consider uncertainty, leads to a clear underestimation of TWR system attractiveness in the last decade of the planning period.

4 Summary and Conclusions

This paper investigates the effect of DF form on aquifer management policy shaping based on TWR. Therefore, a typical aquifer management problem is formulated. For aquifer's optimal management a system of TWR is implemented. Four different DFs were considered and for each of them optimal trajectories were derived for key variables such as aquifer GTL, quantity of groundwater pumped, social welfare resulting from groundwater consumption, TWR price and economic efficiency of groundwater.

The main conclusion, which emerges from conducting simulations based on numerical data from a coastal aquifer in Northern Greece, is that there is sensitivity of the extracted results to the DF. Thus, significant differences in social welfare from groundwater consumption, aquifer's hydrological behavior and TWR system intertemporal economic efficiency emerge. Differences observed in results are due to different time preference implied by each DF, as described for each function in Section 2. Therefore, the choice of the appropriate DF when evaluating alternative management policies for an aquifer is an important issue. The choice of DF form depends both on the way a social planner perceives the uncertainty of future economic conditions and on the region in which the policy under study is to be implemented, since for example a region threatened by climate change and its effects is characterized by greater uncertainty about future. In this case Gamma discounting should be the choice.

Appendix

The function F is the following:

$$F\left(Q_{tot,t}, H_t, t\right) = D(t) \sum_{i=1}^{2} \left[\begin{array}{l} \frac{1}{2k_i}\left(u_i Q_{tot,t} + v_i\right)^2 - \frac{g_i}{k_i}\left(u_i Q_{tot,t} + v_i\right) \\ -c_0\left(s_L - H_t\right)(u_i Q_{tot,t} + v_i) - C_{i,other,t} \end{array} \right] \overset{(5)}{\Rightarrow} \tag{16}$$

$$F\left(\dot{H}_t, H_t, t\right) = D(t) \sum_{i=1}^{2} \left[\begin{array}{l} \frac{1}{2k_i}\left(u_i \frac{R}{(1-a)} - u_i \frac{AS}{(1-a)}\dot{H}_t + v_i\right)^2 \\ -\frac{g_i}{k_i}\left(u_i \frac{R}{(1-a)} - u_i \frac{AS}{(1-a)}\dot{H}_t + v_i\right) \\ -c_0\left(s_L - H_t\right)(u_i \frac{R}{(1-a)} - u_i \frac{AS}{(1-a)}\dot{H}_t + v_i) - C_{i,other,t} \end{array} \right]$$

$F\left(\dot{H}_t, H_t, t\right)$ has continuous second derivatives and thus its concavity will be confirmed by *"checking the sign definiteness or semidefiniteness of the quadratic form q"* as stated by Chiang (1999) of the following form (Chiang 1999):

$$q = F_{HH}dH^2 + 2F_{H\dot{H}}dHd\dot{H} + F_{\dot{H}\dot{H}}d\dot{H}^2 \tag{17}$$

where F_{HH}, $F_{H\dot{H}}$ and $F_{\dot{H}\dot{H}}$ are partial derivatives.

If q is everywhere negative definite, $F\left(\dot{H}_t, H_t, t\right)$ will be concave. The sign definiteness of q can be revealed by applying the characteristic-root test (Chiang 1999). The first step for applying the characteristic root test is to form and solve the following characteristic equation:

$$\begin{vmatrix} F_{\dot{H}\dot{H}} - r & F_{\dot{H}H} \\ F_{H\dot{H}} & F_{HH} - r \end{vmatrix} = 0 \tag{18}$$

The partial derivatives can be easily calculated and thus the following results can be obtained:

$$F_{\dot{H}\dot{H}} = D(t)\left[\frac{AS}{(1-a)}\right]^2\left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right) \tag{19}$$

$$F_{H\dot{H}} = F_{\dot{H}H} = -D(t)\frac{c_0 AS}{(1-a)} \tag{20}$$

$$F_{HH} = 0 \tag{21}$$

Substituting Eqs. (19)-(21) into Eq. (18) the characteristic equations that has to be solved is obtained:

$$r^2 - D(t)\left[\frac{AS}{(1-a)}\right]^2\left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)r - \left[D(t)\frac{c_0 AS}{(1-a)}\right]^2 = 0 \tag{22}$$

Equation (22) has a positive discriminant and its roots are the following:

$$r_1 = \frac{D(t)\frac{AS}{(1-a)}\left\{\frac{AS}{(1-a)}\left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right) + \sqrt{\left[\frac{AS}{(1-a)}\right]^2\left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2 - 4c_0^2}\right\}}{2} \tag{23}$$

$$r_2 = \frac{D(t)\frac{AS}{(1-a)}\left\{\frac{AS}{(1-a)}\left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right) - \sqrt{\left[\frac{AS}{(1-a)}\right]^2\left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2 - 4c_0^2}\right\}}{2} \tag{24}$$

As for r_1 it holds that:

$$\left[\frac{AS}{(1-a)}\right]^2 \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2 - 4c_0^2 < \left[\frac{AS}{(1-a)}\right]^2 \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2 =>$$

$$\sqrt{\left[\frac{AS}{(1-a)}\right]^2 \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2 - 4c_0^2} < \sqrt{\left[\frac{AS}{(1-a)}\right]^2 \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2} =>$$

$$\sqrt{\left[\frac{AS}{(1-a)}\right]^2 \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2 - 4c_0^2} < \frac{AS}{(1-a)} \left|\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right| \stackrel{\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2} < 0}{\Rightarrow} \quad (25)$$

$$\sqrt{\left[\frac{AS}{(1-a)}\right]^2 \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2 - 4c_0^2} < -\frac{AS}{(1-a)} \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right) =>$$

$$\frac{AS}{(1-a)} \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right) + \sqrt{\left[\frac{AS}{(1-a)}\right]^2 \left(\frac{u_1^2}{k_1} + \frac{u_2^2}{k_2}\right)^2 - 4c_0^2} < 0$$

Because of (25) and since $D(t) > 0$, $A > 0$, $S > 0$, $1 - a > 0$, $k_1 < 0$ and $k_2 < 0$ it will be $r_1 < 0$. From Eq. (24) it is obvious that it will also be $r_2 < 0$. According to Chiang (1999) because of the fact that $r_1 < 0$ and $r_2 < 0$ there is negative definiteness of q and thus the function F is jointly concave in $\dot{H}_t$ and H_t.

Declarations

References

Amir I, Fisher FM (1999) Analyzing agricultural demand for water with an optimizing model. Agr Syst 61:45–56. https://doi.org/10.1016/S0308-521X(99)00031-1

Anari R, Gaston TL et al (2023) New economic paradigm for sustainable reservoir sediment management. J Water Res Pl 149. https://doi.org/10.1061/(ASCE)

Arvaniti M, Krishnamurthy C, Crépin A (2018) Resource management, present bias and regime shifts. Working paper

Biancardi M, Iannucci G, Villani G (2022) Groundwater exploitation and illegal behaviors in a differential game. Dyn Games Appl. https://doi.org/10.1007/s13235-022-00436-0

Brill TC, Burness SH (1994) Planning versus competitive rates of groundwater pumping. Water Resour Res 30:1873–1880. https://doi.org/10.1029/94WR00535

Broughel J (2020) The social discount rate: a primer for policymakers. Mercatus Center, George Mason University. https://www.mercatus.org/research/policy-briefs/social-discount-rate-primer-policymakers. Accessed 26 Jan 2024

Chiang AC (1999) Elements of dynamic optimization. Waveland Press, Prospect Heights

Duarte TK (1995) Long-term management and discounting of groundwater resources with a case study of Kuki'o, Hawai'i. PhD thesis, Massachusetts Institute of Technology

Esteban E, Albiac J (2011) Groundwater and ecosystems damages: questioning the Gisser-Sánchez effect. Ecol Econ 70:2062–2069. https://doi.org/10.1016/j.ecolecon.2011.06.004

Esteban E, Albiac J (2012) The problem of sustainable groundwater management: the case of La Mancha aquifers, Spain. Hydrogeol J 20:851–863. https://doi.org/10.1007/s10040-012-0853-3

Farmer JD, Geanakoplos J (2009) Hyperbolic discounting is rational: valuing the far future with uncertain discount rates. Cowles Foundation Discussion Paper No. 1719. https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1448811. Accessed 27 Jan 2024

Fu Q, Zhao K, Liu D et al (2016) The application of a water rights trading model based on two-stage interval-parameter stochastic programming. Water Resou Manage 30:2227–2243. https://doi.org/10.1007/s11269-016-1279-9

Gisser M, Mercado A (1973) Economic aspects of ground water resources and replacement flows in semi-arid agricultural areas. Am J Agr Econ 55:461–466. https://doi.org/10.2307/1239126

Gisser M, Sanchez D (1980) Competition versus optimal control in groundwater pumping. Water Resour Res 16:638–642. https://doi.org/10.1029/WR016i004p00638

Gollier C, Hammitt J (2014) The long-run discount rate controversy. Annu Rev Resour Econ 6:273–295. https://doi.org/10.1146/annurev-resource-100913-012516

Green L, Myerson J (1996) Exponential versus hyperbolic discounting of delayed outcomes: risk and waiting time. Am Zool 36:496–505

Green GP, Richards TJ (2018) Discounting environmental goods. J Agr Resour Econ 43:215–232. https://doi.org/10.22004/ag.econ.273447

Hamill P (2014) A student's guide to Lagrangians and Hamiltonians. Cambridge University Press, New York

Harpman DA (2014) Discounting for long-lived water resources investments. Report prepared by the U.S Department of Interior, Bureau of Reclamation, Technical Service Center, Denver, Colorado

Hepburn C, Duncan S, Papachristodoulou A (2010) Behavioural economics, hyperbolic discounting and environmental policy. Environ Resource Econ 46:189–206. https://doi.org/10.1007/s10640-010-9354-9

Karp L (2005) Global warming and hyperbolic discounting. J Public Econ 89:261–282. https://doi.org/10.1016/j.jpubeco.2004.02.005

Kemper K, Foster S, Garduno H, Nanni M, Tuinhof A (2003) Economic Instruments for Groundwater Management. World Bank, Global Water Partnership Associate Program, Briefing Note Series, Briefing Note 7.

Koundouri P, Roseta-Palma C, Englezos N (2017) Out of sight, not out of mind: developments in economic models of groundwater management. Int Rev Environ Resour Econ 11:55–96. https://doi.org/10.1561/101.00000091

Latinopoulos D, Sartzetakis ES (2014) Using tradable water permits in irrigated agriculture. Environ Resour Econ 60:349–370. https://doi.org/10.1007/s10640-014-9770-3

Latinopoulos P (2003) Development of a water recourses management plan for water supply and irrigation in the Municipality of Moudania. Final Report, Research Project, Department of Civil Engineering, Aristotle University of Thessaloniki (in Greek)

Loewenstein G, Prelec D (1992) Anomalies in intertemporal choice: evidence and interpretation. Q J Econ 107:573–597. https://doi.org/10.2307/2118482

Mazur JE (1987) An adjusting procedure for studying delayed rein- forcement. In: Commons ML et al (eds) Quantitative analyses of behavior: the effect of delay and of intervening events on reinforcement value, 5th edn. Psychology Press, New York, pp 55–76

Pearce D, Groom B, Hepburn C, Koundouri P (2003) Valuing the future: recent advances in social discounting. World Econ 4:121–141

Samuelson P (1937) A note on measurement of utility. Rev Econ Stud 4:155–161. https://doi.org/10.2307/2967612

Sargisson RJ, Schöner BV (2020) Hyperbolic discounting with environmental outcomes across time, space, and probability. Psychol Rec 70:515–527. https://doi.org/10.1007/s40732-019-00368-z

Sozou PD (1998) On hyperbolic discounting and uncertain hazard rates. Proc R Soc Lond 265:2015–2020

Spackman M (2006) Social discount rates for the European Union: an overview. In: Florio M (ed) Cost-benefit analysis and incentives in evaluation, 1st edn. Edward Elgar Publishing Limited, Cheltenham, pp 253–279

Strotz RH (1956) Myopia and inconsistency in dynamic utility maximization. Rev Econ Stud 23:165–180. https://doi.org/10.2307/2295722

Strulik H (2021) Hyperbolic discounting and the time-consistent solution of three canonical environmental problems. J Public Econ Theory 23:462–486. https://doi.org/10.1111/jpet.12497

Theodossiou N (2016) Assessing the impacts of climate change on the sustainability of groundwater aquifers. application in Moudania aquifer in N. Greece. Environ Process 3:1045–1061. https://doi.org/10.1007/s40710-016-0191-x

Tsiarapas AE, Mallios Z (2023) Tradable water rights system optimization for efficient water resources allocation. In: Matsatsinis NF et al (eds) Operational research in the era of digital transformation and business analytics. Springer, Cham, pp 11–19

United Nations (2015) Transforming our world: the 2030 agenda for sustainable development. NY, USA. https://sdgs.un.org/2030agenda. Accessed 20 Feb 2023

Weitzman ML (2001) Gamma discounting. Am Econ Rev 91:260–271. https://doi.org/10.1257/aer.91.1.260

Winkler R (2009) Now or never: environmental protection under hyperbolic discounting. Economics. https://doi.org/10.2139/ssrn.1726741

Zhang LH, Jia SF, Leung CK, Guo LP (2012) An analysis on the transaction costs of water markets under DPA and UPA auctions. Water Resour Manag 27(2):475–484. https://doi.org/10.1007/s11269-012-0197-8