Chapter

# Groundwater Management Competitive Solutions: The Relevance of the Gisser-Sanchez Model

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## Abstract

The main subject of this chapter is related to the relevance of the Gisser-Sanchez effect in groundwater. It is important to point out that groundwater resources provide a primary source of irrigation water throughout much of the world. Two main questions need to be indicated when taking water extractions into account. The first has to do with water scarcity in local watersheds or whole basins created by excessive surface and groundwater withdrawals. The other is related to water degradation and the pollution loads leading to many tracts of rivers and whole aquifers being spoiled and losing their capacity to sustain ecosystem functioning and human activities. These conclusions were called into question by the Gisser and Sanchez analysis. These authors argue that the difference in producer surplus between the open access and optimally managed cases was numerically insignificant for large aquifers subject to inelastic water demand. Perhaps the most interesting point in the work by Gisser and Sanchez is multidisciplinarity.

**Keywords:** Gisser-Sanchez effect, groundwater, property rights

## 1. Introduction

Groundwater management is an issue which remains a practical matter in many human regions throughout the world [1]. Besides, it is very necessary to clarify that groundwater represents the largest stock of accessible freshwater and accounts for about one-third of freshwater withdrawals globally [2–4]. However, increased rainfall scarcities have resulted in an augmented use of groundwater, in order to satisfy the increasing domestic, agricultural, and environmental-ecosystem preservation for different water.

Nevertheless, it is necessary to take into account that historically, surface water has been the main source of water for human consumption, as it was easy and cost effective to access. So, it can be expected that during the second half of the twentieth century, groundwater withdrawals will increase. It is also very relevant to reflect that groundwater supply could represent around one third of the world population [5].

This wide use of groundwater in many parts of the world has resulted in water level decline and groundwater depletion and is mainly related to phenomena such as biodiversity loss, pollution, and seawater intrusion in coastal aquifers.

An example could be found in the paper by El Moujabber et al. [6], in which the state of groundwater desalination by seawater intrusion in the Lebanese cost is introduced (specifically in the region of Choueifat-Rmeyle, located in the south of Mount-Lebanon). The main consequence that is obtained is related to the fact that groundwater management can behave like relevant backstop technologies and also that substitutes have become a practical concern in many arid and semiarid regions throughout the world [7].

A fundamental idea that needs to be pointed out is that groundwater is essential for sustaining agriculture production patterns, as well as consumption models and the biodiversity or the resilience of ecosystems. The combination of this fact with the intense scarcity in many parts of the world makes necessary the development of rules for the corrected and efficient allocation of resources among competing uses over time and space.

This presents an economic question which has been close to groundwater economics since the middle years of the decade of 1950s. It is necessary to point out that the question of how to manage this resource, mainly because groundwater constitutes about 89% of the freshwater on earth (discounting that in the polar ice caps). From this, an important economic concept could be deduced related to water scarcity and which is related to the fact that the world water scarcity is one of the most important hydraulic resources that need to be taken into account.

It is also necessary to point out that groundwater systems are rather dynamic with groundwater in motion from zones of recharge to areas of discharge and that a great number of years could, hundreds of years, interfere in the passage of water through this subterranean part of the hydrological cycle. Since flow rates regularly do not ordinarily go beyond a small number of meters per day and can be as low as 1 meter per year (these groundwater velocities compare to rates of up to 1 meter per second for river flows) [8].

Groundwater resources provide a primary (or supplemental) source of irrigation water throughout much of the world, yet overpumping and subsequent aquifer depletion may pose "the single largest threat to irrigated agriculture" [9, 10].

Two main questions need to be indicated in when taking water extractions into account. The first is double: one is water scarcity in local watersheds (or whole basins created by extreme surface and groundwater withdrawals). The other is water degradation from pollution loads leading to many tracts of rivers and whole aquifers being damaged and losing their capacity to sustain ecosystem functioning and human accomplishments.

Following the wide-scale development of groundwater pumping for agriculture in 1950s, some results have been obtained that the open access nature of groundwater implied that farmers were overextracting water, and therefore, it could be exhausted much before than it might be economically optimal.

These conclusions were called into question by Gisser and Sanchez. These authors, mainly in their very influential paper argue that the difference in producer surplus between the open access and optimally managed cases was numerically insignificant for large aquifers subject to inelastic water demand. Perhaps the most interesting point in the work by Gisser and Sánchez is multidisciplinarity. An essential assumption that we need to take into account is that the GSE model is a dynamic model. Besides, we need to take into account that variables in the model are economic, hydrological, and agronomic variables of groundwater use. In this chapter, the demand and supply functions for irrigated water are defined, and these functions are associated with the hydrological characteristics of the aquifer. Then, the path of water allocation through time is calculated under the policy regime and the free-market regime [11].

This effect has remained controversial, and numerous studies have analyzed whether the Gisser and Sanchez Effect (GSE) persists under a variety of specific conditions, such as convex pumping costs [12], shifting (nonconstant) water demand [13], adaptation by crop shifting [14], confined aquifers [15], heterogeneous users [16]; strategic decision-making [17, 18], conjunctive management [19], risk aversion [20], and backstop water sources [21]. These studies generally find support for the GSE, even under all these different conditions.

Nevertheless, it is necessary to point out that authors, such as Stratton et al. [22], apply the GSE model, although relaxing a very important significant assumption of a fixed irrigation technology. Results indicate that the GSE fails when irrigation technologies with different water use efficiency become available. These results are robust and hold even when maintaining some of the very fundamental statements in the original model (such as constant marginal pumping costs per linear foot of lift). Besides, the gains from optimal groundwater management become even more significant when irrigation technology is not only variable but also endogenous variables. That is, variables whose values the model is designed to explain. In the model, there are also exogenous variables. That is, variables whose values are taken as given from outside the model [23]. The expression "Endogenous Technical Change" implies that higher water costs could induce the development of technologies that might improve water use efficiency [19, 24]. The expression "Endogenous Technical Change" implies that higher water costs could encourage the development of technologies that might improve water use efficiency [24, 25].

The main objective of this chapter is to re-evaluate the validity of the GSE hypothesis in groundwater management. In this chapter, the conceptual framework within which the elements interacting in the management of groundwater resources is examined. The most important conclusion obtained is that the role of the market is limited with respect to the price of water in an aquifer. This is an important result, because it points to the mechanism that could pull competitive water prices and quality-graded quantity of groundwater, in line with their equilibrium levels. In Section 2, some models of groundwater use and management are introduced, and the most important economic models for groundwater use can be found (joint with the potential of groundwater management control variables in such models). In Chapter 3, some relationships between the Gisser and Sanchez effect and the difficulties to establish clear groundwater property rights are discussed. In Section 4, the robustness of GSE under a private if property rights regime is discussed, both in quantity and in quality terms. In Section 5, a discussion section is introduced. Finally, some conclusions are provided.

## 2. Some models of groundwater use and the potential for groundwater management

It is necessary to take into account that implicit in the different concerns about groundwater, an essential principle can be found. This is related to the fact that if no intervention exists, then groundwater pumping will be mismanaged. Another important point that needs to be pointed out is that if groundwater pumping is inefficient, then, the lack of central (and optimal), control, underlines that the estimates of the welfare loss (under the common property regime) should depend on the specific model of firm behavior which might be enlisted in the analysis. This should allow to conclude in favor of an existing potential and pressing need for the development and implementation of management policies for groundwater resources [32].

It is also interesting to point out that when groundwater withdrawals exceed recharge, water will be mined over time until either supplies are exhausted or the marginal cost of pumping additional water should become extremely expensive [33]. An essential issue related to this assumption is that a marginal user cost is associated with mining groundwater, and this is related to the opportunity cost which is connected with the unavailability in the future of any unit of water used in the present.

A well-organized distribution should consider this user cost, which effectively signals the scarcity of the resource and is called the resource's scarcity rents. Therefore, efficient pricing of a resource that exhibits natural supply constraints incorporates both marginal cost of extraction and scarcity rents. Scarcity rents must be imposed on current users.

Given the complexity of establishing clear groundwater property rights, scarcity rents are frequently difficult to be recognized and are not easy to be estimated. Some authors in which a discussion about this point could be found are, for instance [31, 34–37].

Ignoring scarcity rents implies that the price of groundwater is usually too low and extraction is above the socially optimal level. If an optimal dynamic management of common-pool groundwater resources is not considered, or in the presence of a competitive extraction regime ignoring scarcity rents, results in inefficient pricing and misallocation of resources. This essential argument has to do with the way markets behave, and it could perfectly be competitive. Under these circumstances, the problem is not so much with the market mechanism but with the way property rights behave.

## 3. Groundwater property rights

Given the difficulty of establishing clear groundwater property rights, scarcity rents are frequently difficult to be estimated. Ignoring scarcity rents should imply that groundwater prices could be too low and extraction might be above the socially optimal level. From this, the main conclusion is that, in the absence of optimal dynamic management of common pool groundwater resources, or, alternatively, in the presence of a competitive extraction regime, ignoring scarcity rents, could result in inefficient pricing and misallocation of resources.

Just in the case, there is no optimal dynamic management of common pool groundwater resources, or, alternatively, in the presence of a competitive extraction regime, ignoring scarcity rents results in inefficient pricing competitive extraction regime, inefficient pricing, and misallocation of the resource.

From this, an interesting question might be pointed out: How could be explained that a competitive dynamic solution of groundwater exploitation is almost identical (in terms of derived social welfare) to the efficient management solution, in the way it is claimed by the GSE effect?

### 3.1 The Gisser-Sánchez effect

The GSE explains a contradictory empirical result, present and persisting in the dynamic solutions of groundwater exploitation under different extraction regimes (since 1980) [1]. In spite of the fact that depletion of aquifers is a major threat to many freshwater ecosystems all over the world, the social benefits from managing groundwater are numerically insignificant. It needs to be pointed out that GSE encompasses to a general rule, and then the role and scope of water management are severely limited. It is also essential to point out that, even if implementing optimal extraction is not going to be costless. In this section, a review of [38] is introduced about the theoretical and empirical attempts to address the GSE and discuss the potential for groundwater management.

### 3.2 The Gisser-Sanchez model and groundwater management

Problems of groundwater allocation have been studied basically in the context of the theory of mine [26–29]. The basic model by Gisser and Sanchez is a simplified representation of the economic, hydrologic, and agronomic facts that must be considered relative to the irrigator's choice of water pumping [1]. The validity of the GSE model rests on the key assumption that the aquifer has to be quite large and on the secondary assumption of a small slope in the water-demand function.

A separate literature should also have to be taken into account, which deals with groundwater quality. Some papers in this line can be found such as [30–32].

Groundwater allocation problems have been studied mainly in the context of mine and economists like [33–35]. Some principles of inventory management to derive decision rules for the optimal temporal allocation in a dynamic programming format can also be found in such papers. The effects of different policy instruments that could correct misallocation of commonly owned groundwater can be found in papers such as [31, 35–39], which studied the effects of different policy instruments that might correct the misallocation of commonly owned groundwater. One of the main results of this chapter is that net benefits from groundwater management could amount to over \$100 per acre, but noted that these benefits could decline with increases in interest rate. One of the solutions to this problem was obtained by authors such as Allen and Gisser [40], who derived a formula for a tax that should be imposed on groundwater which was pumped in order to yield the optimal control solution. Finally, in papers such as [41], it can be recognized the issue of congestion externality in aquifers with open access characteristics and suggested a charging tax to accommodate this externality.

When this point is achieved, farmers will either import supplemental water or be restricted to use a smaller amount of water by being assigned water rights. Nevertheless, some changes in the hypothesis related to regulation of water pumping in the aquifer could be made. This case allows to model consistently an optimal control problem and also allows one kind of clarification that should be related with the case of no control. This is the departure point for the works [9, 10] by Gisser and Sanchez.

The basic model analyzed by Gisser and Sanchez is a simplified representation of the economic, hydrologic, and agronomic facts that should be considered for the irrigator's choice of water pumping. An irrigator benefit function could be represented using this function suggested by [44]:

$$\pi(t) = V((wt)) - C(H(t))w(t) \tag{1}$$

where π(t) denotes profits at time t. Net farm revenue from water use π(t) neglecting pumping costs is denoted by

$$V(w) = \int_0^w p(x)dx \tag{2}$$

where p(x) is the inverse demand function for water. C(H) is the average and marginal pumping costs per acre-foot of water and H(t) is the height of water table above some arbitrary reference point at time t [1, 40]. The change in the height of water is given by differential Eq. (2), which represents the hydrologic state of the aquifer (or equivalently, the environmental constraint of the problem)

$$\acute{H} = \frac{1}{AS}(R + (a - 1)w), H(0) = H0 \qquad (3)$$

In this equation, R exemplifies a constant recharge determined in acre feet per year; a is the constant return flow coefficient (which could be considered to be just a simple number); $H_0$ is the initial level of the water table measured in feet above sea level; A is the surface area of the aquifer (uniform at all depths), measured in acres per year; and S is the specific yield of the aquifer. These equations are based on the UNESCO-Encyclopedia Life Support Systems and also on the papers by [1, 43, 45] on the Gisser-Sanchez effect.

More precisely, the aquifer in Gisser and Sanchez's work is modeled as a bathtub, unconfined aquifer, with infinite hydraulic conductivity. It is necessary to point out that infinite hydraulic conductivity implies that the aquifer will never dry up, irrespective of groundwater extraction rates, which is equivalent to the assumption of a bottomless aquifer. The adoption of this hypothesis can be acknowledged by the hypothesis that it is implied by an standard hypothesis which is related to the literature and which implies that time goes to infinity [1]. Nevertheless, if this is not this way, a steady-state solution might not be reached. Besides, Provencher [43] showed that the optimal pumping rate can be substantially lower when the hydraulic conductivity is small enough to result in a significant cone of depression around the well. The assumption of constant return flow in the presence of fixed irrigation technology suggests a constant rate of water application.

The hypothesis of deterministic and constant recharge in conjunction with the hypothesis of constant return flow suggests constant types of land use [44], independence of surface water and groundwater systems, and constant average rainfall. Besides, sunk costs, replacement costs, and capital costs in general are overlooked, and it is implicitly assumed that energy costs are constant. It is also indirectly accepted that the well pump capacity constraint is nonbinding. Finally, refinement in Gisser and Sanchez's model could be also achieved by assuming that only land superimposing the aquifer can be irrigated. That is, the demand curve does not shift to the right over time. This implies that, the unambiguous recognition of the fact that the main hypothesis behind the GSE indicates that the result should be carefully when working on real aquifer systems.

Given the above hydroeconomic model, Gisser and Sanchez used a linear water demand function (estimated by [31, 32]) using parametric linear programming, hydrologic parameters that were considered realistic in the 1960s, and a discount rate of 10%, and simulated the intertemporal water pumpage for Pecos Basin in New Mexico, once under the assumption of no control and once under the assumption of optimal control. The most interesting result is that the trajectories under the two regimes are almost identical. This result leads to the main conclusion that there is no substantive quantitative difference between socially optimal rules for pumping water and competitive rates. Therefore, the welfare loss from intertemporal misallocation of pumping effort is negligible. This conclusion amounts to the GSE.

An important effect to consider is that, solving analytically the model, Gisser and Sanchez main result is that, if Eq. (3) is true, then the difference between the two strategies is so small that it can be ignored for practical consideration, where Eq. (3) is

$$\left[\frac{k\,C_t(a - 1)^2}{AS}\right] \simeq 0 \qquad (4)$$

In Eq. (4), k can be considered to be the reduction in demand for water per $1 intensification in price (that is, the slope of the uncompensated demand curve for groundwater), $C_t$ is the intensification in pumping cost per acre-foot per 1-foot decline in the water table, and AS are given in Eq. (2). If Eq. (3) holds, then the rate of discount will be practically identical with the exponent of the competition result. Therefore, as long as the slope of the groundwater demand is small relative to the aquifer's area times its storativity [1], GSE will persist. From this, the main conclusion is that, if differences between optimal and competitive rates of water pumping are small, then policy considerations can be limited to those which ensure that the market operates in a competitive fashion, and concerns relative to rectifying common property effects could be removed.

### 3.3 Robustness of the GSE effect

The GSE effect presents important policy implications. Some empirical papers discussing the robustness of this effect are, Noel et al. [35] found that control increases the value of groundwater in the Yolo basin in California, by 10%. This result is fairly different from [37], who found that control raised the net benefit of groundwater in the Ogallala basin by only 0.3% empirical estimates of benefits from groundwater management in Kern county (California, USA) do not exceed 10%. Nevertheless, in works such as [39], it can be found that groundwater management in the Texas High Plains would be unwarranted, and he proceeded with a sensitivity analysis of present value profits using different slopes and intercept values for the groundwater-demand curve. It is interesting to point out that this analysis indicated that benefits from groundwater management do not increase monotonically as the absolute value of the slope increases.

A basic hypothesis of the Gisser and Sánchez model is that the demand curve for water is linear. This is a fairly conventional hypothesis in most economic demand models. In order to study the relative importance of this hypothesis for the GSE, optimal control and no-control strategies are compared, using a nonlinear demand curve [40]. This comparison confirmed that, for the case of the nonlinear demand function, what had been demonstrated by the GSE for the case of a linear demand function.

However, in works such as [20], it can be found that the differences between the two regimes may not be trivial if the relationship the average extraction cost and the water table level and/or if there exist significant differences in land productivity, applying dynamic programming to a model of a confined aquifer underlying the Crow Creek Valley in South-Western Montana.

It is essential to take into account that when land is assumed to be homogeneous, the gross returns function with respect to water use tends to be nearly linear. Nevertheless, with greater heterogeneity in productivity, the returns function is more concave, and differences in the optimal use policy under a common property setting are more pronounced [1]. Hence, the need for more theoretical work is to determine an asymmetric groundwater pumping differential game, where differences in land productivity are taken into account.

### 3.4 Variable relations and endogenous rates of change

Implicit in GSE model is the hypothesis of nonvariable economic relations (that is, time-independent demand) and/or exogenous and constant rates of change (that is, constant and fixed exogenous crop mix, constant crop requirements, fixed irrigation technology), and some significant exceptions can be found such as [43, 44], with constant exogenous kinds of land use and nonvariable hydrologic conditions.

Nevertheless, in studies with a long run perspective, predictable results could turn out to be weaker as the steady state is approached. Estimated benefit and cost functions used in the simulations of GSE may bear little relation to the actual benefit and cost functions when economic, hydrologic, and agronomic conditions are much different. More complex representations of increasing resource scarcity incorporate opportunities for adaptation to the rising resource prices which are a main indicator for scarcity. In the long run, adoption of new techniques, substitution of alternative inputs, and production of a different mix of products offer rational responses to increasing scarcity [1], [38].

## 4. The robustness of GSE under a private property rights regime

The solution which is commonly proposed for the inefficiencies arising in common property resource extraction is central-optimal control by a regulator, who uses taxes or quotas to obtain the efficient allocation of resources over time.

In the background of groundwater depletion, a solution has been commonly suggested which is based on a tradable permit scheme [37, 38]. In the framework of groundwater reduction, a number of authors have recommended a similar institutional arrangement in which firms are arranged and endowment of tradable permits to the in situ groundwater stock, which they control over time. Each firm's bundle of permits represents its private stock of groundwater.

This private stock is worsening due to groundwater pumping and intensifications to reflect the firm share of periodic recharge. It also changes in response to the activity of the firm in the market for groundwater stock permits, increasing when permits are purchased and decreasing when permits are sold. The market price for permits serves to allocate groundwater over time.

It is necessary to point out that this particular regime is inefficient, mainly because both the pumping cost externality and the risk externality persist after the allocation of permits. Moreover, this regime is time inconsistent. However, different efforts to quantify the value of groundwater resource under both optimal control and the private property rights regime indicate that groundwater privatization recovers most of the potential gain from management. In particular, a programming model for Madera County, in California (USA), can be found in [37]. This regime recovered 95% of the potential gain from management.

### 4.1 The GSE in models of conjunctive use of surface and groundwater

A tributary aquifer is characterized by a groundwater stock that is hydrologically connected to a body of surface water. In this aquifer, surface water may recharge the underground aquifer, or groundwater may supplement surface flows depending upon hydrological conditions.

In papers such as [38], results can be found in which an analytical economic model is developed and is focused primarily on the hydrologic link between surface and groundwater, by modeling the instantaneous rate of aquifer recharge caused by groundwater pumping, through river effects. In this chapter, some externalities river effects can be found, which reinforced groundwater overpumping present due to the usual common property effects. Results of this chapter indicate that optimal policy requires compensation to be paid for both river effects and aquifer depletion net of river effects. This work points to an externality created by groundwater overpumping provoked mainly by the common property effects.

From this, the main conclusion which needs to be pointed out is that optimal policy requires a recompense to be paid for both river effects and aquifer depletion net of river effects [39]. It is necessary to highlight that these effects indicate the existence of some externalities which could be related to groundwater pumping, which might be adjusted with the precise management. The main consequence probably could be that GSE might be very likely removed by the improvement in management benefits.

Unfortunately, no empirical results exist of these results focusing primarily on the hydrologic link between ground and surface water, and at the same time acknowledging the stochastic nature of surface water supplies. Instead, the main literature that incorporates stochastic surface supplies into a groundwater model in which surface water and groundwater are modeled as substitute goods, aquifers are not connected with surface water, and they only benefit from substantial natural recharge.

## 5. Discussions

Regarding the GSE model, it needs a number of important assumptions. One of the most significant has to do with the disregard for aquatic ecosystems linked and dependent on aquifer systems.

In the GSE model, a very special point needs to be pointed out, which is that the aquifer is presented as a "bath-tub", unconfined aquifer, with infinite hydraulic conductivity [40]. A bath-tub approach to modeling an aquifer assumes that it responds uniformly and instantly to groundwater extraction [41, 46, 47]. From this, the spatial distribution of the users of the resource is not so relevant, and the evolution of the spatial profile of drawdown does not affect current and future extraction choices. Gisser-Sánchez assumes a deterministic and constant recharge, constant return flow and average rainfall, independence of surface water and groundwater systems, and a bottom-less aquifer. Since their competitive steady state presents a positive water stock, their estimation of welfare gains from optimal management excludes stock externality [42].

Another important assumption which is discussed in this chapter is the appropriateness of the stock effect assumption. This hypothesis reflects the dependence of extraction costs and the eventual benefits on the stock of the resource. From this, it could be established the way these assumptions might affect the time variation of the shadow price of groundwater externality. In this chapter, the main result is that this could lead to a declining value of in situ resource over time. Therefore, the addition on nonmarginal extraction costs could be close to inappreciable, which could imply the validation of the Gisser-Sanchez effect, which also presents the remarkable hypothesis that groundwater markets have the benefit of allowing more flexible movement of water to serve changing conditions and demands.

Finally, a main conclusion could be derived from the paper introduced which is that a very relevant model such as [4, 5] is a very appropriate work to analyze groundwater management, mainly because it states the conditions under which welfare improvements from policy interventions could be significant in aquifer administration. This result could be compared with nonregulation or free market solutions in groundwater management.

## 6. Conclusion

The main conclusion of this chapter has to do with the GSE effect and points mainly to the different effects related to welfare improvements and aquifer management. In this work, an optimal policy requires a compensation to be paid for both river effects and aquifer depletion, which points to an additional externality created by groundwater pumping. This externality could be corrected with an appropriate management of the groundwater, which could eventually eliminate the GSE effect and even increase management benefits.

No empirical results have been obtained in order to test these results, which have to do mainly with the eventual links between ground and surface water. These results could be pertinent in order to improve groundwater management, because from this, the stochastic nature of surface water flows could be acknowledged.

Nevertheless, probably the most significant result in this chapter is that different effects related to welfare improvements and aquifer management and the relevance of the GSE effect exists. Besides, it is necessary to indicate that an optimal aquifer management policy requires a compensation to be paid for both the existing river effects and aquifer depletion. These conclusions stem from the fact that externalities exist, which are linked to groundwater pumping. This externality could also be corrected with a suitable management of the groundwater. This result is quite relevant because it could potentially remove the GSE effect, and therefore, even increase management benefits.

It is similarly essential to take into account the appropriateness of some of the assumptions in the model, since some of them (like the linear relationship between pumping costs for nonconsumptive benefits), and which are an essential tool in groundwater management.

Environmental uses of groundwater water and the way markets work present a significant impact on users and the environment. An interesting conclusion is provided by [48], in his paper for the journal *Resources* (from Resources for the Future), which is that there is rapid depletion of aquifers in the United States, and this presents significant impacts on users and the environment, requiring stakeholders across the country to look for creative and effective policy solutions. So, there is an interesting conclusion that groundwater markets can be applied broadly in groundwater management in order to protect one the most relevant freshwater environmental resource.

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## References

[1] Koundouri P. Current issues in the economics of groundwater resource world management. Journal of Economic Surveys. 2004;**18**(5):703-740

[2] Gorelick SM, Zheng C. Global change and the groundwater management challenge. Water Resources Research. 2015;**51**:3031-3051

[3] Farmigletti JS. The Global groundwater crisis. Nature Climate Change. 2014;**4**:945-948

[4] Siebert S, Burke J, Faures JM, Frenken K, Hoogeveen J, Doll P, et al. Groundwater use for irrigation. A global inventory. Hydrology and Earth System Sciences. 2010;**14**:1863-1880

[5] Oki T, Kanae S. Global hydrological cycles and world water resources. Science;**313**:1068-1072

[6] El Moujabber E, Bou Samra B, Darwish T, Atallah T. Comparison of different indicators for groundwater contamination by seawater intrusion on the Lebanese coast. Water Resources Management. 2006;**20**(2):161-180

[7] Momejian N, Abou Najm M, Alameddine I, El_Fadel M. Can groundwater vulnerability models assess seawater intrusion? Environmental Impact Assessment Review. 2019;**75**:13-26

[8] Ge S, Gorelick SM. Groundwater and surface water. In: Encyclopedia of Atmospheric Sciences. 2nd ed. Oxford, Elsevier, Academic Press

[9] Gisser M, Sánchez DA. Some additional economic aspects of groundwater resources replacement flows in semi-arid agricultural areas. International Journal of Control. 1980a;**31**(2):331-341

[10] Gisser M, Sánchez DA. Competition vs optimal control in groundwater pumping. Water Resources Research. 1980b;**31**:638-642

[11] Esteban E, Albiac J. Groundwater and ecosystem damages: Questioning the Gisser-Sanchez effect. Ecological Economics. 2011;**70**:2062-2069

[12] Negri D. The common property aquifer as a differential game. Water Resources Research. 1989;**25**(1):9-15

[13] Rubio S, Casino B. Competitive versus efficient extraction of a common property resource: The groundwater case. Journal of Economic Dynamics and Control. 2001;**25**(8):1117-1137

[14] Provencher B, Burt O. The externalities associated with the common property exploitation of groundwater. Journal of Environmental Economics and Management. 1993;**24**:139-158

[15] Knapp KC, Olson L. The economics of conjunctive groundwater management with stochastic surface supplies. Journal of Environmental Economics and Management. 1995;**28**:340-356

[16] Koundouri P, Christou C. Dynamic adaptation to resource scarcity and backstop availability: Theory and application to groundwater. Australian Journal of Agricultural and Resource Economics. 2006;**50**:227-245

[17] Kim H, Kaown D, Mayer B, Lee J. Identifying the sources of nitrate contamination of groundwater in an agricultural area (Haean basin, Korea) using isotope and microbial community analyses. Science of the Total Environment. 2015;**533**(15):566-575

[18] Brill TS, Burness HS. Planning versus rates of groundwater pumping. Water Resources Research. 1994;**30**:1873-1880

[19] Kim CS, Moore MR, Hanchar JJ. A dynamic model of adaptation to resource depletion: Theory and an application to groundwater mining. Journal of Environmental Economics and Management. 1989;**17**:66-82

[20] Worthington V, Burt O, Brustkern RL. Optimal management of a confined groundwater system. Journal of Environmental Economics and Management. 1985;**12**(3):229-245

[21] Saak AE, Peterson JM. Groundwater use under incomplete information. Journal of Environmental Economics and Management. 2007;**54**(2):214-228

[22] Stratton SE, Simon LK, Marchiori C. Promoting groundwater reform in the Guadiana Basin. American Journal of Agricultural Economics. 2008;**90**:1343-1349

[23] Hoy M, Livernois J, McKenna C, Rees R, Stengos T. Mathematics for Economics. Cambridge, Massachusetts: The MIT Press; 2001

[24] Kim CS, Guilfoos T. The effect of cost-share programs on groundwater exploitation and nonpoint-source pollution under endogenous technical change. Agricultural and Resource Economics Review. 2016;**45**(2):394-417

[25] Kim CS, Fuglie K, Wallander S, Wechser S. Endogenous Technical Change and Groundwater management: Revisiting the Gisser-Sanchez Paradox. AAEA and EAEA Joint Meeting; July 26-29. San Francisco, CA; 2015

[26] Provencher B, Burt O. A private property rights regime for the commons: The case for groundwater. American Journal of Agricultural Economics. 1994;**76**:875-888

[27] Groom B, Koundouri P, Swanson T. The watershed economics management approach: An application to Cyprus. In: Koundouri P, Pashardes P, Swanson T, Xepapadeas A, editors. Economics of Water Management in Developing countries: Problems, Principles and Policies. Cheltenham, UK: Edward Elgar; 2003a

[28] Groom B, Koundouri P, Swanson T. Integrated resource management in Cyprus: Introducing and applying a new methodology. In: Brower R, Pearce D, editors. The Economics of Water. Dordrecht, The Netherlands: Kluwer; 2003b

[29] Knapp K, Barenklau K. Groundwater quantity and quality management: Agricultural production and aquifer salinization over long time scales. Journal of Agricultural and Resource Economics. 2006;**31**:616-641

[30] Milliman JW. Commonality, the price system and the use of water supplies. Southern Economic Journal. 1956;**22**:426-437

[31] Gisser M, Mercado A. Integration of the agricultural demand functions for water and the hydrologic model of the Pecos Basin. Water Resources Research. 1972;**8**:1373-1384

[32] Gisser M, Mercado A. Economic aspects of groundwater resources and replacement flows in semiarid agricultural areas. American Journal of Agricultural Economics. 1973;**55**:461-466

[33] Cummings R, McFarland JW. Groundwater management and salinity control. American Journal of Agricultural Economics. 2003;**56**:830-836

[34] Silveira L. Special issues in Groundwater. In: Silveira L, Usunoff E, editors. Groundwater, vol. III. Eolss Publishers Company Limited; 2009

[35] Noel JE, Gardner BD, Moore CV. Optimal regional conjunctive water management. American Journal of Agricultural Economics. 1980;**62**:489-498

[36] Gisser M, Mercado A. Economic aspects of groundwater resources and replacement flows in semiarid agricultural areas. American Journal of Agricultural Economics. 1973;**55**:638-642

[37] Lee KC, Short C, Heady EO. Optimal groundwater mining in the Ogallala Aquifer: Estimation of economic losses and excessive depletion due to commonality. In: Center for Agricultural and Rural Development. Iowa, USA: Iowa State University; 1981

[38] Das S. The economics of groundwater resource management. International Journal of Ecosystems. 2015;**5**(3A):65-68

[39] Nieswiadomy M. The demand for irrigation water in the High Plains of Texas. American Journal of Agricultural Economics. 1985;**67**:619-626

[40] Allen RC, Gisser M. Competition versus optimal control in groundwater pumping when demand is nonlinear. Water Resources Research. 1984;**20**:752-756

[41] Burness H, Brill TC. The role for policy in common pool groundwater use. Resource and Energy Economics. 2001;**23**:19-40

[42] Shah FA, Zilberman D, Chakravorty U. Technology adoption in the presence of an exhaustible resource: The case of groundwater extraction. American Journal of Agricultural Economics. 1995;**77**(2):291-299

[43] Provencher B. Issues in the conjunctive use of conjunctive use of surface water and groundwater. In: Bromley DW, editor. The Handbook of Environmental Economics. Oxford, UK/Cambridge, MA: Blackwell; 1995

[44] Reddy V. Costs of resource depletion externalities: A study of groundwater overexplotation in Andhra Pradesh, India. Environment and Development Economics. 2005;**10**:533-556

[45] Tietenberg T, Lewis L. Environmental Economics & Policy. 10th ed. London: Pearson; 2018

[46] Katic PG. Three essays on the economics of groundwater extraction [Ph.D. thesis]. Australia: The Australian National University; 2011

[47] Katic PG, Grafton RQ. Economic and spatial modelling of groundwater extraction. Journal of Hydrology. 2012;**20**:831-834

[48] Kuwayama Y. Groundwater markets: Managing a critical, hidden resource, resources. Resources for the Future. 2014;**43**:1-11