University of Hawai`i at Mānoa
Department of Economics
Working Paper Series

Saunders Hall 542, 2424 Maile Way,
Honolulu, HI 96822
Phone: (808) 956 -8496
www.economics.hawaii.edu

Working Paper No. 14-14

Integrated Groundwater Resource Management

By

James Roumasset
Christopher Wada

May 2014

Integrated Groundwater Resource Management

James Roumasset
Department of Economics
University of Hawai‘i at Manoa
& University of Hawai’i Economic Research Organization
jimr@hawaii.edu

Christopher Wada
University of Hawai’i Economic Research Organization
cawada@hawaii.edu

Abstract

General principles of groundwater management for a single aquifer are extended to the management of multiple water resources, including additional aquifers, recycled wastewater, and desalinated seawater. Optimal groundwater extraction can be incentivized by pricing according to the *Pearce equation* for renewable resources, although the standard version of the equation must be modified in certain situations, e.g. to accommodate corner solutions or governance costs. Groundwater management and pricing must be coordinated with the management of watershed and related resources lest the benefits of conservation are squandered by wasting the water saved. Joint optimization also provides the basis for correctly pricing ecosystem services such as groundwater recharge. From the models and examples discussed, one can conclude that a systems approach is necessary, and ad hoc rules-of-thumb such as maximum-sustainable-yield are welfare reducing. Inasmuch as actual groundwater management may be far from efficient, the Gisser-Sanchez effect notwithstanding, we discuss the problem of optimal resource governance.

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

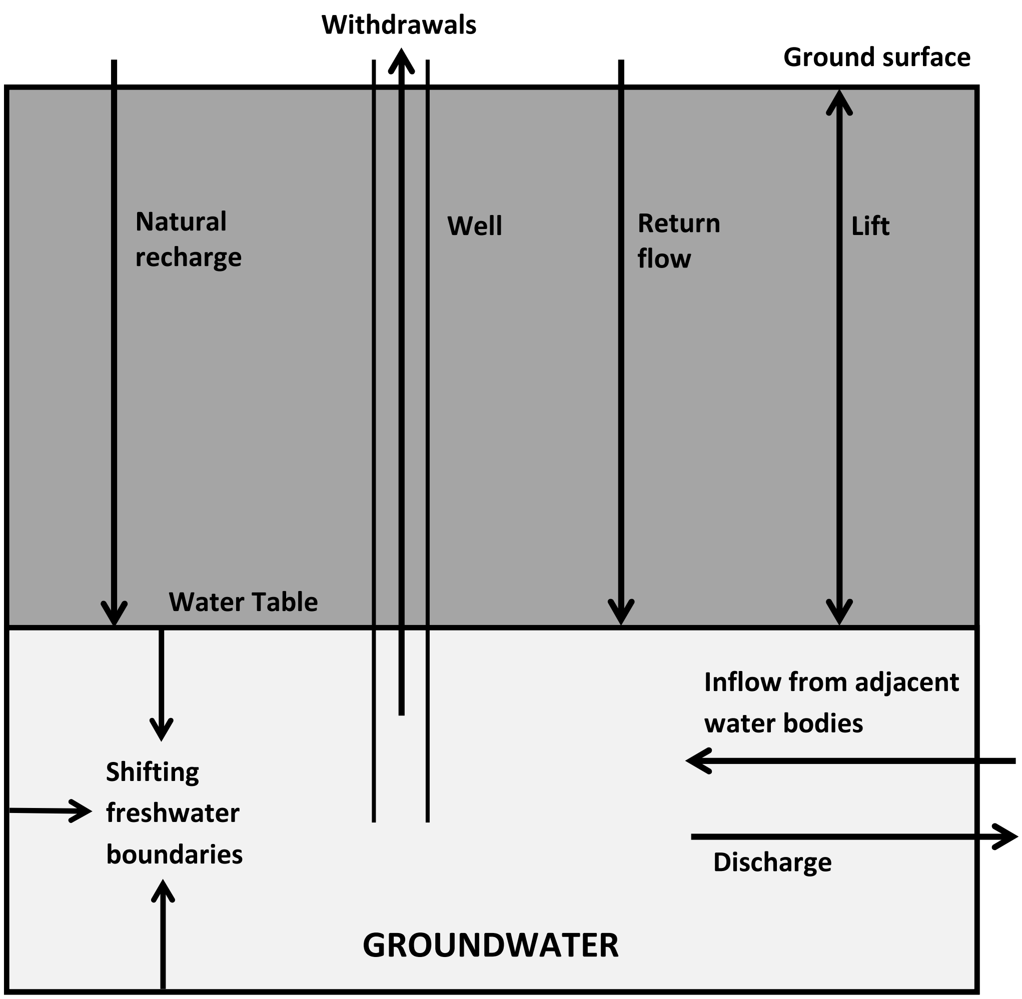
JEL codes: Q20, Q25

1. GROUNDWATER MANAGEMENT: FROM SUSTAINABLE YIELD TO DYNAMIC OPTIMIZATION

In many parts of the world, irrigation and other freshwater uses are largely dependent on groundwater. Figure 1 portrays the cross-section of a typical *aquifer*, or subsurface layer of water-bearing, porous materials. Over time, an aquifer is recharged naturally from precipitation that infiltrates below ground. It can also be recharged via irrigation return flow, due either to canal leakage or excess applied water not consumed by crops. The cost of withdrawing water is a direct function of lift, which is the distance between the water table and the surface. In some cases, water can also naturally discharge from the aquifer to adjacent water bodies, or in the case of a coastal aquifer, into the ocean. One aquifer can also be recharged from an adjacent (and more elevated) aquifer. Thus groundwater satisfies both characteristics of the canonical renewable resource: left unharvested, the stock grows, and the rate of growth depends on the stock. The management problem is to determine how much groundwater to withdraw over time.

Analogous to biological recommendations for fisheries and forests, a common recommendation by hydrologists is to limit extraction of a renewable resource (e.g., groundwater) to the maximum sustainable yield (MSY) — the amount of resource regeneration that would occur at the stock level that maximizes resource growth. In the single-cell aquifer case, this may be given by the minimum freshwater stock before further withdrawals become salty or which would otherwise damage the integrity of the aquifer. Economists often criticize the MSY criterion for harvesting from a renewable resource, noting that the steady-state resource stock is likely to be above the maximum-yield level in order to conserve on harvesting (extraction) costs. In the case of groundwater, however, the change in lift from its initial condition to the point of MSY is sufficiently small that the MSY may well be the optimal steady state (e.g., Roumasset and Wada, 2012). This still leaves open the question of what sequence of groundwater withdrawals over time maximizes the present value (PV) of a single groundwater aquifer, or system of aquifers. The next section begins with a framework for the optimal management of a single groundwater resource. The model is then extended to allow for multiple water resources, watershed conservation, and endogenous resource governance. The chapter concludes with a discussion of key policy implications and directions for further research. To a large extent, the lessons below apply to other renewable resources as well.

Figure 1. Single-cell aquifer model



2. OPTIMAL MANAGEMENT OF A SINGLE GROUNDWATER AQUIFER

Figure 1 shows that groundwater has all the features of a generic renewable resource and can be modeled the same way. The standard groundwater management model is extended to allow for desalination as a backstop resource.[1] Keeping return flow constant for now and including it in recharge, the extraction problem is formally represented as:

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

subject to

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

where r is a positive rate of discount; B is the benefit of water consumption, measured for example as consumer surplus or farm profits; q is the amount of water extracted for consumption; b is the quantity of a backstop (such as desalinated water) that may be used to supplement groundwater; $c_q(h)$ and c_b are the unit costs of groundwater extraction and backstop production, respectively, with the former a convex function of the groundwater stock; the head level (h), or the distance from some reference point to the top of the water table, is an index for groundwater volume; R is the amount of exogenous recharge to the aquifer; D is the amount of groundwater that discharges from the aquifer naturally (e.g., to the sea), net of inflows from adjacent water bodies; and γ converts head level to water volume.[2] The optimal steady state head level, where extraction equals net recharge, will depend on a variety of factors, including the

[1] If the aquifer has already been depleted below its steady state level, desalination may be employed as a "frontstop." (Roumasset and Wada, 2012).

[2] For example, in Gisser and Sánchez (1980) the aquifer is modeled as a rectangular “bathtub” such that γ is the area of the rectangle.

aquifer's physical characteristics and the demand for water. When water demand is rising, it may be optimal to gradually draw down the groundwater stock to the MSY level, and thereafter supplement with an alternative water source, such as desalinated brackish water.

2.1 Transitional Dynamics

Calculating the optimal steady state head level is generally straightforward, but that level will rarely coincide with the initial state of the system. Optimal extraction in each period is determined by withdrawing groundwater until the marginal benefits (MB) of water fall to equal the full marginal cost (FMC) of withdrawal. The history of extraction determines, in turn, the path of the head level as it transitions from its initial state to the optimal long-run target. Since the FMC is determined only after the solution to the dynamic optimization problem is known, one cannot characterize ex ante the extraction and stock paths. A few general results have been established, however, with respect to time-dependence. For a single resource, if the demand and cost functions are stationary over time, the paths of extraction and head will be monotonic (Kamien and Schwartz, 1991). That is, if the initial head level is above (below) the optimal steady state level, it will fall (rise) smoothly over time until it reaches the target level. If demand is growing over time, however, it may be appropriate to accumulate groundwater initially before drawing it down and finally stabilizing groundwater stock at the optimal steady state level (Krulce et al., 1997).

2.2 The Pearce Equation and Pricing for Optimal Extraction

A measure of social welfare ideally includes not only the consumption benefits and physical extraction costs of the resource, but also non-use benefits and environmental damage costs. Thus, the FMC of resource consumption should include any externality cost (e.g., irrigation-induced salinization of underlying aquifers) and user cost, which is defined as the cost of using the resource today in terms of forgone future benefits. In the case of groundwater, extracting a unit of water today lowers the water table — thus increasing stock-dependent extraction costs in all future periods — and forgoes capital gains that could be obtained by leaving the resource in situ to be harvested at a later date. David Pearce (Pearce and Markandya, 1989; Pearce et al., 1989; Pearce and Turner, 1989) suggested that efficient resource extraction satisfies:

$$MB_t = c_t + MUC_t + MEC_t \equiv FMC_t \tag{3}$$

where FMC includes marginal extraction cost (*c*), marginal user cost (MUC), and marginal externality cost (MEC). Setting the price of the resource equal to the marginal benefit along the trajectory described by Eq. 3 ensures optimal resource management.[3]

Inasmuch as the "Pearce equation" integrates microeconomics, resource economics, and environmental economics, it is important to provide a rigorous definition and to explore under what conditions the equation holds.[4] The equation is quite standard for the case of fund pollution, wherein there is no MUC and the corrective tax is set equal to MEC, which is simply the contemporaneous marginal damage cost. For the case of carbon pollution from burning coal, MB is the value of marginal product of coal, c and MUC are the extraction and marginal user cost of coal, and MEC is the incremental present value of damages from the carbon emissions of the marginal unit of coal (Nordhaus, 1991; Farzin, 1996; Perman et al., 2003; Endress et al. 2005). Again, the corrective tax is set equal to MEC.

[3] For a nontechnical exposition of market-based instruments, see Pearce (2005).

[4] This was suggested by Ed Barbier (personal communication), who worked closely with David Pearce.

However, if the externality arises indirectly from the impact that depletion of one resource has on another resource stock, optimality requires $p = c + MUC$, where externalities are accounted for within the MUC (Pongkijvorasin et al., 2011; Roumasset and Wada, 2013a). For example, depletion of a groundwater aquifer reduces submarine groundwater discharge, which supports brackish ecosystems in estuaries and bays. In this case, the full MUC is increased beyond the value of water for human extraction. And because these external effects are included in the MUC, a separate MEC term is not necessary (Pongkijvorasin et al., 2010).

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

3. EXTENSIONS AND EXCEPTIONS TO THE PEARCE EQUATION

The Pearce equation corresponding to a standard resource management problem includes three terms on the cost side: marginal extraction cost, marginal user cost, and marginal externality cost (Eq. 3). However, resource management problems may involve one or more constraints in addition to the resource's equation of motion. This section discusses the possibility of corner solutions wherein the standard Pearce equation should be modified and/or should account for one or more shadow price terms.

3.1 Pearce Equation for Multiple Water Resources

When multiple water resources are available, optimality requires that the MB of water consumption be equal to the FMC of extraction, as in the standard case. However, if at least one resource stock is below its long-run equilibrium level, there will be periods in transition to the steady state during which one or more of the resources are not being used, i.e., a corner solution. For the resources not in use, the Pearce equation does not apply (Roumasset and Wada, 2012). That is, the necessary conditions for the maximization problem require only that $MB = FMC$ for the resource(s) with positive extraction. Zero harvest is optimal for some resources precisely because $MB < FMC$ during certain stages of extraction. For an arbitrary demand sector i and resources j=1,…J, the following modified version of the Pearce equation ensures optimal extraction from the resource system:

$$MB_t^i = \min\left\{FMC_t^{i1}, FMC_t^{i2}, \ldots FMC_t^{iJ}\right\} \quad (4)$$

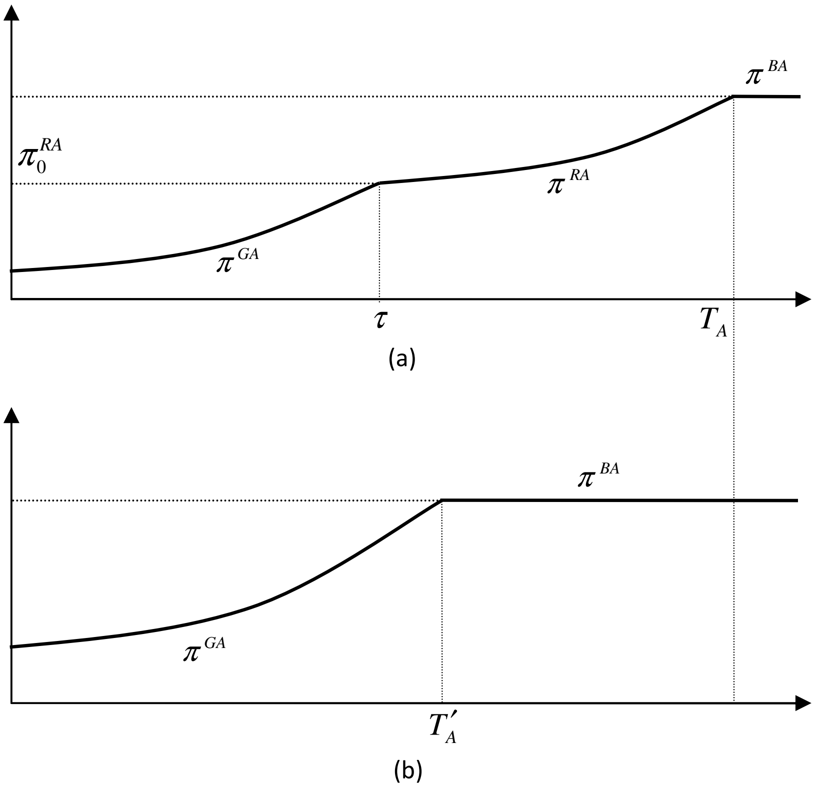
The *min* operator in Eq. 4 requires that the MB for sector i be equal to the least FMC. For all other resources, $MB < FMC$ and extraction is optimally zero.

For the case of multiple aquifers on Oahu, for example, the Pearl Harbor Aquifer (PHA) is initially a lower-cost resource compared to the Honolulu aquifer because of its greater leakage. Optimal management calls for drawing down the "leakier" aquifer first until it reaches the minimum head level (defined by the EPA limit of 2% of ocean salinity). Thereafter, PHA is no longer governed by the Pearce equation, but maintained at its minimum level by setting extraction at the maximum sustainable yield. Instead the Pearce equation governs the Honolulu aquifer once PHA is at its minimum and accordingly drawn down until it too reaches the minimum head level. Once both aquifers are being maintained at their MSY levels, additional increases in quantity demanded at backstop cost are satisfied by desalination. This joint management reduces the waste of independent management by $4.7 billion (Roumasset and Wada, 2012).

As another example, consider the case where groundwater can be supplemented by recycled wastewater and/or desalinated seawater.[5] For simplicity, water is consumed in either the agricultural (A) or household sector (H), and recycled water (R) is a perfect substitute for groundwater (G) in the agricultural sector only -- that is, the treated water does not meet the minimum quality standard for household consumption. Desalination (B) is a perfect substitute for groundwater in both sectors. If groundwater is relatively abundant, then the price path is likely to follow a kinked, upward sloping path (Figure 2a). In the first stage (until year τ), groundwater is used exclusively in the agricultural sector. As water scarcity rises, groundwater is eventually supplemented by recycled water ($p = \pi^{GA} = \pi^{RA} < \pi^{BA}$). At year T_A, all FMCs are equal, and groundwater is supplemented by both alternatives in the steady state. The price as determined by the modified Pearce equation (Eq. 4) is graphically a lower envelope of the FMC curves for the various water resources. Figure 2b illustrates how the need for costly groundwater supplementation can be pushed much closer to the present when all alternatives are not optimally included in a resource management plan.

[5] For a detailed discussion of results and derivations, see Roumasset and Wada (2011).

Figure 2. Hypothetical time paths of FMCs (π): (a) agricultural sector with water recycling, (b) agricultural sector without water recycling.



Adapted from Roumasset and Wada (2011).

3.2 Pricing and Finance of Watershed Services

Now assume a privately owned watershed whose quality (stock of suitably measured natural capital) affects the quantity of recharge. While often mentioned as a supply-side groundwater management instrument, watershed conservation is typically undertaken independently of groundwater extraction decisions. Thus, sizeable potential welfare gains generated from joint optimization of groundwater aquifers and their recharging watersheds go to waste under current water management programs. This section builds on the basic theoretical framework introduced in Section 2 to illustrate management principles that are capable of capturing those potential gains.

The objective of the problem is still to maximize the PV of groundwater, but Eq. 1 must be modified to incorporate the cost of watershed conservation measures. In the simplest case, a unit of investment in conservation (I_t) has a constant cost c_I such that the total investment cost paid in period t is $c_I I_t$. The equation of motion for the aquifer head level (Eq. 2) must account for the fact that investment affects recharge via its contribution to the conservation capital stock (N). Thus, recharge is transformed from a scalar to a function of conservation capital: $R(N_t)$. 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.[6] This presumes that investment expenditures are allocated optimally among 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 the following:

$$\dot{N}_t = I_t - \delta N_t \tag{5}$$

Given proper boundary conditions, the problem can be solved using optimal control, and the necessary conditions can be used to derive a Pearce equation, 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, independent management of the aquifer and watershed would clearly not yield the same results. An analogous efficiency condition can be

[6] 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.

derived for the conservation of natural capital (Roumasset and Wada, 2013b). At the margin, the resource manager should be indifferent between conserving water via watershed investment and demand-side conservation:

$$\frac{c_I(r+\delta)}{R'(N_t)} = \lambda_t \tag{6}$$

The right-hand side of Eq. 6 is the MUC 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. 6 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 because the value of the gained recharge would more than offset the investment costs. Thus, the "system shadow price" of groundwater, λ, governs both optimal groundwater extraction and optimal watershed investment decisions.

In many cases, the optimal management program can be implemented with a system of ecosystem (recharge) payments to private watershed owners. One option is to pay landowners for all service units, starting from zero. That seems excessive, however, inasmuch as providing zero units (e.g., for recharge) is not a feasible option. Another approach is to integrate conservation financing into a block-pricing scheme for water. To properly serve the public interest, the public utility must not only be constrained by the zero profit condition, but it should charge the FMC in order to incentivize efficient extraction so that the value of a set of aquifers is maximized. Pricing each unit of water at FMC would generate a surplus. Part of the surplus can be returned to consumers through lower-priced inframarginal units of water, and the remainder can be used to finance ecosystem payments. Landowners are paid the shadow price for marginal units of recharge but not for inframarginal units below the level of conservation required by zoning.

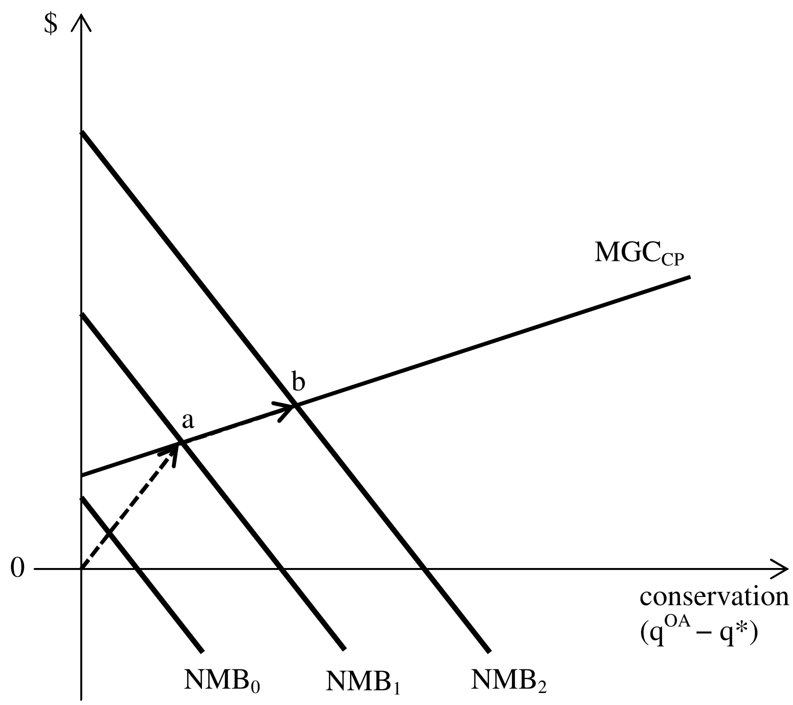
3.3 Measuring Natural Capital

The Pearce equation can also be used to measure changes in natural capital. Suppose for example that a resource manager wants to evaluate the potential benefits of a watershed conservation project that will prevent the loss of groundwater recharge services. Satisfying the Pearce equation for groundwater extraction in each period, with and without conservation, provides the present values for the two scenarios. The difference in the present values gives the groundwater benefits of watershed conservation, to which can be added other conservation values (Kaiser and Roumasset, 2002).

From this perspective, the value of natural watershed capital is always relative to some alternative land cover. Even if there were no flora whatsoever, there would still be some recharge. So if this method were to be used to estimate the total value of watershed capital, it would have to be relative to the hypothetical scenario wherein all ecological services are zero. In this sense, natural capital is that which provides ecosystem services. Caution is needed, however, in attributing the value of natural capital to something specific such as trees.

Another difficulty relating to the use of the Pearce equation in resource valuation has to do with the question of which side of the Pearce equation should be used. Some economists have recommended using net price as a proxy for shadow price on the grounds that it is observable. But from the above discussion, and as others have shown (Arrow et al., 2003; UNU-IHDP and UNEP, 2012), net price is only equal to the resource shadow price (its MUC) when the resource is being optimally extracted. In the more typical case of overextraction, however, the net price undervalues the MUC. In fact, a resource harvested at the open-access equilibrium has a net price of zero.

Figure 3. Governance increases with resource scarcity. The net marginal benefit of water (*NMB*), defined as the difference between *MUC* and the *MB* of consumption, shifts outward over time as water scarcity increases. The marginal governance cost (*MGC*) is an increasing function of conservation. In period 0, the marginal cost of common property (*CP*) governance exceeds the NMB_0 curve for all levels of consumption, i.e., open access (*OA*) is optimal. In period 1, the MGC curve is less than NMB_1 up to some positive quantity, meaning a CP arrangement like a user association becomes optimal (point a). In future periods, costly governance increases as water becomes scarcer (point b). Note that we are considering the long run, i.e. initial costs are treated as capital and the implicit rental cost of capital is included in the marginal cost.

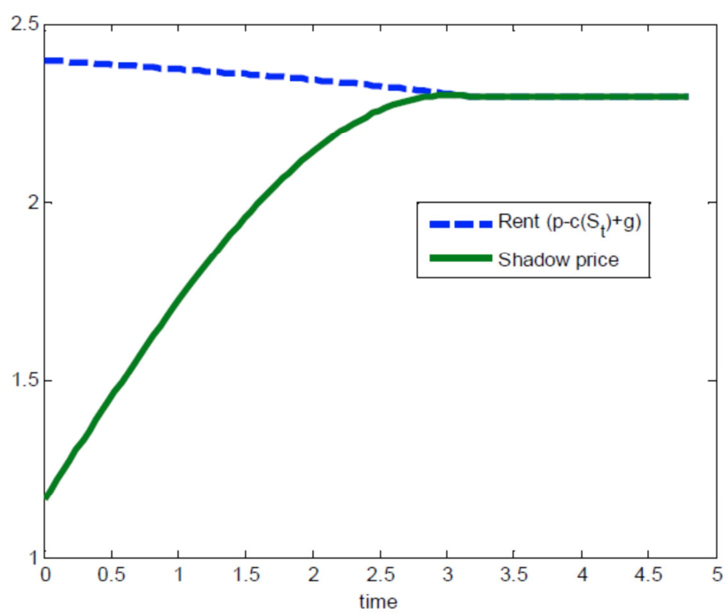


3.4 Pearce Equation with Endogenous Governance

Because common pool resources may face overuse by multiple consumers with unrestricted extraction rights, additional governance may be warranted if the gains from governance exceed the costs (Demsetz, 1967; Ostrom, 1990). The optimal solution may be unattainable when enforcement and information costs are considered. Which of several institutions (e.g., privatization, centralized ownership, user associations) maximizes the net PV of the groundwater resource depends on the relative benefits generated from each option net of the governance costs involved in establishing the candidate institution.

For example, if the initial demand for water is small and the aquifer is large, the gains from management are likely to be small, and open access might be preferred (NMB_0 in Figure 3). As demand grows over time and water becomes scarcer (net benefits shift out to NMB_1 and eventually NMB_2), however, a common property (CP) arrangement such as a user association may become efficient. Eventually, another institution such as a water market, with lower initial MC but lower slope, may become optimal. It is also possible that an intermediate institution such as common property may never be optimal, in the case wherein the lower-slope/higher-initial-MC institution dominates for all levels of positive governance.

Figure 4. Marginal net benefit and shadow price under transition to governance (C=0)



Adapted from Roumasset and Tarui (2010).

Figure 4 illustrates the dynamics of the full marginal net benefit (FMB) and shadow price of a resource in transition to governance using a relatively simple constant-price model. The simulation assumes a constant price p= 2, an extraction cost function $c(S)$=1/S, an initial resource stock S_0=9.9, a discount rate ρ=0.03, a resource carrying capacity K=10, an intrinsic resource growth rate r=0.5, and a marginal governance cost g=1. The FMB of harvesting is defined by p - $c(S_t)$ + g and the shadow price (λ) is the costate variable associated with the resource stock under the optimal solution. The non-instantaneous convergence of the FMB and λ appears to contradict the tendency to associate scarcity with net price or MUC, the justification being that they are all equal along the optimal path. However, this puzzle is resolved by examining the necessary conditions for the maximization problem. Solving a modified version of the standard groundwater problem (Eq. 1) with MGC in the objective functional and a nonnegativity constraint on governance results in the following optimality condition:

$$p - c(S_t) + g = \lambda + \theta \qquad (7)$$

where θ is the Lagrangian multiplier associated with the governance constraint. Without g and θ, the condition can be described as net price = MUC or equivalently that price = FMC (Eq. 3). If the full marginal benefit (FMB) is interpreted as the net price + g, then optimality requires that FMB = MUC + θ or FMB = FMC, where the FMC includes the shadow value of meeting the nonnegative governance constraint. Even though the FMB is declining over time, the shadow price (the true scarcity value) is in fact rising as the resource becomes scarcer. In this particular example, the FMB declines by roughly 0.1 units in the three periods required for the system to reach a steady state, while the shadow price rises by almost 1 unit. The declining value of θ reflects the fact that harvest is moving (from above) toward open access. Thus, the standard

Pearce equation needs to be modified to allow for θ, the difference between FMB and MUC, when governance is endogenous.

4. OPEN ACCESS AND THE GISSER-SÁNCHEZ EFFECT

In many parts of the world, 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 groundwater until MB equals unit extraction cost. In this *open-access* equilibrium, each user ignores the effect of individual extraction on future value. Gisser and Sánchez (1980) found that under certain circumstances, the PV generated by the competitive solution is almost identical to that generated by the optimal solution. The surprising result that the potential welfare gain from groundwater management is negligible has come to be known as the Gisser-Sánchez (GS) effect. Welfare gains may be larger, however, when one or more of the original model's simplifying assumptions are relaxed, e.g., when extraction costs are nonlinear, demand is nonstationary, the discount rate is low, and the aquifer is severely depleted at the outset. From the perspective of section 3.4, the GS effect, under conditions when it is operative, can be recast as prima facie evidence that open access is at least nearly optimal.

The welfare effects of open access also tend to increase dramatically when 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. Recent work in this area (Brozović et al., 2006, 2010) has integrated spatial dynamic flow equations into the equation of motion for an aquifer (Eq. 2 in the basic nonspatial 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, gains from optimal spatial pumping management are likely to be substantial.

5. POLICY IMPLICATIONS AND DIRECTIONS FOR FURTHER RESEARCH

Standard renewable resource economics techniques can be applied to the management of a single groundwater resource. In particular, full marginal cost (FMC) pricing – which takes into account the scarcity value of water – incentivizes optimal consumption. Even when spatial pumping externalities are not considered, FMC pricing creates substantial welfare gains, except in certain specific circumstances, e.g., when the aquifer is particularly large relative to the quantity demanded at extraction cost. Although FMC prices are typically much higher than the marginal extraction cost, zero excess-revenue restrictions that may be imposed on the water manager can be maintained through appropriate block pricing. Because only the marginal price block needs to be equal to the FMC to incentivize optimal consumption, lower blocks can be reduced to offset revenue gains. Relatedly, first-block price reductions can be used to ensure that price reform does not disadvantage the poor or (as in the case of watershed management) the present generation.

When the standard problem is extended to include joint management of additional groundwater resources, simultaneous watershed management, or endogenous governance, the solution method becomes more complicated but the same basic principles apply. For example, when multiple resources are considered, pricing at the *minimum* FMC of all available resources incentivizes optimal consumption, and there are likely to be transitional stages of extraction wherein some resources are not used at all. Whether or not the additional benefit of joint management warrants incurring the additional computational costs will depend on the particular situation, but anecdotal evidence suggests that welfare gains can be large. For example, Roumasset and Wada (2012) found that jointly optimizing the two aquifers underlying South Oahu (Hawaii) would generate a present value welfare gain of $4.7 billion relative to independent management.

Whether the management problem involves a single resource or multiple water resources, efficiency pricing promises substantial welfare gains. Although across the board price increases would likely be viewed as undesirable to current taxpayers, pricing policies that effect efficiency gains can be win-win if designed correctly. In the case of payments for watershed services, for example, sizeable investments in conservation during earlier periods may be optimal, even though the biggest gains are realized far into the future when water prices are much higher. In other words, the cost of investment in earlier periods is likely to outweigh the contemporaneous benefits. Nonetheless financing the investment can be based on the principle of benefit taxation. Because the beneficiaries are water users, the price blocks for water can be adjusted to incorporate a lump sum conservation charge that is proportional to the water benefits received. Provided that the present value sum of conservation fees collected from water users is equal to the present value cost of investment – much of which is incurred in earlier periods – a bond could be issued to finance the project and the fees used to pay off the bond.

Groundwater economics can also be generalized to incorporate the spatial dimension. For a single integrated demand network, this simply involves adding transportation cost to the right-hand side of the Pearce equation for each location in the system. The resulting solution is a matrix of efficiency prices over time and space. There is a minimum-cost, wholesale shadow price for each time, and the location-specific shadow prices are given by this *system* shadow price plus the distribution cost (Pitafi and Roumasset, 2009; Roumasset and Wada, 2012). A natural extension of this system would be to allow for endogenous demand networks and multiple water resources (e.g., separate aquifers, watershed capital, conjunctive use of surface and groundwater, and freshwater substitutes such as desalinated water and treated wastewater). Separate networks would then be characterized by the condition that the shadow prices of any two locations in the separate networks would differ by less than the transportation costs, such that no interdistrict transport is economic (see Jandoc et al., forthcoming). Note, however, that this condition need only hold for a particular point in time. As scarcities (or transport costs) change, so may the system boundaries. This theoretical development could provide an important tool for planning water transportation infrastructure.

The above is still partial equilibrium in nature, however, inasmuch as demand functions at various locations are taken as given, as are interest rates. A further step would be to endogenize the accumulation/depreciation of produced capital for the rest of the economy, investment in water infrastructure, and watershed capital. Presumably, the necessary conditions would involve a generalized version of the extended Hotelling conditions discussed above plus a Ramsey condition for the accumulation of produced capital (Endress et al., 2005). This formulation would allow for the exploration of water (or resource)-related limitations to sustainable development.

REFERENCES

Arrow, K.J., Dasgupta, P., Mäler, K.-G. (2003). "Evaluating projects and assessing sustainable development in imperfect economies". Environmental and Resource Economics 26(4), 647-685.

Brozović, N., Sunding, D.L., Zilberman, D. (2006). "Optimal management of groundwater over space and time". In: Berga, D., Goetz, R. (Eds.), Frontiers in Water Resource Economics, Natural Resource Management and Policy Series. Vol. 29, Springer, 275 p.

Brozović, N., Sunding, D.L., Zilberman, D. (2010). "On the spatial nature of the groundwater pumping externality". Resource and Energy Economics 32,154-164.

Demsetz, H. (1967). "Toward a theory of property rights". American Economic Review 57(2), 347-359.

Endress, L., Roumasset, J., Zhou, T. (2005). "Sustainable Growth with Environmental Spillovers". Journal of Economic Behavior and Organization 58(4), 527-547.

Farzin, Y.H. (1996). "Optimal pricing of environmental and natural resource use with stock externalities". Journal of Public Economics 62, 31-57.

Gisser, M., Sánchez, D.A. (1980). "Competition versus optimal control in groundwater pumping". Water Resources Research 31, 638–42.

Jandoc, K., Juarez, R., Roumasset, J. (forthcoming). "Efficient distribution in water networks". In: Burnett, K., Howitt, R., Roumasset, J., Wada, C.A. (Eds.), Handbook of Water Economics and Institutions. Routledge.

Kaiser, B., Roumasset, J. (2002). "Valuing indirect ecosystem services: the case of tropical watersheds". Environmental Economics and Development 7(4).

Kamien, M.I., Schwartz, N.L. (1991). Dynamic Optimization: The Calculus of Variations and Optimal Control in Economics and Management. North-Holland, New York.

Krulce, D.L., Roumasset, J.A., Wilson, T. (1997). "Optimal management of a renewable and replaceable resource: the case of coastal groundwater". American Journal of Agricultural Economics 79, 1218–28.

Nordhaus, W.D. (1991). "To slow or not to slow: the economics of the greenhouse effect". The Economic Journal 101(407), 920-937.

Ostrom, E. (1990). Governing the Commons: The Evolution of Institutions for Collective Action. Cambridge University Press, Cambridge.

Pearce, D. (2005). "Environmental policy as a tool for sustainability". In: Simpson, R.D., Toman, M., Ayres, R. (Eds.), Scarcity and Growth Revisited: Natural Resources and the Environment in the New Millennium. Resources for the Future, Washington, DC.

Pearce, D.W., Markandya, A. (1989). "Marginal opportunity cost as a planning concept". In: Schramm, G., Warford, J.J. (Eds.), Environmental Management and Economic Development. The Johns Hopkins University Press, Baltimore.

Pearce, D.W., Markandya, A., Barbier, E.B. (1989). Blueprint for a Green Economy. Earthscan Publications, Ltd., London.

Pearce, D.W., Turner, R.K. (1989). Economics of Natural Resources and the Environment. The Johns Hopkins University Press, Baltimore.

Perman, R., Ma, Y., McGilvray, J., Common, M. (2003). Natural Resource and Environmental Economics. Pearson Addison Wesley, New York.

Pitafi, B., Roumasset, J. (2009). "Pareto-improving water management over space and time". American Journal of Agricultural Economics 91(1), 138-153.

Pongkijvorasin, S., Roumasset, J., Duarte, T.K., Burnett, K. (2010). “Renewable resource management with stock externalities: Coastal aquifers and submarine groundwater discharge”. Resource and Energy Economics 32, 277-291.

Pongkijvorasin, S., Roumasset, J., Pitafi, B. "Pricing resource extraction with externalities: the case of indirect stock-to-stock effects”. (unpublished manuscript, 2011)

Roumasset, J., Tarui, N. (2010). “Governing the resource: scarcity-induced institutional change”. Working Paper Series #10-15, Department of Economics, University of Hawai‘i.

Roumasset, J., Wada, C.A. (2011). “Ordering renewable resources: groundwater, recycling, and desalination”. The B.E. Journal of Economic Analysis & Policy – Contributions 11(1), Article 28.

Roumasset, J.A., Wada, C.A. (2012). “Ordering the extraction of renewable resources: the case of multiple aquifers”. Resource and Energy Economics 34, 112-128.

Roumasset, J.A., Wada, C.A. (2013a). “Economics of groundwater”. In: Shogren, J.F. (Ed.), Encyclopedia of Energy, Natural Resources and Environmental Economics, vol. 2. Elsevier, Amsterdam.

Roumasset, J.A., Wada, C.A. (2013b). “A dynamic approach to PES pricing and finance of interlinked ecosystem services: watershed conservation and groundwater management”. Ecological Economics 87, 24-33.

UNU-IHDP and UNEP. (2012). Inclusive Wealth Report 2012. Measuring Progress toward Sustainability. Cambridge University Press, Cambridge.

WCED (World Commission on Environment and Development). (1987). Our Common Future (The Brundtland Report). Oxford University Press, Oxford.