Economic and spatial modelling of groundwater extraction

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Introduction

This essay examines the underlying spatial assumptions prevalent in economic models of groundwater extraction. Due to the common pool nature (see Glossary at the end) of aquifers, economists have long claimed that when groundwater is extracted under competition—in the absence of regulations in terms of the location and rates of extraction—a series of externalities prevent the efficient exploitation of the resource (Provencher and Burt 1994). Specifically, extraction of an additional unit of groundwater reduces the total stock, which creates two consequences. First, a lower stock reduces future availability and extraction alternatives; thus, a stock externality arises whenever the stock constraint is binding. Second, a pumping cost externality arises because a lower stock increases the depth to groundwater and, consequently, the extraction costs of other users. Other types of externalities including third-party effects in the form of groundwater quality deterioration and greater income risk may also arise with extraction. Given the spatial-dynamic nature of groundwater flow, the extent of all these externalities depends on the quantity, location and time of extraction and on the type of strategic behaviour under competition (Negri 1989).

In the presence of a competitive and unregulated extraction regime, the temporal and spatial profile of external effects results in inefficient pricing and misallocation of the resource. Users extract too much, too quickly and from the wrong locations. Aquifers are depleted faster, pumping costs increase and water quality may deteriorate, resulting in lower profits from groundwater extraction and resilience of the groundwater system.

Gisser and Sanchez (1980) were the first to provide a counter-intuitive result contrary to the prevailing view that groundwater extraction is inefficient in the absence of regulations or ways to internalise the externalities of water withdrawal. Under restrictive economic, hydrologic and agronomic assumptions, they found that there is no substantive quantitative difference between optimal rules for pumping water and competitive/unregulated rates. This has become known as the Gisser-Sanchez effect (GSE) and still dominates economic thinking in terms of groundwater management. Namely, that the welfare loss from inter-temporal misallocation of pumping effort is negligible.

This essay briefly reviews the underlying assumptions of the GSE and then presents alternative model specifications that allow for spatial heterogeneity and both spatial and endogenous decision making by aquifer extractors. The conclusion describes two key findings of spatial and endogenous location (SEL) models that are in contrast to the GSE.

Gisser-Sanchez effect and bath-tub models of aquifers

Central to the derivation of the GSE, and typical in most of the economic literature on groundwater extraction, is the single-cell or bath-tub representation of the groundwater flow. In the Gisser-Sanchez model, the aquifer is modelled as a 'bath-tub', unconfined aquifer, with infinite hydraulic conductivity. A bath-tub approach to modelling an aquifer assumes it responds uniformly and instantly to groundwater extraction. Thus, the spatial distribution of resource users is irrelevant and the evolution of the spatial profile of drawdown does not affect present and future extraction decisions. Gisser and Sanchez also assume 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 has a positive water stock, their estimation of welfare gains from optimal management excludes the stock externality.

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Other assumptions implicit in the Gisser-Sanchez model and in much of the follow-up research are fixed economic relations (e.g. time-independent demand) and/or exogenous and constant rates of change (e.g. constant and fixed exogenous crop mix, constant crop requirements, fixed irrigation technology, constant energy costs and constant exogenous types of land use). Further, sunk costs, replacement costs, and capital costs in general are ignored (Koundouri 2004).

The GSE initially motivated a number of studies to investigate its robustness by performing sensitivity analysis on all of its assumptions, with the exception of the spatial uniformity of the aquifer. Some of these studies found a significant divergence between optimal and competitive extraction paths (Brill and Burness 1994; Feinerman and Knapp 1983; Kim et al. 1989; Provencher and Burt 1994; Shah et al. 1995; Worthington et al. 1985), while others did not (Allen and Gisser 1984; Knapp and Olson 1995; Nieswiadomy 1985). Knapp and Olson (1995) examined the GSE while including stochastic surface supplies and artificial recharge and suggest that, in this setting, the benefits of groundwater management may be large under risk aversion.

Recently, the validity of the GSE has been tested under alternative spatial representations of the aquifer's dynamics. Depending on the specific underlying behaviour of each aquifer, Brozovic et al. (2010) suggest that the welfare gains from optimal management may be under or over-estimated if a bath-tub representation is used. It may be the case that a GSE is found when the gap between optimal and competitive extraction paths is large. The representation used to depict aquifer dynamics has important repercussions in the policy prescriptions derived from the model. Further, even if bath-tub models adequately capture the behaviour of some aquifers, spatial regulations cannot be analysed using bathtub models. Under some conditions, these spatial regulations may have excellent equity and efficiency effects, by themselves or complementing extraction control measures.

In recognition of the limitations of bath-tub models, recent economic studies offer a more realistic interpretation of groundwater hydraulics. For instance, two-cell models divide the simulation region into two cells and allow flow between them in proportion to the difference in stock levels. Nevertheless, these models only examine interdependency between two areas (such as two adjacent aquifers) and ignore micro-level incentives of individual users within each area (Chakravorty and Umetsu 2003; Saak and Peterson 2007; Zeitouni and Dinar 1997).

A closer approximation to realistic groundwater dynamics has been achieved by a few economic studies that model aquifers as multi-cell basins. These studies represent water movement between cells with finite difference approximations of groundwater flow equations and linearise the system to include it in the economic optimisation. The shortcoming of these models is that the evolution of the spatial profile of drawdown cannot be estimated as the partition is not fine enough (Chakravorty and Umetsu 2003; Noel et al. 1980; Noel and Howitt 1982).

Spatial models of groundwater extraction

The limitations of bath-tub models are beginning to be recognised in the economic literature and spatially differentiated hydrological components are increasingly being developed. This advance in hydroeconomic modelling has been facilitated by the availability of detailed data from improved information and monitoring technologies and by interdisciplinary cooperation in groundwater management research.

Brozovic et al. (2006, 2010) built a theoretical model for the optimal extraction of groundwater by spatially distributed users. They conclude that some aquifers may be more akin to private property rather than open access and may be subject to significant lagged effects from pumping. A few decades earlier, Bredehoeft and Young (1970) incorporated spatially dynamic characteristics of aquifer behavior into a simulation program and directly embedded it into an economic optimisation problem. However, they only investigated the effects of two policy instruments fixed in space and time. Young et al. (1986) generated response functions to specialised excitations from a finite-difference model and analysed several institutional alternatives for managing a groundwater-surface water system. Faisal et al. (1997) have also used a discrete kernel-based hydrological model to compare socially optimal and open access extraction schemes from a hypothetical basin.

Notwithstanding the existing groundwater modelling literature, there still has been no study that examines the sensitivity of groundwater use to different spatial and temporal specifications of the aquifer's response when the location of new wells is also a choice variable. In particular, the spatial-dynamic pattern of externalities depends not only on the level and location of current wells' extraction, but also on the characteristics of new wells such as their location and depth. This feature is particularly relevant given increasing demand for groundwater (and thus, increasing number of wells). As a result, it is essential to develop spatially differentiated dynamic optimisation models that also allow for spatially based decision variables (such as well location or depth). Further, the policy implications of uncertain impacts of overexploitation such as the intrusion of saltwater from underlying aquifers, have yet to be studied with spatial dynamic hydroeconomic models.

Spatial modelling and endogenous spatial variables in groundwater management

Analysing extraction externalities as a spatial-dynamic process poses significant analytical challenges. However, it also broadens the choice variable set available for the dynamic optimisation of extraction benefits. The dispersal process of groundwater is dependent upon extraction and spatial choices which are available at different stages of an aquifer's development. Hence, optimally setting these multiple variables achieves higher levels of hydrological and economic objectives.

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An alternative to the existing modelling approaches is to develop a spatially differentiated and dynamic model of endogenous site location for groundwater extraction. Recent work by Katic (2011) provides optimal and competitive extraction paths and well location decisions that are compared to the outcomes under alternative and more restrictive assumptions about the spatial distribution of groundwater. In the Katic model, the typical assumption of a homogeneous bath-tub representation of groundwater flow is found to substantially underestimate the welfare and hydrological costs from unregulated well location based on the maximization of own profit. In this case, optimal well location does matter when a spatially differentiated model is used if the 'interference' areas are properly acknowledged in the modelling context. Thus, a regulation that locates new wells in areas with low hydraulic interference may result in significant welfare gains even if extraction rates are unregulated.

Spatially differentiated dynamic models have also recently been used to explore the sensitivity of optimal instrument mixes to the introduction of uncertainty, and to quantify the trade-off between risk and efficiency involved in different instrument combinations (Katic 2011). Under the uncertain threat of irreversible saltwater intrusion, the use of multiple instruments (that is, extraction and depth controls) yields higher economic benefits than a single instrument. Further, although the use of a single instrument (extraction control) leads to more conservative extraction paths, the risk of crossing the threshold is actually higher than when multiple instruments are used. Thus, a cautionary single extraction policy can result in a double loss in economic benefits and in the resilience of the aquifer's system.

There is much yet to be done in terms of developing models of efficient groundwater management over space and time. First, more studies are needed that quantify the transaction costs of first- and second-best groundwater policies and unitisation schemes. The efficiency payoffs of each alternative instrument do not provide enough information for the policy evaluation process. A remaining question is how costly different policies are to implement and monitor, and how these costs depend on the spatial dynamics of the aquifer.

Secondly, few studies exist on decentralised spatially based approaches to self-regulate groundwater extraction. Since a wide variety of decentralised groundwater management initiatives are in place such as location norms and zoning systems, it would be informative to assess which factors condition whether coordination-based gains exceed internal transaction costs. Chief among these factors may be the mechanisms available to manage inequities and perverse incentives.

Thirdly, the effects of other types of uncertainty on optimal groundwater management designs represent an important research agenda. Given the expansion of climate change-induced alterations in soil, land cover and rising sea levels, risk management studies are needed to quantify the trade-offs among conflicting objectives. Alternative stochastic optimisation techniques could be examined to analyse different shock structures to the groundwater system.

Finally, the incorporation of spatially based control variables in the modelling of groundwater depletion problems raises important institutional design questions. The use of spatial regulations means that location matters for the system outcome. Hence, the implementation of rent-maximising spatial policies will often require cooperation among agents and agencies in different regions or nations. In this context, the design of transboundary institutions should be analysed so as to incorporate these policies in integrated water-management schemes.

Concluding remarks

Much of the economic literature on groundwater extraction assumes that aquifers are uniform or a single cell. Such an assumption has led to the commonly held view, known as the Gisser-Sanchez effect, that there is little difference between optimal and competitive extraction.

Spatially heterogeneous models of groundwater extraction give a much richer and deeper understanding of the economics of groundwater extraction. These models generate two key insights. First, extraction paths are likely to be sub-optimal if a heterogeneous aquifer is depicted by a homogeneous spatial representation. Second, the optimal location of new wells will be incorrect if a homogenous representation of the aquifer is used, unless the evolution of the groundwater's stock is independent of the location of new users.

Spatially differentiated dynamic models aim to develop tractable and easy to understand tools, where complexity is not simplified, but translated into insightful policy information. As part of an integrated groundwater management approach, additional instruments complement extraction controls and raise overall welfare. One example is optimal groundwater management under the uncertain threat of irreversible saltwater intrusion. In this context, an additional regulation on well depths is found to simultaneously increase the resilience of the system and the economic returns of users, relative to a single instrument policy.

The use of multiple instruments is another important issue, especially when the demand for groundwater is increasing. In this case, an optimal policy should account for interconnections among new users. Even if extraction rates are optimally controlled, welfare is not maximised unless the locations of new users are also optimally chosen. Moreover, during the early stages of an aquifer's development, when hydrological stresses are incipient, a simple and easy to enforce location tool may generate large benefits to users.

In sum, spatial and endogenous location models of groundwater extraction allow extractors to optimally determine the spatial location of their wells according to the spatial dynamics of the hydrology. The findings from these models show the importance of incorporating: (1) spatial dynamics; (2) uncertainty in terms of threshold

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effects; and (3) endogenous spatial location of wells into economic models of groundwater extraction.

Glossary of economic terms

Common-pool resource A natural resource such as an aquifer where use is rivalrous and it is costly to exclude users from undertaking withdrawals from the resource.

Competitive extraction Extraction of natural resources which is unregulated such that there are no institutional limits placed on the rate of withdrawal by an individual resource user.

Gisser-Sanchez effect (GSE) The view that there is little difference between the optimal rate of groundwater extraction when it is undertaken optimally and when it occurs under competitive/unregulated extraction.

Pumping cost externality Additional costs imposed on other extractors from a given decision by an extractor to pump water from a well, and that are not accounted for in the pumping decision of an individual.

Stock externality Reduction in the water available for use by others from a given extractor's decision to pump water from a well, and that are not accounted for in the pumping decision of an individual.

Sunk cost An expenditure or cost that has already been incurred (such as the purchase of capital equipment) but which has no impact on current or future returns.

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