GROUNDWATER AND ECONOMICS: GISSER–SANCHEZ’S EFFECT RECONSIDERED

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Summary

This chapter provides a critical review of the theoretical and empirical literature on groundwater economics. In particular, it points at various misconceptions, inaccuracies and omissions of the current state of the literature that could potentially resolve part of a paradoxical empirical result, which persists in this literature. This result points to an insignificant numerical magnitude of benefits from optimally managing groundwater, even when aquifers are seriously depleted.

1. Introduction

Gisser-Sanchez’s Effect (GSE) refers to a paradoxical empirical result, present and persisting in the dynamic solutions of groundwater exploitation under different extraction regimes, since 1980. Namely, although serious depletion of aquifers is a major threat to many freshwater ecosystems all over the world, the social benefits from managing groundwater extraction are numerically insignificant. Clearly, if GSE extends to a general rule then the role and scope of water management are severely limited. This is even more evident when we take into consideration that implementing optimal extraction is not going to be costless.

When groundwater withdrawals exceed recharge, the resource will be mined over time until either supplies are exhausted or the marginal cost of pumping additional water becomes prohibitive. The first implication of this is that a marginal user cost is associated with mining groundwater, reflecting the opportunity cost associated with the unavailability in the future of any unit of water used in the present. An efficient allocation considers this user cost, which effectively signals the *in situ* scarcity of the resource and is called the resource's scarcity rents. Hence, 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.

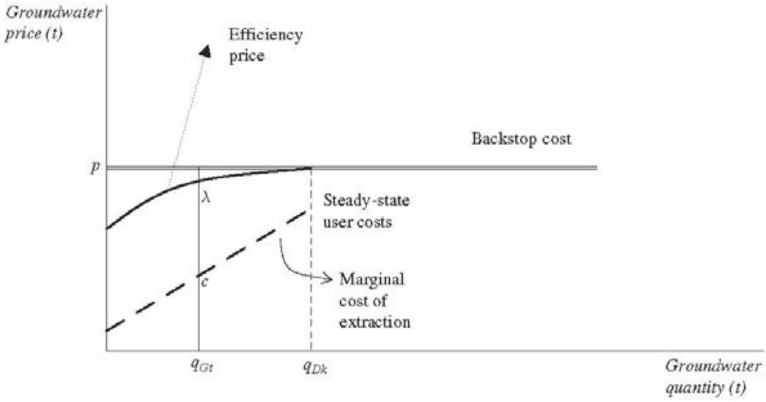

Figure 1. Extraction cost, scarcity value, and efficiency price of groundwater

Figure 1, graphs this argument. The dotted line depicts marginal extraction costs at a moment of time for existing, conventional water sources, such as irrigation wells. If these sources were not available, the alternative would be a backstop source such as desalination, which we assume to be available in unlimited quantities though at the high (and constant) cost $(\bar{p})$. Suppose that, contrary to the common situation, all rights to *in situ* groundwater could be owned and sold independently of the overlying land. The shadow price of groundwater would be bounded at the high end by what prospective buyers are willing to pay - the buyer can either purchase water rights covering an existing source, with extraction cost $(q_{Gt}c)$, or develop the backstop at cost $(q_{Gt}\bar{p})$; thus for the incremental source at capacity (q_{Gt}), the buyer's maximum willingness to pay for existing rights is represented by the distance $(c\bar{p})$ —and at the low end by what sellers are willing to accept - the basis for determining owners' reservation price is the awareness that if today's rate of use increases by one unit, the buyer will incur sooner the higher costs of supra-marginal wells. At (marginal) capacity (q_{Gt}), potential scarcity rent is the distance $(c\lambda)$. The efficiency price line shows the efficient price for water, incorporating extraction costs as well as *in situ* value.

The extensive use of groundwater in many parts of the world and related environmental harm (i.e. water level drawdown, aquifer mining, saltwater intrusion, stream baseflow reduction and land surface subsidence) implies that groundwater users do not pay the efficiency price for the resource, i.e. they free-ride on scarcity rents. The source of this inefficient behavior is the difficulty of efficiently and equitably defining, allocating and protecting rights to a common, fluid resource through market mechanisms without guidance from publicly agreed and enforced rules. It is doubtful, however, that groundwater pumpers are unusually irrational or perverse. Why then well owners continue to pursue heavy groundwater use, despite the attendant environmental problems mentioned above? Why do pumpers appear to ignore these problems and fail to take steps to reduce the damage or compensate those harmed? Why have efficient well supply schemes, such as coordinated spacing arrangements, not been more widely adopted? Why have more efficient water use policies and conservation devices not been employed? Failing these measures, why haven't those responsible for the harm faced injunctions or damage judgments? A norms-based answer to some of these questions may simply be that the problems are just not severe enough to merit concern or response. This argument and related research will be critically reviewed in Sections 2, 3, 4 and 5 of this chapter. Alternatively, it may be the case that the problems and feasible solutions are seen, but cannot be agreed upon. We now turn to a number of factors that reduce the likelihood that voluntary agreements will be initially sought, then negotiated, and finally enforced and obeyed.

For many years, there was *little understanding of groundwater sources, quantities, and behavior*. Pumpers were unaware of the effects of groundwater use and unlikely to consider, much less enter in on agreements to coordinate their use with affected parties. As time has passed, understanding of groundwater dynamics has improved greatly. Still, though, knowledge is somewhat restricted to theoretical generalities and aggregate supply and use figures; that is, key factors in groundwater availability and flow often turn on site-specific and widely varying parameters such as storativity and conductivity. Although not precise, knowledge about groundwater and consequently knowledge about benefits derived from groundwater management, remains costly to acquire. The costs include technical expenses such as well monitoring, aquifer computer modeling, legal costs for negotiating and drawing contracts for surface canal and allocation of yield shares may also arise.

Secondly, the classical *prisoner's dilemma* can be used to frame the options facing one pumper considering whether to cooperate with a second pumper. The prisoner's dilemma is a typical game of strategy in which individual incentives lead to a non-optimal (non-cooperative) outcome. If a bargain for coordinating or reducing pumpage can be reached, this dilemma can be used to describe the choices available to each pumper, considering whether to comply with the deal he has made or not. In such a case the benefits of defection are tempting (i.e. a prompt supply of water at an individually convenient flow rate and location can be developed immediately) and the risks of defection are quite slight (i.e. monitoring compliance with a well pumpage scheme would be difficult, given the great number, wide spacing and private location of wells). Conversely, the benefits of cooperation are difficult to show given that they rely on site-specific aspects of an aquifer and on data-intensive monitoring of pump flow rates, well sites and screen depths, and they will only be evident in comparison with the lone-ranger pumping scheme which the contracting pumpers have supposedly abandoned.

A third factor, related to prisoner's dilemma, is introduced by the *limits of self-help and enforcing agreement.* That is, if a pumper suspects that his neighbor is not complying with a supply or use agreement, he has few effective ways to enforce that agreement. First, it is difficult to identify who is defecting from the agreement. Second, even if a pumper knew who the culprit was, he would have limited means of forcing his cooperation. Moreover, the difficulties of negotiating a cooperative agreement with another pumper and subsequently complying with that agreement are compounded if other, third-party pumpers are considered. The individual harms of shunning agreements or subsequently defecting from agreements will seem small relative to the cumulative aquifer effect and the pumper's foregone wellwater. Here the pumper faces a situation similar to the paradigm posed by Hardin in 1968, referred to as the *"tragedy of the commons"*.

Finally, the *effects of racing* (rule of capture) also limit the likelihood of successful voluntary agreements for the exploitation of groundwater resources. If a pumper shares his groundwater supply with others, he can no longer be sure that unused groundwater will remain for his use tomorrow: another pumper may have already pumped it. His opportunity cost quickly becomes uncertain, and more so as the number of competing pumpers grows and the size of the aquifer diminishes. Other, more general factors may also reduce the opportunity cost: high interest rates and dubious survival of the groundwater-dependent business may contribute. Ultimately, there may remain little reason to forestall today's pumping to allow future withdrawals.

Given the difficulty of establishing clear groundwater ownership rights by publicly agreed and enforced rules, scarcity value frequently goes unrecognized and is difficult to estimate. Ignoring scarcity rents means that the price of groundwater is too low and extraction is above the socially optimal level. 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 results in inefficient pricing and misallocation of the resource. This results in the imposition of a stock/cost externality on future users of the resource. (Competitive behavior need not be myopic, the problem is not with the market mechanism, but the property rights institution; however, this misuse seems to be fairly commonplace, so we will not interfere with its perpetuation and hope that readers will suffer this imprecision.) How then can it be that the no-management (competitive) dynamic solution of groundwater exploitation is almost identical (in terms of derived social welfare over an infinite time horizon) to the efficient management (optimal control) solution, as GSE claims?

A number of possible rationalizations of GSE can be offered: (a) the hydrogeological physical structure of aquifers is such that eliminates this externality, (b) the marginal benefit curve derived from groundwater use is very steep and as a result not significantly sensitive to increases in the price of the resource implied by adding marginal scarcity rents to marginal extraction costs, (c) the marginal value of groundwater *in situ* scarcity is insignificantly small and as such it does not cause significant behavioral changes in the market for water, (d) another positive externality is involved in groundwater extraction that reduces the effect of common property externalities, and/or (e) there is a major fault in the way the literature attempts to measure management benefits. The main aim of this survey is to investigate which of the above rationalizations are empirically relevant and identify additional factors that could potentially reduce or eliminate this effect.

In Section 2, we concentrate on the findings and consecutive research resulting from the seminal paper of Gisser and Sanchez in 1980. Section 3 examines the long-run robustness of GSE. Section 4 reviews the robustness of GSE in a game theoretic framework, i.e. when the interaction between extracting agents is explicitly taken into account. Section 5 reviews studies that examine the presence of GSE when the link between surface and groundwater is recognized or the stochastic nature of groundwater recharge is acknowledged. Section 6 concludes the survey.

2. Gisser-Sanchez's Model, Caveats and Robustness

Historically, economists have taken it for granted that the divergence between the temporal allocation of groundwater yielded by optimal control and the free market, is practically significant for social welfare because of the absence of well defined groundwater property rights and related resulting externalities, which lead current resource users to ignore or free-ride on groundwater scarcity rents.

As a result they acknowledged the need for the study of optimal control (or equivalently, dynamic programming) of temporal groundwater allocation. Problems of groundwater allocation have been studied in the context of the theory of mine by a number of economists.

Then, a notable series of papers has drawn on principles of inventory management to derive decision rules for the optimal temporal allocation in a dynamic programming format. The case dealt in this series of papers can be regarded as somewhat more complex than those cases studied in the theory of the mine, in that groundwater stocks were treated as partially renewed by a stochastic process and the value of the resource was imputed by reference to its role as an intermediate product (for production of irrigated crops) by an industry composed of multi-product firms.

A follow-up extension of this work has incorporated a complex groundwater model, taking account of the heterogeneity of a hypothetical aquifer, into a simulation program representing a groundwater basin system, and studied the effects of different policy instruments that might correct the misallocation of commonly owned groundwater.

It was found that net benefits from groundwater management, could amount to over $100 per acre but noted that these benefits would decline with increases in the interest rate or increases in the specific yield coefficient of the aquifer (the specific yield or alternatively, storativity coefficient of an aquifer indicates its storage capacity). Building on this work, economists derived a formula for a tax that should be imposed on groundwater (pumped) in order to yield the optimal control solution.

Then, the issue of congestion externality in aquifers with open access characteristics, and suggested a charging tax for the use of a unit of the variable factor to accommodate this externality.

At the same time other economists studied competitive solutions to the problem of temporal allocation of groundwater, where scarcity rents are completely dissipated by resource's users, and developed a competitive model for farmers pumping water out of an aquifer by integrating the demand function for water with hydrologic theory. They showed that in a free market, farmers will pump until the aquifer reaches an unacceptable water level.

When this point is reached farmers will either import supplemental water or be restricted to use a smaller amount of water by being assigned water rights. Assuming however, that at some future time farmers might reach the bottom of the aquifer anyway, they might want to consider optimal regulation of pumping at times earlier than the actual time of reaching the bottom.

This argument poses an optimal control problem and warrants a solution that should be compared with the case of no control. This was the departure point for Gisser and Sanchez's work in 1980.

2.1. Gisser-Sanchez Effect

The basic model analyzed 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. The irrigators benefit function is represented by

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

where $\pi(t)$ denotes profits at time (t). Net farm revenues from water use $w(t)$ (neglecting pumping costs) is denoted by $V(w) = \int_0^w p(x)dx$, where $p(w)$ is the inverse demand function for water. C(H) is the average and marginal pumping costs per acre-foot of water, where H(t) is the height of water table above some arbitrary reference point at time (t) . The change in the height of the water table is given by differential equation (2), which represents the hydrologic state of the aquifer (or equivalently, the environmental constraint of the problem)

$$\dot{H} = \frac{1}{AS}[R + (a-1)w], \qquad H(0) = H_o \tag{2}$$

where (R) is constant recharge measured in acre feet per year, (a) is the constant return flow coefficient which is a pure number, (H_o) 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 which is a pure number. These inflows and outflows are illustrated in figure 2, where (S_L) indicates the elevation of the irrigation surface measured in feet above sea level.

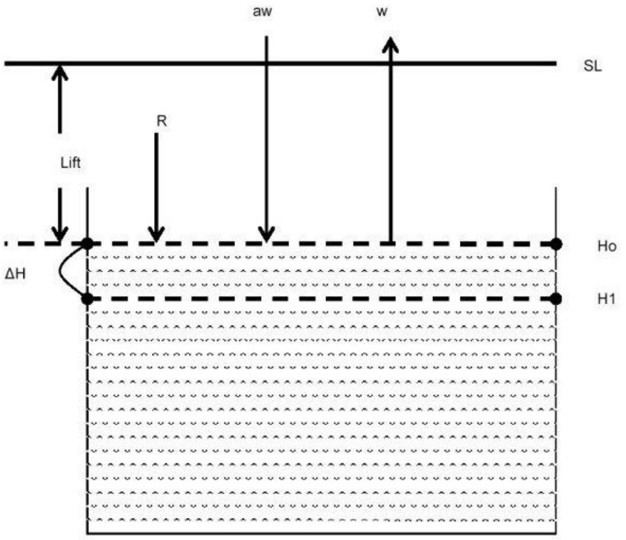

Figure 2. A model of an aquifer

More precisely, the aquifer in Gisser and Sanchez's work is modeled as a "bathtub", (*A "bathtub" is a single-cell aquifer. All users are assumed to pump from the same aquifer and the return flow of water finds its way back into the same aquifer. Implicit in a "bathtub" model is the assumption of zero natural discharge*) unconfined aquifer, (*In an unconfined aquifer the water table is free to fluctuate as the aquifer is not bounded from above by an impervious layer. If water from precipitation flows into the aquifer, the water level will rise. If water is withdrawn from the aquifer, the water level will fall. The upper part of the aquifer, above the water table, is unsaturated while the lower part is saturated*) with infinite hydraulic conductivity. (*Infinite hydraulic conductivity implies that the aquifer will never dry up, irrespective of groundwater extraction rates. This assumption is equivalent to the assumption of a bottomless aquifer. Gisser and Sanchez justified their adoption of the bottomless aquifer assumption by arguing that it is implied by the standard assumption in the literature that time goes to infinity. However, if this is not the case a steady-state solution might not be reached. Moreover, it can be shown 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, where the water height in the well is less than the height in the rest of the aquifer*) Moreover, while the assumption of constant return flow is not inappropriate, it is not innocuous in the presence of fixed irrigation technology. In particular, it suggests constant rate of water application. In addition, the assumption of deterministic and constant recharge in conjunction with the assumption of constant return flow, implies constant types of land use, independence of surface water and groundwater systems, and constant average rainfall. Moreover, sunk costs, replacement costs, and capital costs in general are ignored, and it is implicitly assumed that energy costs are constant. It is also implicitly assumed that the well pump capacity constraint is nonbinding. Finally, exclusiveness in Gisser and Sanchez's model is achieved by assuming that only land overlying the aquifer can be irrigated, i.e., the demand curve does not shift to the right over time. Overall, the explicit recognition of the assumptions behind GSE attempted in this paragraph, indicates that the result should be used with caution on real aquifer systems.

As already indicated in the introduction, the externality described by Gisser and Sanchez's mathematical representation arises because the cost of pumping groundwater depends on the groundwater stock. By pumping the marginal unit of groundwater stock in period (t), a firm affects the cost at which other users may pump groundwater in period $(t+1)$. Firms withdraw water too quickly because, while a firm's decision to

reduce its rate of pumping lowers the future pumping costs of all firms, it is not compensated for its conservation. Given the above hydro-economic model, Gisser and Sanchez used a linear water demand function (which was estimated using parametric linear programming) and hydrologic parameters that were considered realistic in the 1960s but have been revised since then. Assuming a discount rate of 10%, they 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 results of their simulations were as follows:

No control:

$$H(t) = 1\,525 + 1\,875 \cdot \exp(-0.000617)t$$

$$W(t) = 237\,000 + 213\,825 \cdot \exp(-0.000617)t$$

Optimal Control:

$$H(t) = 1538 + 1\,862 \cdot \exp(-0.000613)t$$

$$W(t) = 237\,000 + 211\,056 \cdot \exp(-0.000613)t$$

where (H) and (W) represent the water table (measured in feet above sea level) and pumping (measured in acre feet per annum), respectively. Notice that the trajectories under the two regimes are almost identical. The wealth (present value of future income streams) was estimated at $(\$309\,990\,007)$ under no control and at $(\$310\,002\,484)$ under optimal control. The two figures are practically identical. This result led them to conclude that there is no substantive quantitative difference between socially optimal (planning) rules for pumping water, wherein common property effects are considered, and the so-called "competitive" rates, where common property effects are ignored; hence the welfare loss due to the intertemporal misallocation of pumping effort is negligible. This conclusion amounts to Gisser-Sanchez's Effect.

Solving analytically the model, Gisser and Sanchez concluded that if equation (3) is true, then the difference between the two strategies is so small that it can be ignored for practical consideration.

$$\left[\frac{kC_1(a-1)}{AS}\right]^2 \simeq 0 \qquad (3)$$

In Eq.(3), (k) is the decrease in demand for water per \$1 increase in price (i.e., the slope of the uncompensated demand curve for groundwater), (C_1) is the increase in pumping cost per acre foot per 1 foot decline in the water table, and (a) and (AS) as given in Eq. (2). If (3) holds, then the rate of discount will practically vanish from the exponents of the optimal control formulation of the problem. Thus the exponents of the optimal control result will be practically identical with the exponents of the competition result. This analytical derivation implies that as long as the slope of the (uncompensated) groundwater demand curve is small relative to the aquifer's area times its storativity, then GSE will persist.

The upshot of this result is obvious: if there is no quantitative difference between optimal and competitive rates of water pumping, 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 are obviated. This is even more evident when we take into consideration that implementing optimal extraction is not going to be costless. In other words, GSE establishes that the inefficiency of private exploitation is not a sufficient condition for public intervention since regulation of the resource would have to be based on an accurate cost-benefit analysis. This suggests that there is little or no role for water policy in the form of pumping limitations, a conclusion which seems to contradict apparent common consensus opinion that groundwater is becoming increasingly scarce with many aquifers facing depletion in the foreseeable future. At issue, of course, is whether such depletion is "premature" in any sense. To the extent that it is, then these observations are clearly dichotomous.

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