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The Economics of Groundwater

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Abstract

We provide a synthesis of the economics of groundwater with a focus on optimal management and the Pearce equation for renewable resources. General management principles developed through the solution of a single aquifer optimization problem are extended to the management of multiple resources including additional groundwater aquifers, surface water, recycled wastewater, and upland watersheds. Given an abundant (albeit expensive) substitute, optimal management is sustainable in the long run. We also discuss the open-access equilibrium for groundwater and the conditions under which the Gisser-Sanchez effect (the result that the present value generated by competitive resource extraction and that generated by optimal control of groundwater are nearly identical) is valid. From the models and examples discussed, one can conclude that optimization across any number of dimensions (e.g. space, time, quality) is driven by a system shadow price, and augmenting groundwater with available alternatives lessens scarcity and increases welfare if timed appropriately. Other rules-of-thumb including historical cost recovery, independent management of separate aquifers, and maximum sustainable yield are inefficient and may involve large welfare losses.

Keywords: Groundwater, renewable resources, dynamic optimization, sustainable yield, Pearce equation, marginal user cost, conjunctive use, water institutions, Gisser-Sanchez effect, governance

JEL codes: Q20, Q25

1 Evolution of groundwater resource management

1.1 The economic problem

Groundwater is a renewable resource in the sense that aquifers can be replenished by infiltration, known as groundwater recharge. The natural recharge rate is analogous to the biological growth rate inherent in other renewable resources such as fish or trees. The economic problem, which is also analogous, is to determine the trajectory of resource extraction that maximizes the present value (PV), i.e. to allocate the resource over time in accordance with the principle of highest and best use. Consider the single coastal groundwater aquifer portrayed in Figure 1. The aquifer, or subsurface layer of water-storing permeable rock, is recharged by precipitation. Groundwater exits the aquifer either as natural discharge at the saltwater interface or as pumped water for consumption. If the amount of outflow exceeds recharge, then the stock of groundwater declines over time. PV maximization determines a steady state target and the speed with which the aquifer should be depleted or replenished to reach that target.

In the sections that follow, a simple “single cell” coastal aquifer model will be used to illustrate various theoretical results. Although not identical, the hydrogeological processes for an inland aquifer are for the most part analogous to a coastal aquifer. For example, while there is no seawater boundary along which discharge can occur, groundwater from an inland aquifer can flow out naturally into streams. Also, water quality can decline with the stock level for coastal and inland aquifers as a result of saltwater intrusion and inflow from adjacent lower quality water sources respectively. While fully three-dimensional groundwater models capture localized effects of pumping, the “single cell” model is analytically transparent and is a useful tool for addressing the long-run management of groundwater, i.e. to approximate the efficiency price trajectory and aggregate extraction path. Multidimensional aspects such as pumping-induced cones of depression are discussed in Section 4.1.

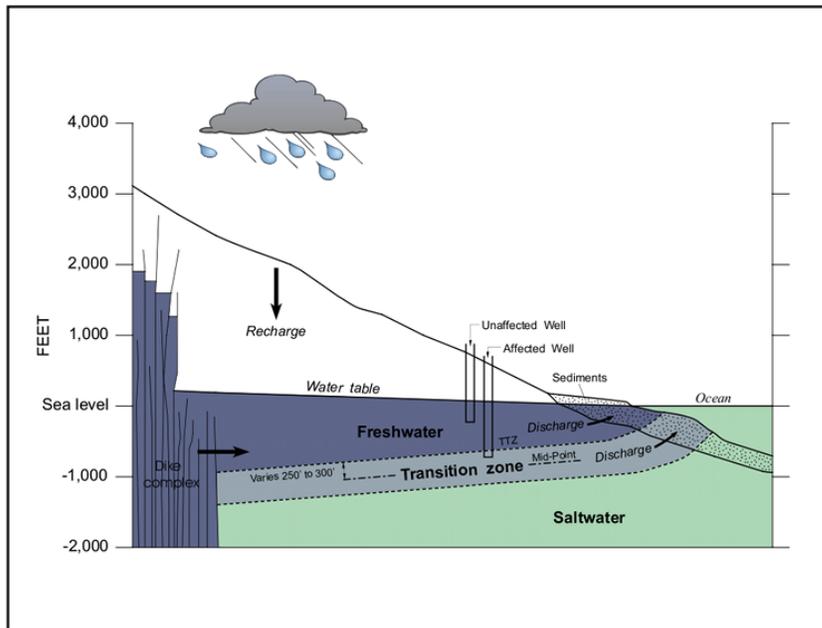


Figure 1. Coastal aquifer cross-section (Source: Hawaii Commission on Water Resource Management)

1.2 From sustainable yield to dynamic optimization

The management of renewable resources by non-economists is often based on the concept of sustainable yield (SY) with the objective of sustaining the resource at a particular population or stock level. In the context of groundwater, SY has been defined as the withdrawal of water for a selected equilibrium head level that can be sustained indefinitely without affecting water quality. However, SY is incomplete as a management strategy, inasmuch as its definition neither specifies the selected equilibrium head level, nor describes the speed with which the system should reach the desired steady state.

The standard economics approach of maximizing the present value (PV) of net benefits generated by the resource, on the other hand, specifies the optimal steady state stock level and characterizes the path of optimal resource extraction in transition to that steady state. Typically, the rate of optimal extraction is not constant over time and the corresponding resource stock level follows an increasing, decreasing or even non-monotonic path as the system moves toward the optimal steady state. Thus, while SY-based management is unlikely to be PV-maximizing (optimal), optimal management is likely to be sustainable (Heal, 2003).

1.3 Optimal management of a single groundwater aquifer

Decision rules for the PV-maximizing allocation of groundwater were developed in a dynamic programming framework in the 1960s (e.g. Burt, 1967). Shortly thereafter, research on the practical aspects of implementation produced a tax scheme that would induce the dynamically efficient groundwater management solution among independent well-operators (Brown and Deacon, 1972). Subsequent literature has developed conditions characterizing optimal management for various specifications of resource growth and extraction costs. The remainder of section 1.3 discusses how the optimal decision rule changes in accordance with those assumptions.

In the context of groundwater, dynamic optimization amounts to managing withdrawals in every period to maximize the PV of net benefits:

$$\max_{q_t, b_t} \int_0^{\infty} e^{-rt} [B(q_t + b_t) - c_q(h_t)q_t - c_b b_t] dt \quad (1)$$

where B denotes the benefits of water consumption, e.g. the area under the inverse demand curve for water, and c_q and c_b denote the unit costs of groundwater extraction and desalination respectively. As is the case for many other natural resources, the resource manager may choose to supplement extraction of the primary resource with an abundant but costly alternative. In the discussion that follows, desalinated brackish or salt water (b) will play the role of the *backstop resource* much as photovoltaic energy would for the management of oil reserves. Since the cost of extracting groundwater is determined primarily by the energy required to lift the water to the surface, c_q is typically allowed to vary with the head level, or the distance between a reference point such as mean sea level and the water table. The discount factor (e^{-rt}) converts the net benefits accrued at each time period t into a comparable present value.

The sequence of management decisions is constrained by a governing equation or equation of motion for the aquifer stock. The head level changes over time according the following differential equation:

$$\gamma \dot{h}_t = R - L(h_t) - q_t \quad (2)$$

where γ converts head level height into stored water volume, \dot{h}_t is the time derivative of head or $\partial h_t / \partial t$, R is recharge, and L is natural leakage.¹ In the simplest case, where the aquifer is modeled as a rectangular homogeneous “bathtub” (e.g. Gisser and Sanchez, 1980), the height-volume conversion factor is constant and dependent on the aquifer’s surface area and specific yield. Leakage is positive and stock-dependent, for example, when pressure from a freshwater coast aquifer lens generates discharge at the saltwater interface. As will be shown, the conditions governing optimal water extraction will depend on the functional forms and various parameters in Eq. 1 and 2.

In sections 1.3.1-1.3.3, rules for the optimal management of groundwater under various assumptions regarding recharge and extraction costs are derived, compared, and contrasted. Section 1.3.4 illustrates how the seemingly different extraction rules are in fact different cases of the Pearce equation. A discussion of the steady state and corner solutions in sections 1.3.5 and 1.3.6 respectively complete the characterization of the solution to the dynamic management problem.

1.3.1 Constant unit extraction cost

In the case that the surrounding geology prevents leakage from an aquifer to adjacent water bodies and changes in stored groundwater-volume do not largely affect the distance that water must be lifted to the surface (e.g. very large and relatively shallow aquifers), constant recharge (net of leakage) and unit extraction cost may be reasonable approximations. Mathematically, this amounts to replacing $c_q(h_t)$ with \bar{c}_q in Eq. 1 and $R - L(h_t)$ by \bar{R} in Eq. 2. The maximization problem (Eq. 1) can be solved in an optimal control framework by applying the *maximum principle* (e.g. Chiang, 2000). Defining *efficiency price* as the marginal benefit of water consumption along the optimum trajectory, i.e. $p_t \equiv B'(q_t + b_t)$, the necessary conditions for dynamic efficiency can be expressed as:

$$p_t = \bar{c}_q + \frac{\dot{p}_t}{r} \quad (3)$$

¹ In the sections that follow, the conversion factor is omitted from mathematical equations for expositional clarity. This does not affect any of the theoretical conclusions, inasmuch as γ is a multiplicative constant.

The second term on the right hand side of Eq. 3 is the *marginal user cost* (MUC), or the loss in present value that would result from an incremental reduction in the resource stock. Intuitively, extracting a unit for consumption today forgoes capital gains that would be obtained by leaving the groundwater *in situ*. The right-hand side of (3) is also called the marginal opportunity cost (MOC). That is, efficiency requires that marginal benefit in each period be set equal to MOC, which is the sum of extraction cost and MUC. Equivalently, $\dot{\rho}_t / \rho_t = r$, where the net price is defined as $\rho_t \equiv p_t - \bar{c}_q$. This is identical to the Hotelling condition for resource extraction; PV-maximization requires that the net price rises at the rate of interest.

Another possible configuration is stock-dependent net recharge and a constant unit cost of extraction. Like in the previous example, the assumption of constant unit extraction cost may be applicable for expansive but relatively shallow aquifers. In this case, however, leakage to adjacent water bodies such as streams or the ocean can vary with the groundwater stock. The efficiency condition for water is now:

$$p_t = \bar{c}_q + \frac{\dot{p}_t}{r + L'(h_t)}, \quad (4)$$

i.e. identical to Eq. 3 except for the additional leakage term in the denominator. Stock-dependent recharge changes the marginal user cost because current extraction affects the head level, which in turn affects future leakage. Leakage is likely to be increasing with the head level because a higher head level creates more pressure and surface area over which groundwater can leak into adjacent water bodies. Consequently, the loss in capital gains of present consumption may be partially offset by leakage reduction resulting from a lower future head level.

1.3.2 Constant recharge and stock-dependent unit extraction cost

Many of the existing groundwater economic models in the literature maintain the assumption of constant recharge and stock-dependent unit extraction costs (e.g. Gisser and Sanchez, 1980; Feinerman and Knapp, 1983; Moncur and Pollock, 1988). With the exception of artesian wells—where a confined aquifer² located down-gradient from its

² A confined aquifer is an aquifer that is overlain by an impermeable layer of rock or substrate, while an unconfined aquifer is one whose upper boundary is the water table. In reality, many aquifers fall between the two extremes. For example, a coastal aquifer may be confined by sedimentary deposits near the coast

recharge zone creates pressurized groundwater that rises naturally above the water table—bringing water from any type of aquifer to the ground surface requires costly expenditure of energy. Thus, unit extraction cost is typically modeled as an increasing function of the distance to the surface, i.e. a decreasing function of the head level. And while most aquifers do experience some natural leakage, many studies abstract from leakage, e.g. by including it as a constant value subsumed in \bar{R} . The efficiency condition for this problem can be written as

$$p_t = c_q(h_t) + \frac{\dot{p}_t - \bar{R}c'_q(h_t)}{r} \quad (5)$$

Again this is a modified version of Eq. 3, this time with an additional term in the numerator of the MUC. When the unit cost of extraction is a function of the head level, the MUC will tend to be higher to reflect the fact that consuming a unit of the resource in the present period increases the marginal extraction cost in every future period by reducing the head level.

1.3.3 Stock-dependent recharge and stock-dependent unit extraction cost

The most general case allows both the net recharge and unit extraction cost to vary with the aquifer head level. Applications have typically addressed the management of coastal aquifers, wherein leakage at the freshwater-saltwater interface comprises a more than nominal fraction of water flowing into or out of the aquifer in a given period (e.g. Krulce et al., 1997; Tsur and Zemel, 1995). For a coastal aquifer, leakage to the ocean is clearly a function of the head level; as the head level rises, the freshwater lens expands, thus creating more pressure along a larger surface area over which groundwater can discharge. When leakage and unit extraction cost are endogenous, the efficiency condition becomes

$$p_t = c_q(h_t) + \frac{\dot{p}_t - [R - L(h_t)]c'_q(h_t)}{r + L'(h_t)} \quad (6)$$

In this case, the MUC includes the forgone capital gains, as well as the long-run increase in unit extraction cost and decrease in leakage. Again, the efficiency condition sets the marginal benefit equal to the MOC, given by the extraction cost plus MUC.

but unconfined further inland. While the parameters governing net recharge and extraction will differ, the theoretical results of this section apply to all of these single cell cases.

1.3.4 The Pearce equation

In all of the above cases, the governing equation for optimal groundwater management can be stated as marginal benefit equals MOC, where MOC is comprised of the unit extraction cost and the term for MUC. These cases provide the definitions of MUC for the extended Hotelling equation, $p_t = c_t + MUC_t$. David Pearce has suggested the further generalization: $p_t = c_t + MUC_t + MEC_t$, where MEC stands for the marginal externality cost (in present value terms) associated with extraction of a resource. In the case of groundwater, such an externality cost can be generated when water quality is an issue. For example, drawing water from a confined aquifer and using it to irrigate crops overlying a relatively shallow unconfined aquifer can lower the water quality in the unconfined aquifer due to leaching of salts and pesticides.

Externalities may also emanate from the stock of groundwater. For example, stock-dependent submarine groundwater discharge from a coastal aquifer contributes (mostly positively) to the maintenance of brackish ecosystems in estuaries and bays (Duarte et al., 2010). In this case, the external stock-to-stock effects are taken into account in MUC, and there is no need for a separate MEC term.

1.3.5 Transition to the steady state

When demand is constant, i.e. the problem is autonomous, the approach path to the steady state is monotonic. For example, if the initial head level is above its optimal steady state level, the efficiency price rises, the extracted quantity of groundwater falls, and the head level declines smoothly over time. If demand is growing, however, i.e. the problem is non-autonomous, price and head paths can exhibit non-monotonicity (e.g. Krulce et al., 1997). In particular, future scarcity may warrant a period of accumulation followed by the more standard period of drawdown and eventual transition to the steady state. Clearly the concept of sustainable yield is inadequate in this case.

The optimal steady state may or may not entail supplementation of groundwater with desalination. When demand is stationary, desalination will not be used if the steady state head level corresponding to an internal solution is higher than that associated with the backstop steady state and the efficiency price corresponding to the internal solution is

lower than the backstop cost. A backstop steady state is more likely to be optimal, for example, if the extraction cost function is particularly convex.

When marginal extraction cost is stock-dependent (whether net recharge is constant or endogenous), MUC is positive in the steady state, i.e. marginal extraction cost does not rise to the unit cost of desalination. From Eq. 6, it is clear that when the time derivative of price is equal to zero in the steady state, the MUC remains positive (Figure 2). This is in contrast to the optimal extraction of a nonrenewable resource, wherein extraction is ceased entirely in the steady state and the resource is substituted completely by the backstop alternative. For a renewable groundwater resource, extraction will always be positive and equal to net recharge in the steady state with the remaining quantity demanded met by desalination, which means that there is still an opportunity cost of extracting groundwater in any period of the steady state.

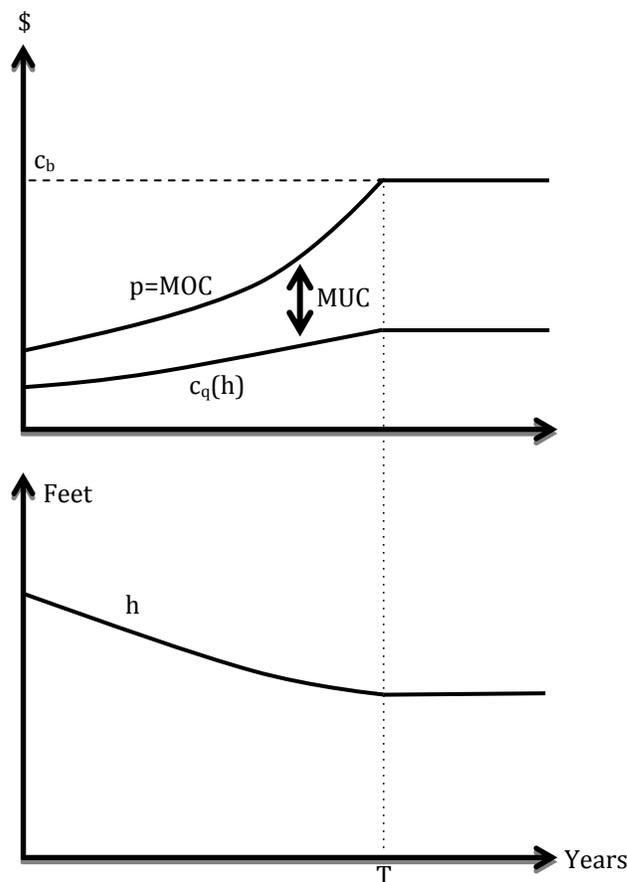


Figure 2. The efficiency price path for groundwater is equal to the sum of marginal extraction cost and MUC. Once the system reaches the steady state at time T , extraction is limited to recharge, the head level remains constant, and the MUC remains positive and equal to $c_b - c_q(h)$.

1.3.6 Corner solutions

Under certain circumstances, it has been shown that extinction of a natural resource can be economically optimal (e.g. Spence, 1973). The reasoning is relatively straightforward; if the natural resource, which can be viewed as a capital asset, does not provide a sufficient rate of return in comparison to alternative investments, profits can be increased by selling off the asset and reinvesting the proceeds. Given that aquifers are recharged by precipitation, complete exhaustion of a groundwater aquifer (i.e. perpetually zero extraction after a finite period) is possible in some situations. For example the amount of overdraft may be sufficiently large and sudden so as to induce land subsidence, the compaction of soil or rocks that occurs when groundwater is continuously withdrawn from certain aquifer systems. Said compaction can irreversibly reduce the size and number of open pore spaces that previously held water, possibly to the extent that water becomes economically unrecoverable. Saltwater intrusion of coastal aquifers can also be viewed as a catastrophic and irreversible event, after which the quantity of usable groundwater in storage is effectively zero. For an aquifer with demand and storage high relative to recharge and an alternative water source, economic exhaustion is not necessarily inefficient.

Alternatively, dynamic efficiency may require drawing the stock of groundwater down to a level just above the threshold, beyond which exhaustion is certain. For the case of potential saltwater intrusion, a minimum head level can be determined, below which further extraction compromises the quality of pumped water. Analogous to the optimal extinction scenario, the minimum head constraint is optimally binding in the steady state under certain conditions. For example, when the unit extraction cost function is relatively flat and/or the net recharge function is relatively convex, it is beneficial to draw the head down as low as possible. Eq. 6 indicates that the MUC is lower in such scenarios, and hence extraction and future head levels are optimally higher and lower respectively.

Another possible scenario is that the demand for water is less than recharge in the optimal steady state. If such a corner solution obtains, the aquifer is allowed to replenish to maximum capacity during the transitional period and remains full thereafter. This does not imply that extraction is zero in any period. Rather, the optimal quantity demanded is

always less than the natural net recharge. Replenishment may be desirable when demand is small/inelastic and/or the amount of recharge is very large.

1.4 Space, time, and the unifying shadow price

In section 1.3, it was shown that the optimal management of a single groundwater resource is always guided by the MOC or a system shadow price (SSP). It turns out that the concept extends to the case where consumers are spatially differentiated (Pitafi and Roumasset, 2009). Supposing that consumers are separated into a finite number of elevation categories and that consumption is positive for each category, localized shadow prices can be determined by solving for the system shadow price and appending the appropriate distribution cost. Geometrically this amounts to shifting each demand curve down by its respective unit distribution cost, aggregating the demands horizontally, and determining where the aggregate demand intersects the MOC of the resource. The resulting system shadow price can then be traced back to the individual shifted demand curves to determine the optimal quantities for each elevation category. The solution to the two-demand case is depicted in Figure 3. For expositional clarity, it is assumed in this example that the cost of distributing water is negligible for the first elevation category (lowlands) and equal to some positive number c_d for the second elevation category (uplands).

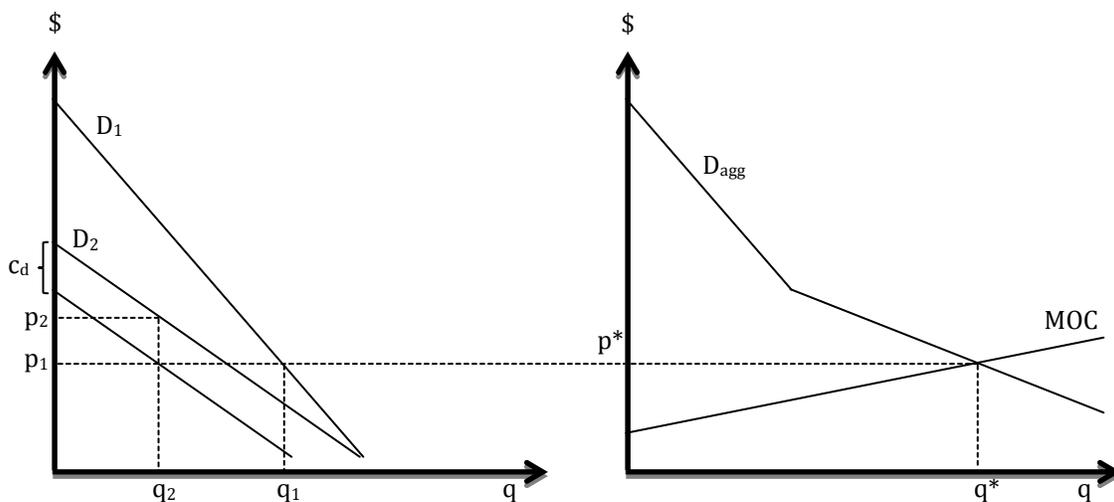


Figure 3. Local shadow prices (p_1 and p_2) are determined by solving for the system shadow price (p^*) via the aggregated demand curve (D_{agg}) and adjusting for the relevant distribution costs (c_d).

2 Optimal ordering of multiple water resources

The guiding principle of a single unifying system shadow price prevails even when management decisions involve multiple water resources. The remainder of section 2 describes how complex multiple-resource problems—managing more than one aquifer simultaneously, using recycled wastewater to supplement groundwater, conjunctively using surface and ground water, and designing an integrated management plan for watershed conservation and groundwater extraction—can be approached in a manner analogous to the single-aquifer resource allocation problem.

2.1 Managing multiple aquifers

While many theoretical groundwater management models consider a single aquifer serving a specific group of consumers, a groundwater utility or other resource manager must typically decide how to simultaneously manage multiple aquifers in real world situations. Even in the absence of direct physical linkages between the aquifers under consideration, managing the resources independently can result in missed opportunities for large potential welfare gains. For example, joint-optimization may entail zero extraction from one or more of the resources over a period of time, while independent-optimization requires monotonic drawdown of each aquifer. Welfare generated from the integrated model may be much larger because gains from recharge and lower extraction costs are captured by allowing one of the resources to replenish over some period prior to the steady state. On the island of O‘ahu in Hawai‘i, the welfare gain from jointly, rather than independently, managing the Honolulu and Pearl Harbor aquifers has been estimated at \$4.7 billion (Roumasset and Wada, 2012).

It is straightforward to modify the single resource maximization problem (Eq. 1) to include the management of additional resources. Assuming a single demand for water, the manager must choose the quantities of extraction from each aquifer ($i=1, \dots, n$) and desalination to maximize PV:

$$\max_{q_t^i, b_t} \int_0^{\infty} e^{-rt} \left\{ B(\sum_i q_t^i + b_t) - \sum_i [c_q^i(h_t^i)q_t^i] - c_b b_t \right\} dt \quad (7)$$

Subject to

$$\gamma^i \dot{h}_t^i = R^i - L^i(h_t^i) - q_t^i \quad \forall i = 1, \dots, n \quad (8)$$

The necessary conditions corresponding to Eq. 7 can be used to derive an efficiency condition analogous to Eqs. 3-6:

$$p_t = \min[MOC_t^1, \dots, MOC_t^n, c_b] \quad (9)$$

where MOC_t^i is the sum of marginal extraction and user cost for aquifer i in period t .

Optimality requires that extraction occurs in every period until the marginal benefit of water consumption is just equal to the lowest MOC of available water resources. If multiple resources are used simultaneously, it follows that their MOCs must be equal.

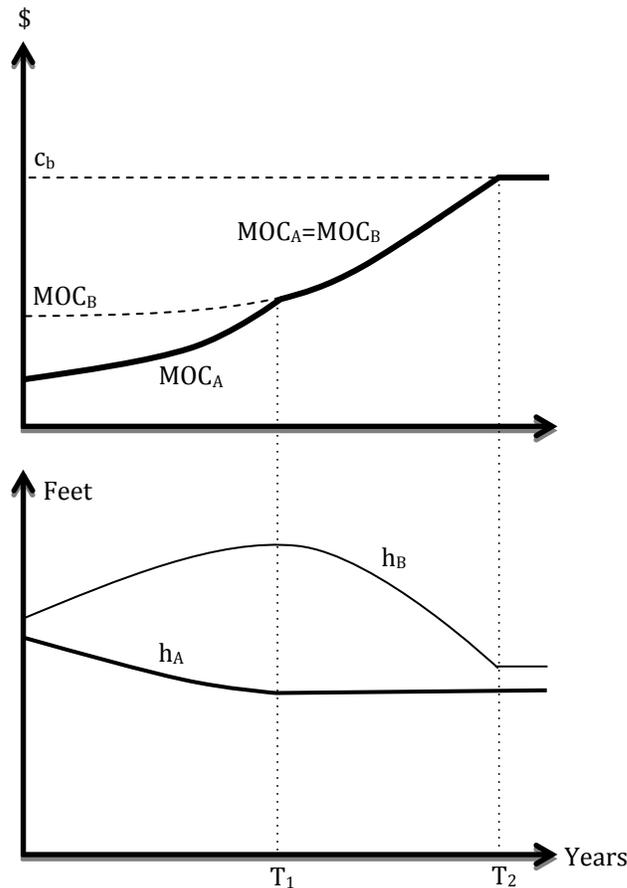


Figure 4. The SSP is determined by the minimum of $\{MOC_A, MOC_B, c_b\}$. Optimality entails drawing down aquifer A and replenishing aquifer B for $0 \leq t < T_1$, drawing down aquifer B and maintaining aquifer A for $T_1 \leq t < T_2$, and maintaining both aquifers at their respective optimal steady state levels (i.e. extracting only recharge) for $t \geq T_2$.

The optimal or governing MOC can be interpreted, like in the single-aquifer case, as a system shadow price. Whether any particular resource i or the backstop is used in a given period depends on whether its MOC is greater than or equal to the SSP. Consequently,

extraction moratoriums for one or more resources can be optimal over periods prior to or throughout the steady state. Figure 4 illustrates a two-aquifer example for which zero extraction is optimal for one of the aquifers over a finite period in transition to the steady state. The resulting head trajectory is therefore non-monotonic.

2.2 Optimal wastewater recycling and groundwater management

In response to the continual growth of water demand across the globe, many demand- and supply-side management strategies are currently in development, including improved pricing structures, quantity restrictions, expansion of reservoir capacity, desalination, and wastewater recycling. As discussed in section 1.3.5, demand growth necessitates the eventual implementation of a backstop resource such as desalination, given the finite volume of groundwater recharge. Recycled wastewater can serve as a supplemental resource or sector-specific backstop when different demand sectors require different qualities of water.

Even in the simplest case of two sectors (e.g. household, agriculture) and two resources (groundwater, recycled water), there are several ways to specify recycling costs. A general specification allows for increasing unit recycling-costs to implicitly incorporate infrastructure expansion costs for spatially differentiated users. Since households cannot use recycled wastewater for drinking, a separate network of pipes is necessary to transport the lower quality water for agricultural or industrial purposes. Such a specification applies especially when planning is likely to involve a large centralized treatment facility. In other situations, e.g. when potential recycled water users are located in spatially differentiated clusters, it may make sense to build smaller identical satellite facilities for each of the clusters. Since the size of the requisite infrastructure at each cluster is predetermined, capital outlays can be amortized and included as part of a constant marginal treatment cost. For either cost scenario, it can be shown that the least-cost principle (Eq. 9) extends to multiple sectors (Roumasset and Wada, 2011):

$$p_t^j = \min \left[MOC_t^{Gj}, MOC_t^{Rj}, c_b \right] \quad (10)$$

In other words, the price of water for use in sector j is determined by the lowest of either the MOC of groundwater, the MOC of recycled water, or the unit cost of desalination. If recycled water cannot be used for a particular sector j (e.g. the household sector) then

price is determined by either the marginal opportunity cost of groundwater or the marginal desalination cost. The general least-cost rule applies within each sector, whether the MOC of recycled water is constant or rising.

If a resource such as groundwater is ever used simultaneously in more than one sector, it must be that marginal benefits of water consumption are equalized and determined by the optimal MOC of groundwater. Thus a system shadow price arises that governs resource use across sectors. The SSP still serves to guide water management within sectors, however. Whenever the MOC of a resource—in this case groundwater or recycled wastewater—within a particular sector exceeds the SSP, the resource should not be used for that purpose. Consequently, immediate implementation of wastewater recycling is often not PV-maximizing because relatively abundant groundwater is available at a lower optimal shadow price in the near term.

2.3 Integrated groundwater and watershed management

Watershed conservation is often mentioned as a supply-side groundwater management instrument, but has only recently been integrated into the resource economics of groundwater. Land cover in aquifer recharge zones largely affects the amount of precipitation that ultimately infiltrates below the ground surface. Thus, sizeable potential welfare gains generated from joint optimization of groundwater aquifers and their recharging watersheds often go to waste under current water management schemes. A simplistic dynamic framework is used here to illustrate management principles that are capable of capturing those potential gains.

The objective of the optimization problem is still to maximize the present value of groundwater, but Eq. 1 must be modified to incorporate the cost of watershed conservation measures (c_I):

$$\max_{q_t, b_t, I_t} \int_0^{\infty} e^{-rt} [B(q_t + b_t) - c_q(h_t)q_t - c_b b_t - c_I I_t] dt \quad (11)$$

and the equation of motion for the aquifer head level must account for the fact that investment in watershed conservation (I) affects recharge via its contribution to conservation capital (N):

$$\dot{h}_t = R(N_t) - L(h_t) - q_t \quad (12)$$

Although conservation capital is modeled as a single stock, there are in reality a variety of instruments capable of enhancing groundwater recharge, e.g. fencing for feral animals, reforestation, and manmade structures such as settlement ponds. For the purpose of illustrating the joint optimization problem, it is sufficient to assume a generic capital stock, such that recharge is an increasing and concave function of N .³ This presumes that investment expenditures are allocated optimally amongst available instruments. The first units of capital are most effective at enhancing recharge, and the marginal contribution of N tapers off. Assuming no natural growth of the capital stock but an exogenous rate of depreciation δ (e.g. a fence), conservation capital changes over time according to:

$$\dot{N}_t = I_t - \delta N_t \quad (13)$$

Given proper boundary conditions, Eq. 11-13 can be solved with optimal control, and the necessary conditions can be used to derive an efficiency price condition identical to Eq. 6, albeit with the constant recharge term replaced by $R(N_t)$. Since the conservation capital stock enters the MUC of groundwater through the recharge function, management of the aquifer and watershed independently would clearly not yield the same results.

An analogous efficiency condition can be derived for the conservation of natural capital (Roumasset and Wada, 2010). At the margin, the resource manager should be indifferent between conserving water via watershed investment and demand-side conservation:

$$\frac{c_t(r + \delta)}{R'(N_t)} = \lambda_t \quad (14)$$

The right hand side of Eq. 14, λ_t , is the costate variable corresponding to the groundwater stock, i.e. the multiplier for the head equation (Eq. 12). It is also the marginal user cost of groundwater, or the marginal future benefits obtained from *not* consuming a unit of groundwater in the current period. The left hand side of Eq. 14 can be interpreted as a supply curve for recharge. Given that the marginal productivity of capital in recharge is diminishing, the marginal cost of producing an extra unit of groundwater recharge is upward sloping. If the marginal cost of recharge were less than the MUC of groundwater, welfare could be increased by investing more in conservation

³ One could also specify a direct relationship between recharge and investment expenditures if parameterization of such a recharge function is feasible for the application of interest.

because the value of the gained recharge would more than offset the investment costs. Thus, the "system shadow price" of groundwater, λ_t , governs both optimal groundwater extraction and watershed investment decisions.

In many cases, the optimal management program can be implemented with a decentralized system of ecosystem (recharge) payments to private watershed owners, financed by the efficiency price of groundwater. Note, however, the appropriate price for the ecosystem service cannot be accurately estimated independently of the entire water and watershed management problem.

In other cases, where the size of the conservation project is given exogenously, principles can be developed and applied to determine appropriate project finance. Volumetric "conservation surcharges" on water consumption have been suggested but these would induce inefficient use by counteracting the moderating effect of watershed conservation on the efficiency price of groundwater. A dynamic lump-sum tax, instead, can finance the requisite investment without distorting incentives. One possibility is to tax each generation in proportion to the groundwater benefits received. Given that investment costs are concentrated in early periods and benefits in later periods, bond financing may be required to ensure a balanced intergenerational budget.

2.4 Conjunctive use of surface and ground water

In many locations, the most commonly available alternative to groundwater is surface water. Where surface water is particularly abundant, groundwater is typically treated as a supplemental source. And given the highly variable nature of surface flows, groundwater serves as buffer to help smooth unexpected fluctuations (Tsur and Graham-Tomasi, 1991). Surface water, like any other groundwater alternative, is characterized by a shadow price reflecting scarcity. And the efficiency conditions for optimal conjunctive use equalize the discounted marginal products and shadow prices of the resources across space and time (Noel and Howitt, 1982; Knapp and Olson, 1995; Chakravorty and Umetsu, 2003). The idea can be illustrated with a simple model of an irrigation project (Pongkijvorasin and Roumasset, 2007).

Suppose that surface water is supplied from a canal-headworks and that farms are located along the canal. Farmers can irrigate crops using diverted canal water or by

pumping groundwater on their farm. Canal conveyance losses are increasing with distance from the headworks, although a fraction of the loss percolates to the groundwater aquifer. The marginal cost of groundwater extraction is decreasing in head level, and precipitation contributes to aquifer recharge. The objective is to maximize the PV net benefit of aggregate farm production, taking into account the costs of surface water transmission and groundwater pumping. The efficiency price of surface water includes the full cost of transmission, less credits for canal return flow and percolation to the aquifer, and is hence increasing with distance. The efficiency price of groundwater is identical to Eq. 6, albeit with two additional terms for canal return flow and groundwater recharge from on-farm use. These conditions define spatial conditions whereby surface water is optimally used up to some distance from the headworks, and groundwater is used at greater distances. The scarcity value of water increases with distance from the headworks and is uniform over space outside the area. The equality of groundwater and surface water scarcity prices determines the critical distance where farms start using groundwater. This is the least-MOC condition described by Eq. 9.

The marginal opportunity cost of each resource varies not only across space, but also over time. As the aquifer head level declines and groundwater becomes scarcer, the efficiency price of groundwater increases and some groundwater farmers will switch to surface water, i.e. the surface water irrigation area expands over time. There are many conceivable orderings of optimal resource use over time, depending on how the efficiency prices evolve. Figure 5 illustrates the case where a farmer switches from groundwater to surface water, then back again to groundwater along the optimal temporal path.

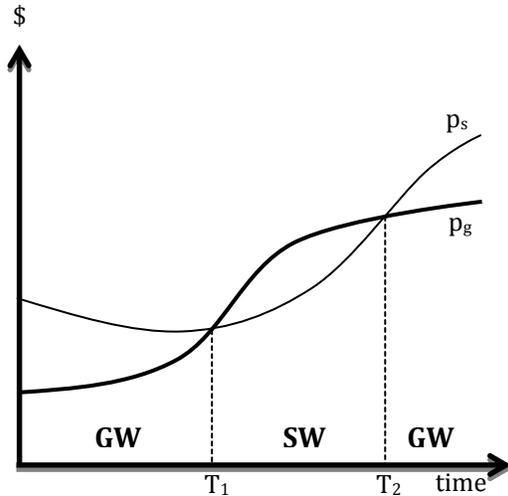


Figure 5. Reswitching may be optimal for the conjunctive use of surface and ground water. A farm might initially use groundwater (GW) for $0 \leq t < T_1$, then switch to surface water (SW) as scarcity increases and $p_s < p_g$. When scarcity rent falls as the surface water irrigation area shifts, the farm switches back to groundwater at T_2 .

Even when water transmission costs are small enough that potential spatial inefficiencies are negligible, managing groundwater and surface water conjunctively is welfare enhancing. Widening the resource problem to a resource system instead of managing each resource independently lowers the scarcity value of groundwater. Figure 6 illustrates this idea with a simple example (Roumasset and Smith, 2001; Smith and Roumasset, 2004). Supposing that the supply of surface water in a region is fixed at some quantity S_s , the supply curve for water can be constructed by horizontally adding S_s to the MOC (quasi-supply) curve for groundwater. The intersection of the aggregate supply curve and demand curve determines the optimal quantities and the MB of water consumption (p^*). If groundwater is optimized independently, the scarcity value, and hence, the MOC at the optimum (p') is higher. As demand for water grows over time, groundwater scarcity increases, but less so than if the demand shift occurred for surface water or groundwater independently; the price of surface water would have to be increased by the total amount of the demand shift if the resources were optimized independently. In other words, the optimal conjunctive price rises, albeit more slowly. Even when abstracting from uncertainty, surface water acts as a buffer by ameliorating the scarcity of groundwater due to the increase in demand.

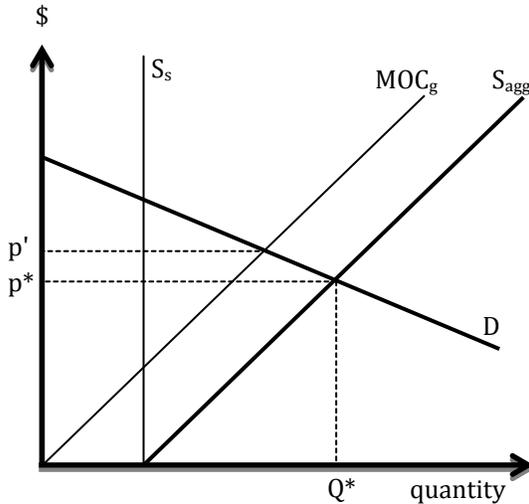


Figure 6. Widening the management problem to include alternative resources lowers the scarcity value of groundwater. Supposing that the supply of surface water (S_s) is fixed, the aggregate supply of water (S_{agg}) can be constructed by horizontally adding S_s to the MOC or quasi-supply curve of groundwater. The efficiency price (p^*) is determined where $S_{agg}=D$. In the absence of surface water, the price would be higher (p') to reflect the higher scarcity value of groundwater.

2.5 Water-energy nexus

Groundwater economics models often assume the existence of an abundant substitute such as desalination, which can be obtained at a constant unit price. Yet, a large proportion of the cost comes from the energy required to filter or thermally-treat the water, and the price of energy tends to fluctuate over time. Thus, the optimal long-run groundwater management strategy should actually depend on how energy prices and energy-generating technology evolve.

Consider the example where two types of desalination are available: electricity-based (E-desal) and solar-based (S-desal). As fossil fuel and coal becomes scarcer, the price of electricity generated by the public utility is expected to rise, thus increasing the scarcity value of groundwater. At the same time, technological innovations in solar-based desalination will have the opposite effect. The optimal management strategy is likely to involve several stages of water use. In the case that groundwater is relatively abundant, and the cost of S-desal (c_S) exceeds the cost of E-desal (c_E) in the current period, groundwater is used exclusively in the first stage. Eventually the MOC of groundwater rises to c_E , provided that its rate of increase is relatively larger. In the second stage, groundwater is supplemented by E-desal as the efficiency price continues to rise. If

advances in technology continue to reduce c_S , then the third stage is characterized by a switch from E-desal to S-desal. Two scenarios are feasible in the long-run: (i) technological advances do not stagnate, and S-desal is eventually used to satisfy all of the optimal demanded quantity, meaning the aquifer is allowed to replenish completely, and (ii) technological advances are limited by a lower-bound on desalination cost, at which point steady-state extraction from the aquifer is limited to recharge, and any additional quantity demanded is met by S-desal. The switch-points T_1 , T_2 , and T_3 (to E-desal, S-desal, and the steady-state) are determined endogenously by the maximization procedure. Figure 7 illustrates the optimal paths for the efficiency price (given by MOC) and the head level for the case where the system eventually reaches a steady state with positive groundwater extraction.

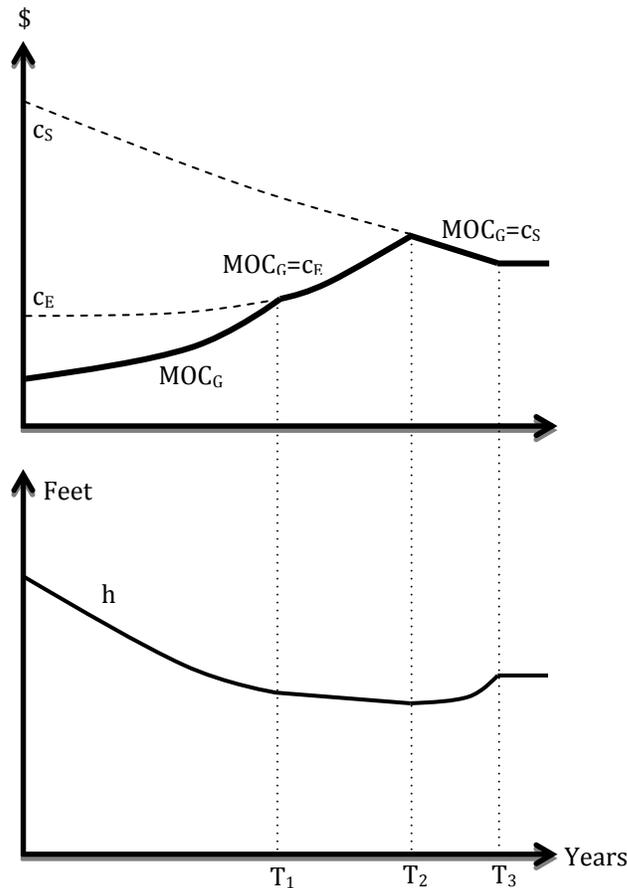


Figure 7. Incorporating energy prices and technology in a groundwater management framework alters the optimal time paths. For periods $0 \leq t < T_1$, groundwater is used exclusively. It is then supplemented by E-desal for $T_1 \leq t < T_2$. Eventually, technological innovation makes S-desal a desirable alternative and E-desal is replaced by S-

desal for $T_2 \leq T_3$, thus allowing for the aquifer to partially replenish. The system eventually reaches a steady state when technology stagnates at T_3 .

2.6 Corner solutions

As in the single aquifer case, optimal management of multiple resources simultaneously may entail temporary or permanent extraction moratoriums over a period of time. Regardless of the type of resource serving as an alternative to groundwater, optimal use is always driven by a system shadow price, and that optimal shadow price is determined by the resource with the lowest MOC. With the exception of resources assumed to have a constant unit cost (e.g. desalination, recycled wastewater), however, the MOCs are not identifiable *ex ante*. Instead, they are determined in the process of solving the dynamic optimization problem. Zero-extraction solutions are most likely to be optimal when one of the groundwater resources is either very scarce or very abundant (e.g. demand is met by only one groundwater source for a finite period).

Another type of corner solution can occur in terms of management boundaries. In the examples discussed in section 2.6, the management problem is treated as if joint management is already known to be welfare maximizing. Yet, this may not always be the case if the cost of shipping the resource is prohibitive. Specifically, if the cost of distributing a resource to a particular consumption district is greater than the price differential between that resource and a local alternative, then shipping the resource is not optimal and management should be undertaken according to separate shadow prices in separate consumption districts. However, given that the resource scarcity values evolve according to the extended Hotelling condition (assuming that extraction follows optimal independent management), the size of the optimal management network can change endogenously over time (Roumasset et al., 1988). A network, which is not connected at the outset, can become connected if the price differential gets large enough.

3 Institutions and regulatory issues

3.1 Open access and the Gisser-Sanchez effect

The previous sections described optimal groundwater management. In many parts of the world, especially in agriculture, however, groundwater is characterized as a

common-pool resource, i.e. without appropriate governance, it can be accessed by multiple users who may ignore the social costs of resource depletion. In the limit, it is individually rational for competitive users to deplete the resource until the marginal benefit equals the unit extraction cost, i.e. each user ignores the effect of individual extraction on future value. This is the *open-access* equilibrium.

In 1980, Gisser and Sanchez published a surprising result: Under certain circumstances, the present value generated by the competitive solution and that generated by the optimal control solution for groundwater are almost identical (Gisser and Sanchez, 1980). In other words, the potential welfare gain for groundwater management is trivial. This result has come to be known as the Gisser-Sanchez effect (GSE). The basic groundwater economics set up included a stationary linear inverse demand function, head dependent pumping costs, constant recharge, quantity-dependent linear irrigation return flow, and the unconfined aquifer of interest was modeled as a simple rectangular bathtub.

Under similar circumstances, other empirical studies have found that the welfare gain of optimal control relative to the competitive solution ranges from 0.28% (Nieswiadomy, 1985) to 4% (Provencher and Burt, 1994). However, when one or more of the simplifying assumptions is relaxed, the GSE begins to diminish. The PV difference may not be trivial if extraction costs are non-linear (Worthington et al., 1985). The more convex is the extraction cost function, the larger is the inefficiency created by myopic consumption decisions that do not account for the MUC of groundwater. In other words, if the marginal extraction cost rises rapidly as the head level declines, the cost of consumption today in terms of higher future extraction costs is larger.

The GSE also tends to be small when demand is non-stationary. Studies have show that the divergence in welfare between optimal control and competitive pumping can be as high as 17% (Brill and Burness, 1994). As discussed in section 1.3.5, growing demand increases the scarcity value of water, and the dynamically efficient solution may entail a non-monotonic approach path of the head level in transition to the steady state. Restricting extraction to the point where the aquifer is allowed to replenish in earlier periods suggests that large welfare gains are expected in future periods when demand is higher. Thus, consuming at the competitive level is even more inefficient if demand growth is positive.

Other parameters such as the discount rate and the initial head level can also affect the magnitude of the GSE. A lower discount rate increases the benefits of management by weighting future consumption more heavily in the present value calculation. A higher discount rate, on the other hand, favors present consumption and pushes the optimal solution toward the competitive outcome. Severely depleted aquifers also tend to have high potential welfare gains from optimal management. If the scarcity value of water is large from the outset, competitive consumption is highly inefficient because it ignores the sizeable MUC. Moreover, in the case of a coastal aquifer where well salinization is a concern, there is added risk of a high and potentially irreversible cost.

3.2 Potential gains from management: Hawai'i as a case study

In Hawai'i, the distribution of groundwater is carried out by a public utility, and the price is based on cost recovery. Failing to account for the marginal user cost in setting the price amounts to institutionalizing open access and encourages excessive groundwater depletion. Accordingly, potential NPV gains from optimal management relative to the status quo can be interpreted as a measure of the Gisser-Sanchez effect discussed in section 3.1.

Pitafi and Roumasset (2009) calculate a potential net present value gain of \$407 million or 6.6% of the welfare under status quo for the Honolulu aquifer on the island of O'ahu. Simulation results under alternative parameter values indicate that welfare gains from optimal management increase substantially for higher demand growth rates, lower discount rates, and lower elasticities of demand. The convexity of the cost function and the cost of the backstop also affect the NPV, although the effects are relatively small.

The GSE is found to diminish even further when joint management of more than one aquifer is considered. Roumasset and Wada (2012) estimate a NPV gain of \$4.7 billion or 65% of the combined PV from independent management of the Honolulu and Pearl Harbor aquifers on O'ahu. The gain is particularly large because the Honolulu aquifer is depleted very rapidly under independent management, whereas gains from recharge and lower future extraction costs are captured by allowing the aquifer to replenish for the first 40 years under optimal joint management. Generally, the gains

from optimal management are likely to be larger when more groundwater alternatives are available because there are more opportunities to reduce scarcity.

When groundwater alternatives are available, however, accounting for the MUC of groundwater alone does not necessarily ensure NPV maximization. All available resources should be managed jointly, such that the timing of implementation and the quantities of each in the periods that follow are determined endogenously by the integrated framework. For example, applying a two-sector model to the Pearl Harbor aquifer, Roumasset and Wada (2011) show that when wastewater recycling is available as a groundwater alternative, immediate implementation of recycling generates 3.7% less welfare than optimizing groundwater alone (i.e. optimizing as if water recycling is not an available alternative). Optimally managing the resources jointly, on the other hand, generates a NPV gain of \$70 million or 0.6% relative to independent optimization of groundwater.

3.3 Governance and institutions

As Nobel Laureate Elinor Ostrom and others have shown, because common pool resources face overuse by multiple parties with unlimited extraction rights, additional governance may be warranted provided that the gains of governance exceed the costs (Ostrom, 1990). The optimal solutions detailed in sections 1 and 2, i.e. the *first best* (FB) management solutions, may be unattainable when enforcement and information costs are considered. Instead, the FB solution serves as a benchmark to which different forms of governance should be compared. Which of several institutions (e.g. privatization, centralized ownership, user associations) is optimal at a given point in time depends on the relative net benefits generated from each option, including the governance costs involved in establishing the institution and the PV difference between the FB optimal and the candidate for the *second best* institutional arrangement. Inasmuch as the SB solution is not known a priori, the evolution of institutions is not generalizable. For example, if the demand for water starts off relatively small and the aquifer is fairly large, i.e. groundwater is very abundant, the gains from management are likely to be small and open access extraction might be the SB optimal solution (NB₀ in Figure 7). As demand grows over time and water becomes scarcer, however, a user association, government regulations, and/or water markets may become SB optimal.

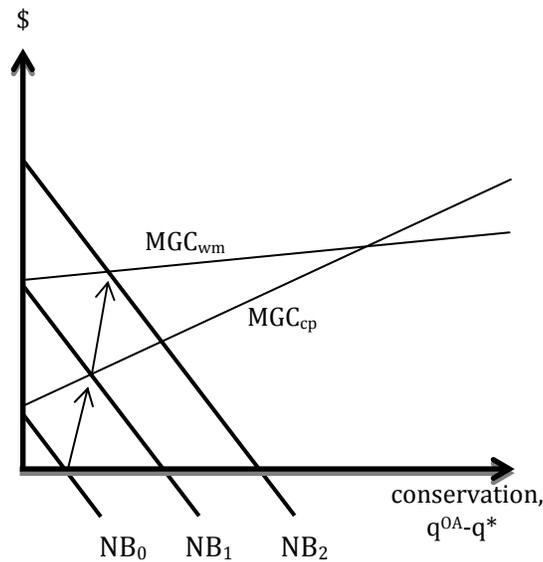


Figure 8. Institutions evolve endogenously. The net benefit of water (*NB*), defined as the difference between *MUC* and the *MB* of consumption, shifts outward over time as water scarcity increases. Marginal governance costs are increasing functions of conservation. In period 0, the fixed cost of governance exceeds the NB_0 curve for all levels of consumption, i.e. open access (*OA*) is optimal. In period 1, the marginal governance cost curve (*MGC*) is less than NB_1 up to some positive quantity, meaning a common property (*cp*) arrangement like a user association becomes optimal. In period 2, demand increases enough to warrant a transition to efficient water markets (*wm*).

While resource allocation under open access and complete privatization is straightforward, communal management requires a mechanism for allocating shares amongst members. Although equalizing shares lowers organization and contracting costs and would likely be an acceptable allocation for homogenous groundwater users, a different mechanism is necessary when users are heterogeneous. The concept of *unitization* can accommodate heterogeneity by allocating shares of the aggregate optimal quantity of extraction in proportion to well capacity (Dixit, 2004). This, however, abstracts from the longer-run problem of regulating the size of the well.

Although carefully-designed institutions that facilitate water-trading between high and lower-value users can potentially increase economic welfare, omitting provisions for efficient groundwater extraction can actually lower welfare, by increasing the incentive to substitute groundwater for surface water and exacerbating groundwater depletion (Knapp

et al., 1995). Thus the optimal evolution of institutions will depend on the relative scarcity of all available water resources.

So far, the discussion in this section has focused on the evolution of institutions without considering the corresponding resource extraction patterns. Yet, different institutions drive different extraction behavior. Under open access, myopic users extract groundwater until the cost of extraction rises to the price. If instead the resource is centrally regulated, the increasing efficiency price of water will tend to induce more demand-side conservation. In some cases, it may be optimal to draw the aquifer temporarily below its optimal steady state level to postpone the fixed cost of governance. In that sense, there may be cases of "optimal overdraft." (Roumasset and Tarui, 2010)

4 Additional dimensions and the frontier

4.1 Spatial heterogeneity of the resource

When groundwater consumers are located at different elevations, the optimal allocation of water over space can be achieved by charging users an amount equal to the system shadow price of water, adjusted for the actual cost of distributing water to that location (section 1.4). Similarly, optimizing the timing and quantities of recycled wastewater over space requires integrating infrastructure expansion and distribution costs into the objective function and charging users according to their distance from the treatment plant (section 2.2). And an analogous story can be told for the conjunctive use of surface and ground water for agriculture; spatial optimization requires surface water to be sent away from the headworks only up until the point where its MOC (inclusive of conveyance costs) is equal to the MOC of groundwater in any given period (section 2.4). While examples of spatial optimization on the demand-side abound, less attention has been paid to spatial heterogeneity on the supply side.

In the economics literature, groundwater management frameworks are typically built upon simple *single-cell* aquifer models, which use a single variable such as the head level to completely characterize the groundwater resource stock. Such a model implies that the pumping lift is constant over space, i.e. equal at every point in the aquifer, and that well location does not matter, i.e. a unit of water pumped from the aquifer has the

same marginal impact regardless of where it is extracted. For relatively small aquifers with surface areas of a few hundred square miles or less, single-cell models reasonably approximate the hydrologic processes and hence remain useful for long-run water management planning (Brozović et al., 2006; Brozović et al., 2010). However, single-cell models fail to capture localized three-dimensional pumping effects, which can be important if spatial groundwater-pumping externalities are a concern.

Pumping groundwater to the surface generates an effect known as a cone of depression, wherein the water table within a certain radius is pulled down toward the well. As a result, nearby users face an increase in lift and consequently extraction costs. Thus, the pumping externality varies over space and depends on the relative locations of the wells. While well-specific first-best regulation would not likely be feasible in practice, the second-best policy would depend on the relative sizes of two effects. A uniform quota would ensure uniform pumping over space, but unequal marginal productivity of water at each well. Alternatively, a uniform tax would maintain equi-marginality of water productivity over space at the expense of variable pumping rates. In general, which instrument generates a larger present value would depend on the location of the pumping wells in relation to each other and the hydrologic properties of the groundwater resource.

Recent work in this area (Brozović et al., 2006; Brozović et al., 2010) has integrated spatial dynamic flow equations into the equation of motion for an aquifer (Eq. 2 in the basic non-spatial case). Although this increases the complexity of the optimization procedure and has more stringent data requirements (e.g. the spatial locations of all wells in the aquifer), welfare gains can be potentially large under certain circumstances. For example, if wells are clustered in a relatively small area over an aquifer with a very large surface area, gains from optimal spatial pumping management are likely to be substantial. In that case, a single-cell model may largely underestimate the pumping externality. For example, in the Brozović et al. study (2010), the estimated marginal impact of pumping (i.e. the ratio of the discounted sum of marginal steady-state externalities for the spatially-explicit and single-cell model) for the Crow Creek Valley aquifer in Montana (60,000 acres) is 8% (2%) greater at the wellhead (0.5 miles from the wellhead) than with a single-cell model. Whereas for a larger aquifer such as the Roswell

Basin in New Mexico (790,000 acres), the marginal effects could be upwards of 500% and 200% greater at the wellhead and 0.5 mile distance respectively.

4.2 Water quality

In addition to space and time, water quality is another dimension that should be considered in certain management scenarios. While the wastewater-recycling model discussed in section 2.2 assumed either zero or perfect substitutability of high and low quality water for each sector, the profitability or marginal benefit of water use may, in practice, vary continuously with water quality. For example, surface water flows and restricted drainage can salinize an aquifer used for agricultural irrigation and consequently reduce crop yields. Mathematically, quality can be integrated into the basic dynamic optimization framework by modifying the objective function:

$$\max_{q_t, b_t} \int_0^{\infty} [B(q_t + b_t; \phi_t) - c_q(h_t) - c_b b_t] dt \quad (15)$$

and adding an equation of motion for the quality variable (ϕ):

$$\dot{\phi}_t = g(\alpha_t; x_t) \quad (16)$$

where α and x are vectors of parameters and endogenous variables respectively that affect water quality, e.g. concentration of a particular pollutant. From the solution to Eq. 15, it can be shown that the optimal steady-state stock is higher relative to the case where quality is ignored. Intuitively further drawdown is not attractive because the marginal productivity of water is lower as quality deteriorates (Roseta-Palma, 2002).

If water quality is affected by a production input, i.e. a member of the vector x enters the benefit function in Eq. 15, then optimality requires that the marginal benefit of the polluting input in terms of production value is equal to the marginal cost in terms of reduced groundwater quality. Unless the act of pumping reduces the groundwater quality directly, optimal extraction of groundwater is still governed by the basic efficiency price condition (Eq. 6). If q is an element in the vector x , then there will be an additional positive term in the MUC of groundwater reflecting the PV implications of reducing quality in all future periods by pumping in the current period. Another possibility is that the volume of available groundwater (h) affects quality through a stock dilution effect. In that case, the MUC includes the marginal contribution of the stock level to quality, i.e.

$\partial g / \partial h_t > 0$. The term increases the marginal user cost because reducing the head level by extracting a unit today reduces the positive dilution effect in future periods.

In empirical applications, the groundwater system can evolve slowly in the quality dimension and relatively quickly in the quantity dimension (Knapp and Baerenklau, 2006). If a high-quality resource is relatively abundant at the start of the management period, the dynamics of the problem are driven initially by water extraction. Extraction rates exceed recharge and the resulting decline in the water table puts downward pressure on the water quality. Assuming a stationary demand for water, over time, extraction costs rise and water quality declines until recharge exceeds the pumped volume. The head level then begins to rise and water quality continues to decline, assuming that the dilution effect is relatively small. The aquifer eventually fills up to its maximum level and continued irrigation from groundwater (or other sources) drives the quality down to an unusable level, i.e. the economic value of the aquifer is exhausted.

Sudden reductions in water quality can also be treated as catastrophic events. Such an event may correspond, for example to irreversible saltwater intrusion of a groundwater resource when the head level falls below some unknown threshold. If the event occurs, the resource can no longer be used, i.e. the aquifer is effectively exhausted. Given a positive rate of natural recharge, the question is whether to extract more than recharge, thus advancing the probability of irreversible salinization, or to extract less than recharge to avoid that risk. When the threshold is known with certainty, the groundwater stock converges to a unique steady state regardless of the initial conditions. If the threshold is unknown, however, the optimal steady state depends on the initial head level (Tsur and Zemel, 1995; Tsur and Zemel, 2004). Intuitively, the expected PV-maximization procedure weighs the benefits of a conservative extraction trajectory in perpetuity against the benefits of higher water consumption from the outset with the possibility of zero extraction after a finite period of time.

4.3 A systems approach

Generally, optimal management of multiple water resources is driven by a system shadow price, and augmenting groundwater extraction with any number of alternatives reduces scarcity. Consequently, a variety of tools have been implemented in recent years

to enhance or supplement existing groundwater resources. In Orange County (California), for example, recycled wastewater is currently being injected deep underground both to augment the coastal aquifer resource and to create a buffer against saltwater intrusion. However, policies driven by the desire to sustain groundwater resources at their current level often fail to account for the resulting temporal patterns of associated benefits and costs. Optimal management, on the other hand, generates a larger present value while typically sustaining groundwater resources in the long run. In that sense, managing for sustainability is unlikely to achieve optimality, but managing optimally typically assures sustainability. Although optimizing across multiple dimensions (e.g. space and time) necessarily increases modeling and computational requirements, continual advances in algorithm design and data processing power are allowing researchers to include more details of the entire water system.

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