THE ECONOMIC RESEARCH ORGANIZATION
AT THE UNIVERSITY OF HAWAI'I

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Working Paper No. 2014-8

June 2014

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Abstract

In many parts of the world, irrigation and groundwater consumption are largely dependent on groundwater. Minimizing the adverse effects of water scarcity requires optimal as well as sustainable groundwater management. A common recommendation is to limit groundwater extraction to maximum sustainable yield (MSY). Although the optimal welfare-maximizing path of groundwater extraction converges to MSY in some cases, MSY generates waste in the short and medium term due to ambiguity regarding the transition to the desired long-run stock level and failure to account for the full costs of the resource. However, the price that incentivizes optimal consumption often exceeds the physical costs of extracting and distributing groundwater, which poses a problem for public utilities facing zero excess-revenue constraints. We discuss how the optimal price can be implemented in a revenue-neutral fashion using an increasing block pricing structure. The exposition is non-technical. More advanced references on groundwater resource management are also provided.

Keywords: groundwater, sustainability, dynamic optimization, maximum sustainable yield

Groundwater Economics without Equations

In many parts of the world, irrigation and groundwater consumption are largely dependent on groundwater. Over time, a typical aquifer, or subsurface layer of water-bearing, porous materials, is recharged naturally from precipitation that infiltrates below ground. It can also be recharged via irrigation return flow, due either to canal leakage or excess applied water not consumed by crops. The cost of withdrawing water is a direct function of lift, which is the distance between the water table and the surface. In some cases, water can also naturally discharge from the aquifer to adjacent water bodies, or in the case of a costal aquifer, into the ocean. The management problem is to determine how much groundwater to withdraw over time.

Long before the World Commission on Environment and Development (1987) launched the modern quest for sustainable development, sustainability was a concern to resource managers. A common recommendation was to limit extraction of a renewable resource (e.g., groundwater) to maximum sustainable yield (MSY) — the amount of resource regeneration that would occur at the stock level that maximizes resource growth. Harvesting MSY in perpetuity indeed ensures the convergence of the resource stock to the level that maximizes growth, provided that the initial stock is sufficiently high. However, while the MSY management strategy is straightforward, it generates two sources of waste: ambiguity regarding the transition to the desired stock level and failure to account for the full costs of resource use. These shortcomings led to a search for a sequence of groundwater withdrawals over time that maximizes the present value (PV) of a single groundwater aquifer, or system of aquifers.

Dynamically efficient or optimal resource management entails selecting the sequence of withdrawals that generates the largest PV of social welfare. The solution describes the optimal resource stock in the long-run (the steady state) — which may or may not coincide with the MSY stock — as well as the optimal transition path to get there.

MSY may turn out to be eventually optimal in the long-run. Managing a resource is a dynamic problem because the stock changes over time in response to natural growth/decay, as well as anthropogenic extraction/replenishment. In the context of groundwater, the volume of stored water in an aquifer is measured by the head level, or the distance from some reference point to the top of the water table. The head level depends on the amount of recharge to the aquifer; the amount of water extracted for consumption; and the amount of groundwater that discharges from the aquifer naturally, e.g. to the sea. Each component may vary over time, but the resource stock becomes constant in the steady state, wherein extraction is limited to the recharge net of discharge. The optimal steady state head level will depend on a variety of factors, including the aquifer's physical characteristics and the demand for water. When water demand is rising, it may be optimal to gradually draw down the groundwater stock to the MSY level, and thereafter supplement with an alternative water source, such as desalinated brackish water. Since discharge is increasing with the head level (a larger volume of stored water means more pressure and a larger surface area through which groundwater can leak), per-period yield is maximized at the head constraint.

Calculating the optimal steady state head level is generally straightforward, but that level will rarely coincide with the initial state of the system. Optimal extraction in each period is determined by pumping until the marginal benefits of water (MB) fall to equal the full marginal cost (FMC) of withdrawal. The history of extraction determines, in turn, the path of the head level as it transitions from its initial state to the optimal long-run target. Since the FMC is determined only after the solution to the dynamic optimization problem is known, one cannot characterize the extraction and stock paths *ex ante*. A few general results have been established, however, with respect to time-dependence. For a single resource, if the demand and cost functions are stationary over time, the paths of extraction and head will be monotonic. That is, if the initial head level is above (below) the optimal steady state level, it will fall (rise) smoothly over time until it reaches the target level. If, however, demand is growing over time, a single aquifer should be accumulated initially, then drawn down, and finally stabilized at the optimal steady state level.

Social welfare ideally includes not only the consumption benefits and physical extraction costs of the resource, but also non-use benefits and environmental damage costs. Thus, the FMC of resource consumption should include any externality cost (e.g., irrigation-induced salinization of underlying aquifers) and user cost, which is defined as the cost of using the resource today in terms of forgone future benefits. In the case of groundwater, extracting a unit of water today lowers the water table — thus increasing stock-dependent extraction costs in all future periods — and forgoes capital gains that could be obtained by leaving the resource *in situ* to be harvested at a later date. The efficiency condition for resource extraction can be obtained by setting the price (P) equal to the FMC, where FMC includes marginal extraction cost, marginal user cost, and marginal externality cost in PV terms. By consuming along their demand curves, resource users will consume until MB is equal to price. The chance that this welfare-maximizing consumption path coincides with MSY is very slim.

Inasmuch as the FMC exceeds the physical costs of extraction and distribution, a public utility may not be legally allowed to charge the optimal price. Another complication arises from the fact that a price increase across the board may decrease welfare disproportionately for lower income users. One potential solution that addresses both efficiency and equity is an increasing block pricing structure (IBP). If consumers respond to prices at the *margin*, the only requirement for efficiency is that the price for the last unit of water is equal to FMC in every period, i.e. the price can be lower for inframarginal units of water. In the simple case of two price blocks, the first-block price can even be set to zero to ensure that all users can afford water for basic living needs. Any units of water beyond the first block would be priced at FMC. If designed properly, the IBP would induce efficient consumption, while returning would-be surplus revenue to consumers via the free block.

In many parts of the world, groundwater is characterized as a common-pool resource. In the limit, it is individually rational for competitive users to deplete the groundwater until MB equals unit extraction cost. In this open-access equilibrium, each user ignores the effect of individual extraction on future value. The surprising result that the potential welfare gain from groundwater management is negligible has come to be known as the Gisser-Sanchez effect. Under certain circumstances, the PV generated by the competitive market solution is almost identical to that generated by the optimal solution. Welfare gains may be larger, however, when one or more of the original model's simplifying assumptions are relaxed, e.g. when extraction costs are non-linear, demand is non-stationary, the discount rate is low, and the aquifer is severely depleted at the outset.

Because common pool resources may face overuse by multiple consumers with unrestricted extraction rights, additional governance may be warranted if the gains from governance exceed the costs. The optimal solution may be unattainable when enforcement and information costs are considered. Which of several institutions (e.g. privatization, centralized ownership, and user associations) maximizes the net PV of the groundwater resource depends on the relative benefits generated from each option, net of the governance costs involved in establishing the candidate institution. For example, if the initial demand for water is small and the aquifer is large, the gains from management are likely to be small, and open access might be preferred. As demand grows over time and water becomes scarcer, however, a user association, government regulations, or a water market may become efficient.

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