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ORDERING EXTRACTION FROM MULTIPLE AQUIFERS

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Chapter 3: Ordering Extraction from Multiple Aquifers

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Abstract

Optimal groundwater extraction satisfies the condition that the marginal benefits of water consumption equal the full marginal cost of extraction in each period, including the opportunity cost of future benefits foregone. But how should this well-known condition be generalized when there are multiple aquifers available? We provide an extension of the "Pearce equation" to guide the optimal ordering of resource extraction and an illustrative application wherein it is optimal to extract from the "leakiest" aquifer first, letting another aquifer increase in volume. This generalized least-cost-first principle contrasts strongly with *the sustainable yield* approach. By including spatial dimensions, the model provides the marginal valuations of water at each time and place, such that full marginal cost pricing can incentivize users to implement the efficient program. While an untrammeled water market would fail to provide the optimal solution, regulators can facilitate efficient water trading by setting appropriate exchange rates.

1 Introduction

The economics of groundwater (e.g. Burt, 1967; Brown and Deacon, 1972; Krulce et al., 1997; Pitafi and Roumasset, 2009; Koundouri, 2004) is typically directed to finding the optimal extraction profile for a single aquifer. But in many cases, water managers have multiple aquifers to coordinate, and the single-aquifer conditions do not provide instruction on which aquifer to use first. As a default, managers may use engineering rules of thumb such as using the nearest available aquifer, even when multiple aquifers are connected to the same distribution system.

In response to this need, this chapter shows how renewable resource economics can be extended to the case of multiple resources. A natural starting point for this research is Herfindahl's (1967) demonstration that different grades of a non-renewable resource should be extracted in the order of "least-cost-first," where cost refers to the unit extraction cost of a particular grade. Subsequent research has shown that Herfindahl's result is a special case of a more general least-cost-first principle, namely that different resources should be extracted in the order of their full marginal cost, including the opportunity cost of foregone future benefits (Chakravorty and Krulce, 1994; Chakravorty et al., 1997; Gaudet et al., 2001; Chakravorty et al., 2005). Less attention has been paid to the optimal ordering of renewable resources, however, partly because the analysis of renewable resources has traditionally focused on the steady state, not the transition thereto.

Several papers have examined problems involving multiple renewable resources, but most have relied on somewhat restrictive assumptions – e.g. constant unit extraction costs and homogenous growth functions (Shimomura, 1984), constant resource growth (Zeitouni and Dinar, 1997), and exogenous prices (Costello and Polasky, 2008) – or have focused primarily on steady-state analysis (Horan and Shortle, 1999). Roumasset and Wada (2012) confirmed that the least marginal opportunity cost rule – a generalization of Herfindahl's least-extraction-cost-first rule – extends to multiple renewable resources and demands but focused their application primarily on the 2-resource, 1-demand case. In this chapter, we review these findings, with an emphasis on the 2-resource, 2-demand case, and discuss the role that transport costs play in determining optimal use. After examining some particular cases of interest, we then discuss a potential extension involving the management of multiple water resources when water quality is heterogeneous across aquifers and water quality requirements are heterogeneous across users.

2 Optimal extraction of multiple nonrenewable resources

Herfindahl (1967) established that deposits of a nonrenewable resource, identical aside from (constant) unit extraction costs, should be extracted in order of least marginal extraction cost. Lewis (1982) comments that "it seems to be almost transparent that it is efficient to exploit low cost deposits first". Indeed, if the marginal benefit and marginal user cost for each deposit is equal, minimizing extraction cost maximizes the present value net benefit of the resource. Chakravorty and Krulce (1994) show that when more than one demand (marginal benefit curve) exists for the resource, however, the least-extraction-cost rule does not generally describe the optimal extraction path. In particular, deposits should be extracted in order of least-price plus conversion cost for each demand, where price is equal to the sum of marginal extraction cost and marginal user cost. Optimal ordering in this case is predetermined in the sense that the relative magnitude of the initial deposit shadow prices can be established using knowledge about the initial value of the resource, i.e. without solving the entire dynamic optimization problem. Assuming that marginal extraction costs are also constant, it is straightforward to see which deposit is “cheapest” initially for each demand sector and then to trace out the phases of extraction.[1]

The conversion costs described by Chakravorty and Krulce (1994) appear at first blush to be specific to energy, e.g. converting coal into electricity and manufacturing an electric car. However, the concept is generalizable to other situations, wherein the “conversion cost” simply represents a cost in addition to extraction that is specific to a particular demand. In the context of landfills, Gaudet et al. (2001) specify the marginal cost as including both the cost of extracting the resource from a particular site and the cost of transporting it to a particular location for consumption. Their *full marginal cost* (FMC) – the sum of extraction cost, transportation cost, and imputed cost or shadow price of the resource – is therefore analogous to the efficiency price described in Chakravorty and Krulce (1994), as is their optimal extraction and allocation rule: each city (demand) will, at any given date, use only the resource with the lowest full marginal cost. Thus if the FMC of a particular city using a particular deposit exceeds the marginal benefit of consumption, that city should not extract from that site during that period.

Chakravorty et al. (2005) further generalize the findings of Chakravorty and Krulce (1994) and Gaudet et al. (2001) by framing resource extraction stages in terms of Ricardian absolute and comparative advantage. They show that in the general m-resource, n-demand case, optimal specialization over time is governed by absolute advantage while specialization across sectors is determined by comparative advantage. A resource that is abundant, i.e. has a relatively low shadow price, and has absolute advantage in all demands, i.e. has the lowest extraction plus conversion cost, may be extracted for a demand sector, even if it does not have comparative advantage in that use. However if more than one resource has absolute advantage in a given demand, specialization is based on comparative advantage. As in the 2 x 2 case, the optimal

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[1] For a stylized application with implications for global warming, see Chakravorty et al. (1997).

ordering of extraction can be established without solving the entire problem if information about the extraction plus conversion costs for each resource and demand are known.

The nonrenewable resource ordering problem can be solved in a variety of ways, but Gaudet et al. (2001) discuss a straightforward and intuitive algorithm for the case of constant extraction costs. First, assign to each resource an initial multiplier (shadow price) and let each multiplier grow at the exogenous rate of interest a la the standard Hotelling condition (Hotelling, 1931). For each demand sector, construct the available FMCs in each time period and select the resource with the lowest FMC in every period. Extraction in each period should occur until marginal benefit equals FMC for each resource and demand. Once the steady state is obtained, the cumulative usage of each resource can be calculated over time and across demands. If the cumulative usage for each resource exactly matches the initial stock, then the extraction paths are optimal. Otherwise, the guesses for the initial values of the multipliers must be adjusted and the process repeated until the candidate paths result in cumulative extraction that corresponds to the initial reserves.

3 Optimal extraction of multiple renewable resources

In this section, we use the example of coastal groundwater aquifers because leakage from the aquifer increases with the head level, which implies that net resource growth is a function of the groundwater stock, a distinguishing characteristic of a renewable resource. Moreover, since the extraction costs are also stock-dependent – a function of the energy required to lift the resource vertically from the water table to the surface – the model remains fairly general. Constant unit extraction costs are a special case.

Even in the case of one demand, Shimomura (1984) has shown that Herfindahl's least-cost rule does not extend to renewables such as groundwater. Because the marginal user cost component of the optimal shadow price for each "deposit" of a renewable resource varies according to the size of each stock, scarcity of each resource with respect to a particular demand can increase or decrease over time, meaning that the Gaudet et al. (2001) least-FMC rule must instead be used. Following Roumasset and Wada (2012), the least-FMC rule for m-resources and n-demands can be summarized as

$$p_t^j = \min[FMC_t^{1j}, FMC_t^{2j}, ..., FMC_t^{mj}] \text{ for j=1,…,n} \tag{1}$$

Optimality requires that the marginal benefit (*p*) and FMC of groundwater be equated in every period for every demand sector. If the marginal benefit for sector *j* is less than the FMC of a unit of groundwater extracted from aquifer *i* for consumption in *j*, then no water should be extracted for that purpose.

One of the FMC terms in equation (1) may correspond to a backstop resource such as desalinated brackish or sea water. Inasmuch as the backstop FMC is, in most cases, relatively high in earlier periods, optimal use of the groundwater alternative is delayed until later periods when groundwater is scarcer. *Corner solutions* or zero extraction from one or more sources is not limited to backstop resources, however. In general zero extraction may be optimal for any resource if its FMC is too high. A special characteristic of renewable resources – and one of the reasons why determining the optimal ordering is generally more challenging than for nonrenewable resources – is that corner solutions along the dynamic path correspond to decreasing scarcity of the unused resource(s) as natural replenishment occurs. This can be more clearly understood by examining the components of the FMC. One can show the FMC of groundwater extracted from aquifer *i* for use by demand sector *j* is comprised of the stock-dependent marginal extraction cost and the marginal user cost (Roumasset and Wada, 2012):

$$FMC_t^{ij} = c_i(h_t^i) + \frac{\dot{p}_t^j - c_i'(h_t^i) f_i(h_t^i) + \mu_t^i}{r - f_i(h_t^i)} \tag{2}$$

where c is the marginal extraction cost, f is the resource growth function, h is the head level which serves as an index for groundwater volume, r is the discount rate, and μ is the multiplier associated with the minimum head constraint, determined for example by EPA salinity requirements for potable water. Unlike in the basic nonrenewable setup wherein the FMC is equal to the unit extraction cost c plus $\dot{p}_t^j / r$, equation (2) varies with the head level.

Because groundwater aquifers replenish naturally via precipitation, all groundwater resources must be used in a steady state; otherwise head levels will continue to rise, which contradicts the condition that the system is in a steady state. Although unlikely to be optimal, a steady state may also obtain if the aquifer is allowed to replenish to its pre-extraction level. If demand for water is also perpetually increasing due to population and per capita income growth, the backstop resource will supplement groundwater in the long run (steady state). The ordering of resources prior to the steady state will vary, however, depending on the parameters of the particular application. We explore various permutations of the 2 x 1 case and discuss which insights carry over to the 2 x 2 case, and more generally to the m x n case.

Suppose we have two coastal aquifers (A and B), each with its own FMC (equation 2), serving a single demand sector. If $FMC^A < FMC^B$ initially, equation 1 tells us that aquifer A should be used exclusively, while aquifer B is allowed to replenish. Eventually, the two FMCs converge, whereupon either aquifer A reaches its steady state head level and extraction from that aquifer is limited to net recharge, or both FMCs rise together in conjunction with simultaneous (non-constant) extraction until one of the aquifers reaches its steady state head level. Once either head constraint becomes binding (say for aquifer A), the shadow price of A rises apace with the shadow price of B, ensuring that the least-FMC rule (equation 1) is not violated. The final stage of extraction is characterized by constant steady-state withdrawal from both aquifers at rates that exactly offset natural net recharge, supplemented by a backstop resource such as desalination. In the unlikely event that $FMC^A = FMC^B$ at the outset, simultaneous extraction is optimal during the entire transition to the steady state. Lastly, if both aquifer head levels lie initially below their respective optimal steady state levels, optimal management entails using the "backstop" resource exclusively at the outset, thus allowing the aquifers to build toward their optimum steady state levels. Desalinated water is used in every period, and groundwater is only extracted in the steady state. Figure 1 illustrates the hypothetical scenario where $FMC^A < FMC^B$ at the outset.

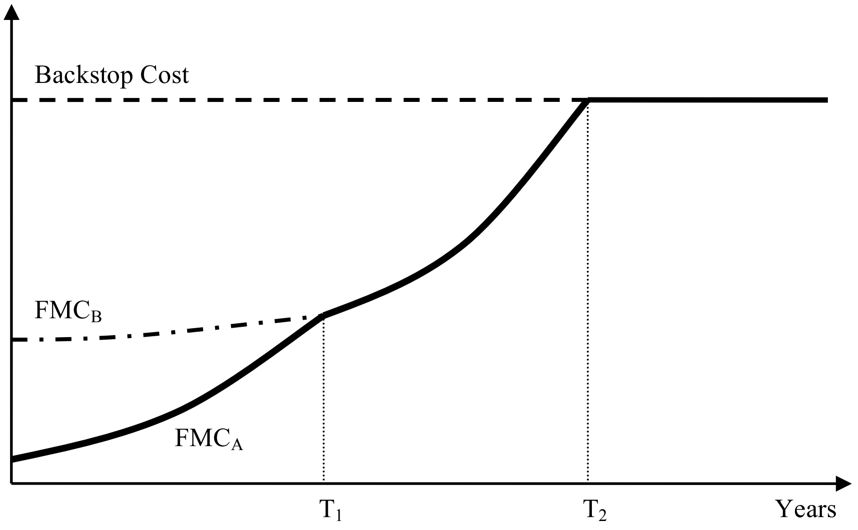

Figure 1. Hypothetical price path
Optimal extraction is guided by the least-FMC rule: extract from A in periods 0 to T_1, extract from A and B in periods T_1 to T_2, extract from A and B and supplement with desalination in periods beyond T_2.

Although the least-FMC condition (equation 1) prescribes optimal resource ordering for a given set of FMCs, the FMC of a renewable resource is not generally known ex ante. Nevertheless, one may be able to obtain a general sense of the optimal ordering on a case by case basis by examining various characteristics of the resource. For example, in the case of two coastal aquifers, using the "leakier" aquifer first may be optimal. Intuitively, drawing down the leaky aquifer and allowing the other aquifer to build reduces aggregate discharge to the ocean. In the case of interior aquifers, where net recharge and extraction costs are approximately constant, equation (2) varies among resources only by extraction cost and recharge. FMC is lower when extraction cost is lower and/or constant recharge is higher. Since both terms are known ex ante, optimal ordering can be ascertained without solving the entire problem. If, moreover, recharge is approximately equal for the two aquifers, least-FMC collapses to the Herfindahl least-cost rule.

To illustrate the 2 x 2 case, we consider a real world example on the island of Oahu, Hawaii. Pearl Harbor aquifer (PHA) is the largest groundwater aquifer in the state and is geographically located near Pearl City. To the southeast, the smaller Honolulu aquifer (HA) underlies the city of Honolulu, the most populated city in the state. Due to the difference in elevation, it is a reasonable assumption that transporting pumped water from Honolulu to Pearl City is costlier than moving water from Pearl City to Honolulu. Based on the "leakier aquifer first" logic discussed previously and the differences in transportation costs, it would likely be optimal to use PHA exclusively for Pearl City and Honolulu, while allowing HA to replenish. Once PHA reached its (minimum) steady state level, net recharge from PHA would supply Pearl City and Honolulu, while extraction from HA would only be used in Honolulu. Assuming that demand in both districts is continuing to grow, it would be necessary to supplement extraction from HA with the backstop (desalination) to supply the Honolulu district once HA is drawn down to its (minimum) steady state level. Eventually, demand growth in Pearl City would initiate desalination to supplement the PHA as well, such that Pearl City uses groundwater from PHA plus desalinated water produced in Pearl City and Honolulu uses groundwater from HA plus desalinated water produced in Honolulu.

The general least-FMC principle extends to the m-resource, n-demand case. In a given period, any number of resources may supply a particular demand simultaneously, so long as the full marginal costs of supplying water from each aquifer to that demand are equal. Because each aquifer has its own recharge, leakage, and extraction cost function, welfare maximization may entail allowing some aquifers to replenish while drawing down others over time, i.e. taking advantage of arbitrage opportunities. If demand is continuously growing, the long run steady state will always be characterized by constant water extraction, supplemented by desalination. However, increasing the number of available groundwater resources tends to delay the need for costly desalination; aquifers allowed to replenish in earlier periods come online in later periods when the scarcity value of water is higher and when implementing desalination may have otherwise been necessary to meet the growing demand.

As the number of resources and users expands, the problem becomes increasingly complicated, and preliminary ordering based on resource characteristics tends to become less feasible. Nevertheless, the Gaudet et al. (2001) approach to numerically solving the management problem can still be applied with some slight modifications. An initial guess is made for the starting value of each resource's shadow price. Each price grows according to the extended Hotelling condition, i.e. not simply at the exogenous rate of interest. In each time period, the resource with the lowest FMC is selected for each demand, and extraction occurs until the marginal benefit is equal to the FMC for each resource and demand. Eventually, all head levels reach their optimal steady state levels (which can be calculated using the necessary conditions). If the price corresponding to the steady state heads is equal to the backstop price, then the extraction paths are optimal. Otherwise the guesses for the shadow prices must be adjusted and the process repeated. If instead the backstop price is reached before the head levels are drawn down to their steady state optimums, the extraction paths are also suboptimal, and the guesses should be adjusted. Alternatively, cumulative extraction upon arrival at the steady state can be compared to the initial stock, after accounting for natural leakage and replenishment in accordance with the candidate head level trajectories.

The framework and derived FMC expression (equation 2) are sufficiently general to be directly applicable to other renewable resources. In particular, the model is easily modified for interior, i.e. not coastal, aquifers. In the case of an interior aquifer, extraction costs may still be stock-dependent, but the resource growth may be better characterized as a recharge quantity (rather than a function) inasmuch as stock-dependent discharge to the ocean is not relevant. If water naturally flows between adjacent inland aquifers, however, the net growth function should be modified to include the head levels of all aquifer under consideration – the relative heights of the head levels largely determine the direction of groundwater flow between aquifers. If the implementation of a backstop such as desalination is deemed unfeasible, a choke price can be set to ensure that the problem is solvable.

4 Spatial dimensions and water markets

Incorporating transportation costs into the framework discussed in Section 3 is fairly straightforward; the expressions for FMC in equations (1) and (2) need be only adjusted by the cost of transporting a unit of resource i from the extraction site to the location of demand sector j.

That is, the full marginal cost of extracting resource i for consumption in sector j is equal to the sum of marginal extraction cost, marginal user cost, and transportation cost. The least-FMC rule still characterizes optimal resource extraction.

The conditions described above imply that there is an efficiency value of groundwater *ex situ* given by the minimum FMC in each period. The efficiency value of delivered water is then just the *ex situ* value plus the transport cost to a particular location. A decentralized implementation of optimal groundwater allocation over space and time can then be achieved by setting the wholesale price equal to the *ex situ* value and retail prices equal to the wholesale price plus location specific transport costs.

Instead of a centralized authority announcing prices, could the same solution be obtained by markets? The problem is that the efficiency values for a particular time are different across space. If water markets are sufficiently "thick", i.e. if potential traders for water in each location are numerous, then the water authority could announce quantities for each location, and the market would provide the efficiency price. Since this condition seems unlikely, especially if location is distinguished by fine gradations, the water authority can implement a water market by announcing exchange rates, given by the ratio of the locational retail price as determined above to the wholesale price. Indeed the failure of authorities to provide such exchange rates partly accounts for the need for ad hoc review boards and the incidence of trade being much smaller than indicated by theory. On the other hand exchange rates presuppose reliable volumetric measurements of the water being traded. Until these are established exchange rates may be premature.

5 Introducing marginal externality costs

In the previous sections, it was assumed that groundwater extraction does not generate any external costs, i.e. costs not directly associated with physical extraction of the resource. When externalities are present, however, not accounting for them in management decisions can result in underpricing and overharvesting of the resource. Pearce and Markandya (1989) provide a useful and intuitive framework for incorporating externalities into optimal resource extraction: when resource use creates a downstream spillover, the FMC should include marginal extraction cost, marginal user cost, and marginal externality cost (MEC), where the last term captures the downstream external cost (e.g. pollution) resulting from extraction. The efficient level of resource use is thus achieved by extracting until the marginal benefit of doing so is equal to the FMC, which includes the MEC.

Although Pearce and Markandya (1989) do not specify expressions for MUC and MEC explicitly, some of the subsequent analyses on optimal resource sequencing – particularly in the area of nonrenewable resources – have incorporated the MEC concept. Chakravorty et al. (2008), for example, include the MEC of pollution associated with the extraction and use of natural gas and coal in their conditions characterizing the optimal order of extraction. They show that when extraction costs are homogeneous across resources but the coefficients of pollutions are heterogeneous, optimal ordering is determined by the FMC, in this case the sum of MUC and MEC. With high discount and/or dissipation rates this may imply that the dirtiest resource (coal) is optimally used first. This result is entirely consistent with the least-FMC cost rule; the MEC should and does account for the dynamic aspects of pollution including its depreciation. In the polar extreme case, with zero rates of pure time preference and dissipation, the dirty resource should never be used since any amount of stock pollution will permanently reduce the level of maximum sustainable consumption (Endress et al., 2005).

More generally, resource-extraction externalities can be classified into four categories: fund externalities, stock externalities, stock-to-fund externalities, and stock-to-stock externalities. Fund externalities, such as air pollution from sulfuric and nitrous oxides, are somewhat transient such that concentrations can be proxied by emission fluxes into a particular airshed; stock externalities are dynamic, direct spillovers such as emissions-induced climate change; stock-to-fund externalities are dynamic but indirect effects such as amenity values from resources, e.g. biodiversity; and stock-to-stock externalities are indirect and dynamic spillovers such as the effect of aquifer levels on nearshore marine environments where groundwater subterraneously discharges. For direct externalities (the first two types), the MEC term is additively separable from the MUC in the full marginal cost. When the effect is instead indirect, the MEC is embedded within the MUC, meaning that the standard “Pearce equation” does not apply. In either case, however, one might expect that optimal resource ordering is determined by the least-FMC extraction rule.

The management framework for multiple groundwater resources could be extended to include various types of externalities. In the case of water pollution (e.g. nutrient leaching from irrigation or pumping-induced saltwater intrusion of a coastal aquifer) each resource would have a different coefficient of pollution, and optimization would require keeping track of the stock of pollutant or water quality over time. Given that water quality requirements typically vary across users, calculations become increasingly complicated with these added dimensions, but the general optimality principle – namely the least-FMC extraction rule – is still expected to apply for each user type. Chapter 4 in this volume discusses the example of incorporating non-potable recycled wastewater use into a groundwater management program when users are sensitive to water quality. Positive externalities (e.g. the effect of submarine groundwater discharge on nearshore aquatic plants which is dependent on the level of the water table) could similarly be incorporated into a resource optimization framework, given aquifer-specific positive spillover coefficients.

6 Conclusions and directions for further research

We have generalized the least-cost rule for optimal extraction from a single aquifer to the case of multiple aquifers by including extraction cost, marginal user cost, marginal externality cost, and the shadow value of the minimum head constraint in the definition of full marginal cost (FMC). In each period, water should be extracted from the least-cost source. Higher cost sources should not be used until the FMC of the source in use rises to the FMC of the higher cost source. In the two-aquifer case reviewed, the leakier aquifer is the cheaper FMC source and is optimally drawn down to its minimum head level while the other aquifer is allowed to accumulate. This simultaneous drawdown/build-up pattern contrasts starkly with the principle of drawing from both aquifers according to their (arbitrarily selected) sustainable yields. (It may also be optimal to build up both aquifers before beginning a period of drawdown.)

The least-FMC ordering rule for groundwater extraction can be further extended to include other water resources. Surface water and recycled water, for example, can supplement groundwater extraction for a variety of end uses. Although not exactly identical in form to the full marginal cost of groundwater, the FMC for alternative water sources should still account for future effects of contemporaneous decisions (i.e. the marginal user cost), in addition to the physical costs of extraction/ production and distribution.

While not explicitly modeled in the optimization framework, energy plays a key role in the operation of groundwater pumps, conveyance of surface water, and treatment of ocean, brackish and waste water. When energy prices are rising, less energy intensive water resources become more desirable. At the same time, however, technological advancement for any of the production processes may drive the overall costs down if improvements in energy efficiency dominate rising energy prices. Consequently, a model with projected energy prices and induced innovation may tell a very different story in the short and medium term than the model developed in this chapter. In the long run however, if the production prices of groundwater alternatives eventually stabilize, the steady state will still ultimately be characterized by constant groundwater extraction, supplemented by the backstop resource.

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