OPTIMAL PROVISION AND FINANCE OF ECOSYSTEM SERVICES:
THE CASE OF WATERSHED CONSERVATION AND GROUNDWATER MANAGEMENT

BY

JAMES ROUMASSET AND CHRISTOPHER WADA

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Optimal Provision and Finance of Ecosystem Services: the Case of Watershed Conservation and Groundwater Management

James Roumasset[*]
Department of Economics
University of Hawai'i at Mānoa
& University of Hawai'i Economic Research Organization

Christopher Wada[†]
University of Hawai'i Economic Research Organization

Abstract:

Payments for ecosystem services should be informed by how both the providing-resource and the downstream resource are managed. We develop an integrated model that jointly optimizes conservation investment in a watershed that recharges a downstream aquifer and groundwater extraction from the aquifer. Volumetric user-fees to finance watershed investment induce inefficient water use, inasmuch as conservation projects actually lower the optimal price of groundwater. We propose a lump-sum conservation surcharge that preserves efficient incentives and fully finances conservation investment. Inasmuch as proper watershed management counteracts the negative effects of water scarcity, it also serves as adaptation to climate change. When recharge is declining, the excess burden of non-optimal watershed management increases.

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[*] Professor, Department of Economics, University of Hawai'i, Mānoa, and Research Fellow for the University of Hawai'i Economic Research Organization, Saunders 542, 2424 Maile Way, Honolulu, HI 96822 USA. E-mail: jimr@hawaii.edu
[†] Postdoctoral Resource/Environmental Research Economist, University of Hawai'i Economic Research Organization. E-mail: cawada@hawaii.edu

1 Introduction

Resource economists often recommend that water utilities price according to marginal cost in order to induce demand-side conservation. These studies typically take groundwater inflow or recharge as constant (e.g. Gisser and Sanchez, 1980; Feinerman and Knapp, 1983; Koundouri, 2004; Pitafi and Roumasset, 2009). However, the quality of watersheds in many regions is in decline due to urban development, invasive species, logging, or other activities that use the watershed, and climate change may exacerbate (or ameliorate) the problem (World Bank, 2004; WWAP, 2009). Consequently, groundwater recharge has been declining in recent years and will continue to do so in the absence of corrective measures. A comprehensive groundwater management program which integrates optimal investment in watershed conservation capital (e.g. fencing for feral ungulates, reforestation, and infiltration-enhancing engineering structures) provides adaptation to declining recharge levels.

Determining the optimal time path of investment in conservation capital requires solving a dynamic problem with multiple control variables and two connected stocks. Pumping subtracts from the groundwater stock directly, and investing in the watershed has a positive effect on the groundwater stock through its impact on aquifer recharge. The objective is to choose extraction and investment simultaneously in every time period to maximize the present value of net social benefits. Inasmuch as watershed conservation is costly, there exists a tradeoff between the costs and benefits of investment, part of which is represented by the impact on the groundwater resource. Although the analysis focuses on water consumption benefits, other benefits from conservation include, for example, recreation, increased biodiversity, reduced sedimentation, and reduced flooding.

Several recent studies focusing on Hawaiʻi have considered the relationship between groundwater aquifers and their associated watersheds, but none have done so in a fully optimal framework. Kaiser and Roumasset (2002) set up a model with conservation expenditures as a control variable but then proceed with a benefit cost analysis for a particular watershed deterioration scenario, i.e. a given reduction in recharge. Pitafi and Roumasset (2006) show that watershed conservation reforms may fail a cost-benefit test if groundwater management reforms are not implemented simultaneously, but the calculations are also based on various recharge-loss scenarios. Neither study examines finance options for provision of the ecosystem services.

More generally, the problem of investing in one resource to increase the growth of an interrelated resource has been examined in the context of coastal wetlands and offshore fisheries (Barbier, 2008). In Thailand, mangrove ecosystems serve as both nurseries and breeding grounds for fish. However, incentives exist for converting mangrove areas to shrimp farms, and when the shrimp farms are eventually abandoned, the ecosystem is unable to revert back to its original state without additional investment efforts, i.e. investment in mangrove rehabilitation has a direct and positive impact on offshore fishery growth.

The use of payments as a tool to induce provision of ecosystem services (PES) has increased in recent years. In a comparative analysis of PES programs, Wunder et al. (2008) observe substantial differences across countries, reflecting ecological, socioeconomic, institutional, or political circumstances, and in some cases simply poorly designed programs. They find that user-financed programs are generally more efficient

than government-financed programs. That is, user-financed programs tend to be better designed to match local conditions and needs, have superior monitoring and enforcement, and are better targeted. Although PES programs have experienced growing popularity in recent years, they often lack "careful analysis of how [they] work, and of [their] strengths and weaknesses" (Wunder et al., 2008). Thus, further analytical work in this area would contribute to a better understanding of current PES programs and inform the design of future programs.

In this paper, we develop and solve a model that jointly optimizes groundwater extraction from a costal aquifer and investment in watershed conservation over time, focusing on the recharge-benefits of conservation. Although the derived efficiency price equation is identical to the optimality condition when groundwater is optimized exclusively, the actual price paths differ inasmuch as they are dependent on the head and capital stock trajectories corresponding to their respective watershed management decisions. In addition to a Hotelling condition for governing extraction of the renewable groundwater resource, the joint optimization model also yields an equimarginality condition for the capital stock, reminiscent of Jorgensen (1963). Groundwater should be priced at its marginal opportunity cost (marginal extraction cost plus marginal user cost), and capital should be accumulated until its marginal value is equal to its implicit rental price.

We also demonstrate that a lump-sum conservation surcharge can simultaneously preserve efficient incentives and finance the optimal pattern of investment. In the context of public utilities, conservation surcharges are generally understood to be volumetric, since their purpose is to induce demand-side conservation by making high volume users

responsible for capacity expansion costs. We show, however, that first-best finance of investment in watershed conservation calls for lump-sum surcharges, albeit individualized according to potential benefits. A related problem is that water utilities are constitutionally constrained to recover the costs of extraction and distribution infrastructure but are not empowered to conserve the watershed, which is the province of another jurisdiction. Nature's infrastructure for delivering recharge requires maintenance, however, just as wells and pipes do. Thus, implementing surcharges may require enabling legislation to facilitate the described principles of public finance.

Lastly, we characterize the resource management implications of climate change. Enhancing groundwater recharge through investment depresses the shadow price of groundwater, and hence increases welfare. The need for investment is therefore amplified by declining recharge. For lower rates of recharge, the excess burden of ignoring the watershed increases, even if groundwater extraction is optimized independently.

2 The dynamic economic-hydrologic optimization model

In this section, we characterize and develop solutions to the problem of jointly managing a watershed and a groundwater aquifer in the absence of climate change. Section 4 extends the framework to allow for declining recharge, thus treating watershed management as climate adaptation.

2.1 Description of the system

When demand for water is growing over time, groundwater must eventually be supplemented by other (non-traditional) water sources. Desalinated seawater (b) serves as a natural backstop resource in the case of a coastal aquifer. A water manager, therefore, has the choice of obtaining water from the aquifer and/or from desalination in

any given period. The volume of groundwater stored in a coastal aquifer depends on the aquifer boundaries, lens geometry, and rock porosity (Mink, 1980). We assume the hydraulic gradient is small enough that the head level (h), or the vertical distance between mean sea level and the top of the freshwater lens, is approximately proportional to the stored volume of groundwater, i.e. we abstract from the true parabolic shape of the lens. Following Krulce et al. (1997), the head level trajectory is governed by natural recharge (R), leakage (L), and extraction (q)

As the head level declines, the distance groundwater must be lifted increases and consequently extraction cost rises, i.e. $c_q'(h_t) < 0$. Since the model considers a coastal aquifer, wells nearest the coast face salt water intrusion soonest as the lens of freshwater shrinks over time due to extraction. Costs may eventually rise drastically as remaining wells reach capacity constraints and costly new wells must be drilled to meet demand. This possibility is modeled by allowing the cost function to be convex in head, i.e. $c_q''(h_t) \geq 0$.[1] Leakage is also a function of head when low permeability sediment deposits bound the freshwater lens along the coast. Pressure from the lens causes some freshwater to discharge via coastal springs or subterraneously into the ocean. As the aquifer head declines, leakage decreases both because of the smaller surface area along the ocean boundary and because of the decrease in pressure due to the shrinking of the lens. Thus $L'(h_t) > 0$ and $L''(h_t) \geq 0$.

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[1] It may be that for political or other reasons, all wells must be protected from saltwater intrusion. In that case, new wells still may be drilled, which would increase the costs non-linearly. However, the assumption of non-strict rather than strict convexity includes the possibility of linear extraction costs. If the current infrastructure is sufficient to meet future demand, then the physical cost of withdrawal is determined entirely by the energy costs required to lift the water.

Natural recharge is an increasing and concave function of capital stock, i.e. $\partial R / \partial N_t > 0$ and $\partial^2 R / \partial N_t^2 < 0$. In addition, we assume that the recharge function satisfies the Inada conditions, i.e. $\lim_{N_t \to 0} R'(N_t) = \infty$ and $\lim_{N_t \to \infty} R'(N_t) = 0$. If investment expenditures are optimally allocated amongst available conservation instruments, then it follows that the first units of capital are most effective at enhancing recharge and that the marginal product of capital eventually tapers off.

Although conservation capital (N) is treated as a single stock in the discussion that follows, in reality, there are a plethora of available recharge-augmenting instruments such as fencing for feral pigs, which prevents the destruction of upland vegetation; reforestation of native flora, which can decrease evapotranspiration and surface runoff; and manmade engineering structures designed to increase infiltration and/or decrease runoff. Optimal watershed management therefore involves selecting a portfolio of instruments that maximizes recharge benefits net of investment costs.[2] Inasmuch as we are interested primarily in the impact of investment (I) on aquifer-level groundwater extraction trajectories, we assume that all expenditures are allocated optimally amongst available conservation instruments. Investment enters the resource manager's problem as a control variable. Capital stock depreciates at an exogenous rate (δ), but the resource manager can steer the time path of capital stock, and hence recharge, by choosing the expenditure on investment in every period. The integrated watershed-aquifer system is depicted in Figure 1.

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[2] In this analysis, we focus on the groundwater recharge benefits of watershed conservation. In general, benefits would include other ecosystem services such reduced flooding, reduced sedimentation, biodiversity, and recreation.
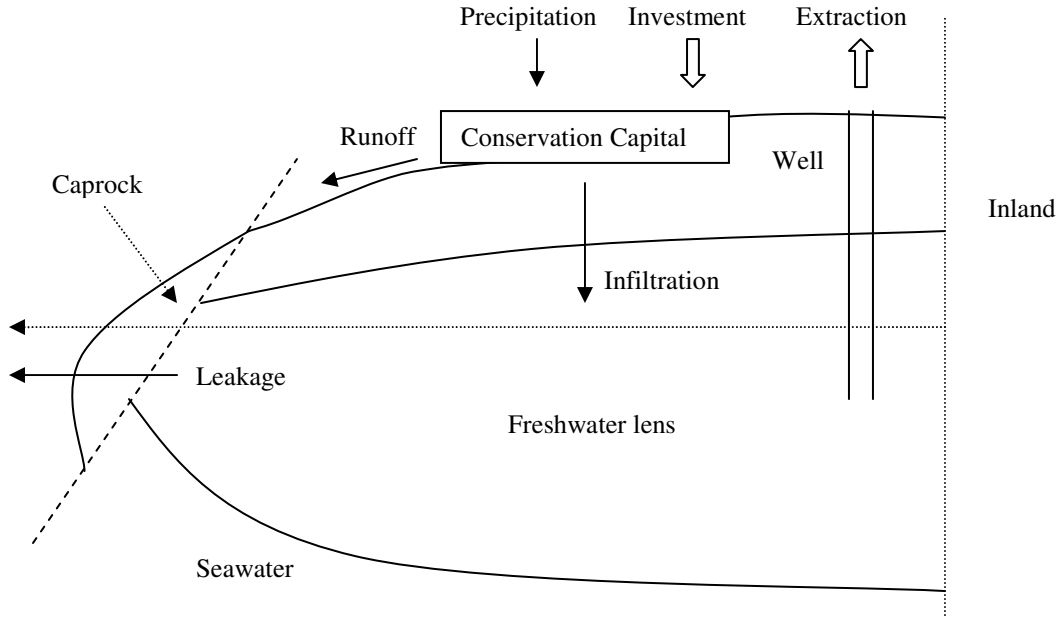
Figure 1: Coastal watershed-aquifer system

2.2 Resource manager's maximization problem

The resource manager must choose the rates of extraction (q_t), desalination (b_t), and investment (I_t) in every period, given a discount rate $r > 0$ to maximize the net present value of social welfare:

$$(1) \quad \underset{q_t, b_t, I_t}{Max} \int_0^\infty e^{-rt} \left\{ \int_0^{q_t+b_t} D^{-1}(x_t) dx_t - [c_q(h_t) + c_d] q_t - [c_b + c_d] b_t - c_I I_t \right\} dt$$

subject to
$$\gamma \dot{h}_t = R(N_t) - L(h_t) - q_t$$

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

$$I_t \in [0, I_{max}]$$

and standard non-negativity constraints on the control variables. Gross benefits from water consumption are measured as the area under the inverse demand curve (D^{-1}). Total costs are calculated using the unit extraction cost of groundwater (c_q), the unit cost of

desalination (c_b), the unit distribution cost (c_d) and the unit cost of investment (c_I).

Since the right-hand side of the aquifer's governing equation is measured in water volume, the change in head level must be converted using a height-to-volume conversion factor (γ). Investment is bounded below by zero and above by I_{max}, which denotes some maximum feasible investment rate, determined for example, by budgetary restrictions.

Along the optimal trajectory, groundwater must be extracted until its marginal benefit is equal to its marginal cost. The efficiency price of water, therefore, is determined where the equimarginality condition is satisfied, and we define it as $p_t \equiv D^{-1}(q_t + b_t)$. More specifically, the necessary condition[3] for optimal groundwater extraction requires that royalty (price minus extraction cost) is equal to the shadow price of water (λ_t) or marginal user cost plus distribution cost. Equivalently, the efficiency price is equal to the marginal opportunity cost (MOC) of groundwater, or the sum of marginal extraction, distribution and marginal user costs. The condition is none other than a modified[4] version of the Hotelling rule for the optimal extraction of a natural resource.

The adjoint equation or the equation of motion for the costate variable (λ_t) can be rearranged as follows:

(2) $\dot{\lambda}_t - c_q'(h_t)q_t = r\lambda_t + \gamma^{-1}\lambda_t L'(h_t)$.

Eq. 2 says that marginal benefit should be equated to the cost of the marginal conserved unit of groundwater. The marginal benefit includes the increase in royalty and the decrease in extraction cost, while the marginal cost includes the forgone interest from the

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[3] See Appendix A for the current value Hamiltonian and the necessary conditions for the maximum principle.
[4] The basic Hotelling rule is extended to include stock-dependent extraction costs and resource growth.

royalty and the lost value resulting from increased leakage. The costate variable is by definition the increase in net present value resulting from an additional unit of the groundwater stock. From a cost perspective, it is the loss in value when the stock is reduced by one unit, or the marginal user cost. We manipulate the necessary conditions to avoid dealing with the path of λ_t explicitly, however, since focusing on the efficiency price allows one to characterize individual components comprising marginal user cost. For $q_t > 0$, it is straightforward to derive the following efficiency price equation:[5]

$$(3) \qquad p_t = c_q(h_t) + c_d + \underbrace{\frac{\dot{p}_t - \gamma^{-1}c_q'(h_t)[R(N_t) - L(h_t)]}{r + \gamma^{-1}L'(h_t)}}_{\text{marginal user cost}}$$

The marginal user cost takes into account the forgone use of the marginal unit when price is higher in the future, the value of the resulting decrease in leakage, and the increase in marginal extraction cost. Eq. 3 remains unchanged when watershed conservation is not part of the resource management strategy, i.e. when $I_t = 0$ for all t. The actual price paths will differ, however, inasmuch as the trajectory of aquifer recharge is influenced by capital stock. For example, relative to the zero investment case, we expect the efficiency price of water under optimal investment to start lower and the aquifer to be utilized for a longer period of time before the switch to the backstop technology.

The capital stock has an equimarginality condition similar to that for the stock of groundwater. For $\mu_t = c_I$, i.e. at the singular solution[6] $N*$,

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[5] To derive Eq. 3, take the time derivative of Eq. A2, substitute the result with Eq. A2 and A5 into Eq. 2, and rearrange.

[6] Singular solutions arise in problems where the Hamiltonian is linear in a control variable. When the switching function vanishes identically over some time interval, the maximum principle does not specify the value of the optimal control. Instead, the singular solution must be used to characterize the optimal value of the control variable (e.g. Conrad and Clark, 1987)

(4) $\gamma^{-1}[p_t - c_q(h_t)]R'(N_t) = c_I(r + \delta)$.

The marginal benefit is the value of the increase in recharge resulting from the marginal

unit of conservation capital stock. The marginal cost can be thought of as the implicit

rental price or user cost of capital (Jorgensen, 1963), which includes the forgone interest

that would have accrued had the income not been spent on conservation capital, and the

cost of depreciation.

Since the current value Hamiltonian (Eq. A1) is linear in I_t, investment is

expected to follow a most rapid approach path (MRAP) to the steady state. One can

define a switching function using the coefficient of I_t:

(5) $\sigma(t) \equiv \mu_t - c_I$.

Then along the optimal trajectory for investment, it must be that

(6) $I_t = \begin{cases} I_{max} & \text{if} \quad \sigma(t) > 0 \\ 0 & \quad \sigma(t) < 0. \end{cases}$

The optimal investment rule is to choose the maximum feasible level of investment when

the shadow value of capital stock exceeds the marginal cost of investment, and choose

zero investment if the cost is instead higher than the shadow value.

2.3 Characterization of the steady state

To operationalize the investment rule, we rewrite Eq. 6 in terms of the singular

solution for the capital stock ($N*$). Following Conrad and Clark (1987), we start by

setting the coefficient of the relevant control in the Hamiltonian equal to zero, which

amounts to setting Eq. 5 equal to zero. The result is then substituted into the adjoint

equation for μ_t, which yields Eq. 4. In the steady state or long-run equilibrium,

$\dot{p}_t = \dot{h}_t = \dot{N}_t = 0$, and $p^* = c_b$. Then the solution $N *$, which belongs to a vector

(p^*, h^*, N^*) that simultaneously satisfies Eqs. 3 and 4, is the singular solution for the

capital stock.[7]

The complete solution for investment is given by:

(7) $$I_t = \begin{cases} I_{max} & N_t < N * \\ I^* = \delta N * & \text{if } N_t = N * \\ 0 & N_t > N *. \end{cases}$$

If the level of capital stock is below its steady state level, the resource manager should

invest at the maximum feasible rate in every period until $N *$ is reached. If instead the

capital stock starts off at a relatively high level, then one should optimally allow the

capital stock to depreciate until the steady state level is obtained, at which point

$I^* = \delta N *$.

Upon solving for the values of $h *$ and $N *$, one can also obtain the steady state

values of groundwater extraction and desalination. Since $\dot{h}_t = 0$ in the steady state, the

equation of motion for the aquifer head level (Eq. A5) implies that $q^* = R(N^*) - L(h^*)$.

In other words, extraction should be constant and equal to recharge net of natural leakage.

Any quantity demanded in excess of net recharge is therefore supplied by desalination,

i.e. $b^* = D(c_b + c_d) - q *$.

It is clear that the capital stocks of both resources are intimately linked in the

dynamic solution to the joint optimization problem (Eq. 1). The same holds true for the

steady state. We consider Eq. 3 in order to study the comparative statics of the long-run

equilibrium solution. One can show using the implicit function theorem that

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[7] We assume the existence of a unique steady state. Therefore, the singular solution coincides with the steady state capital stock.

$\partial h_T / \partial R_T < 0$ and $\partial q_T / \partial R_T > 0$.[8] In other words, for a positive shock to the steady state recharge rate, the optimal long-run head level is lower and groundwater extraction is higher. The intuition is that a higher recharge rate means groundwater is less scarce, and consumption can be increased without decreasing the PV of net social benefits. The result is illustrated in Figure 2. Enhanced recharge resulting from investment effectively shifts the MOC for groundwater downward, which means the optimal quantity of groundwater extraction and consumption increases.
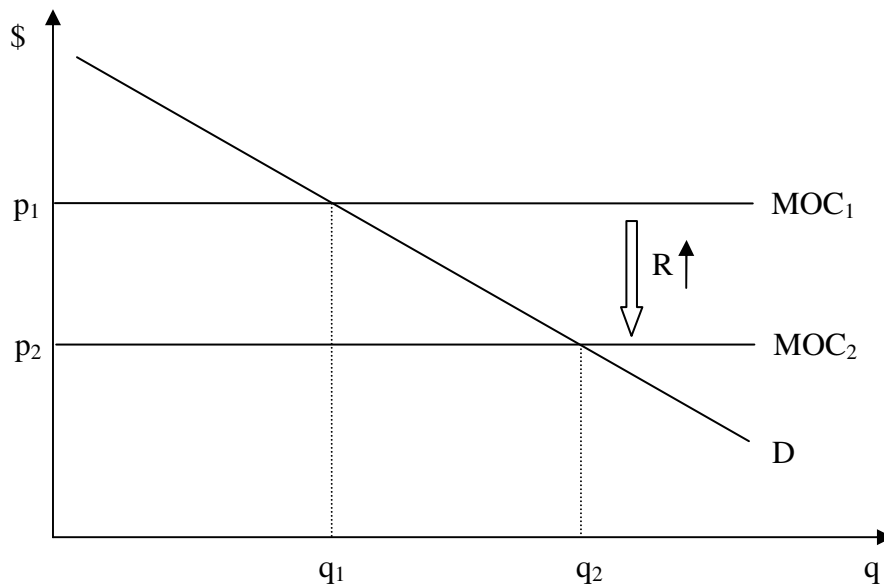

Figure 2. Steady state implications for a positive shock to recharge

In addition, the recharge shock results in a decrease in the efficiency price, thus pushing the system out of equilibrium. A lower price means that the groundwater will be used exclusively, and costly desalination delayed even further, in transition to the new steady state.

2.4 Transition to the steady state

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[8] See Appendix B for a derivation of this result.

Eq. 3, the capital accumulation equation (Eq. A7), and the governing equation for head (Eq. A5) comprise a differential system that can be solved given proper boundary conditions for aquifer head level, conservation capital stock, and price. Field measurements of the initial head level and information about status quo conservation measures are likely available in practice. The steady state price is determined by the cost of the backstop when demand is growing over time, and the terminal values for both state variables can be determined as outlined in Section 2.3.

Inasmuch as the Hamiltonian is linear in investment, the dynamic paths of capital stock and investment will approach monotonically from above or below the steady state target, depending on the initial value N_0. The MRAP does not apply to the other variables, however. The Hamiltonian is non-linear in extraction, and consequently the optimal trajectories of price and head are not so straightforward to characterize. If the system of necessary conditions could be reduced to three variables, then methods for constructing 3-dimensional phase diagrams could be applied (e.g. Kamien and Schwartz, 1991), although characterizing such a reduced system would still be a formidable task. We expect that non-monotonic trajectories of head can turn out to be optimal under certain circumstances, inasmuch as the result has been established for the case of constant aquifer recharge (e.g., Krulce et al., 1997).

3 Financing watershed conservation

One way to finance a comprehensive watershed conservation program is through benefit taxation. Groundwater consumers ultimately benefit from the enhanced recharge that watershed conservation provides through lower water prices and delayed implementation of costly desalination. With no economic objectives, a volumetric tax on

groundwater consumption may seem ideal; it targets the beneficiaries, lowers consumption, and provides revenue to finance investment in recharge capacity. As illustrated in Figure 3, while optimal investment moderates water scarcity and shifts the MOC for groundwater downward, a volumetric tax (τ) has the opposite effect on consumption. Charging consumers a higher price takes away part of the benefits of investment, exactly what we are trying to avoid. Moreover, from a welfare standpoint, volumetric charges put a disproportionately large burden of the investment costs on current generations, even though future generations benefit most from the program. A lump-sum tax can preserve efficient incentives as well as distribute project costs in accordance with benefits.
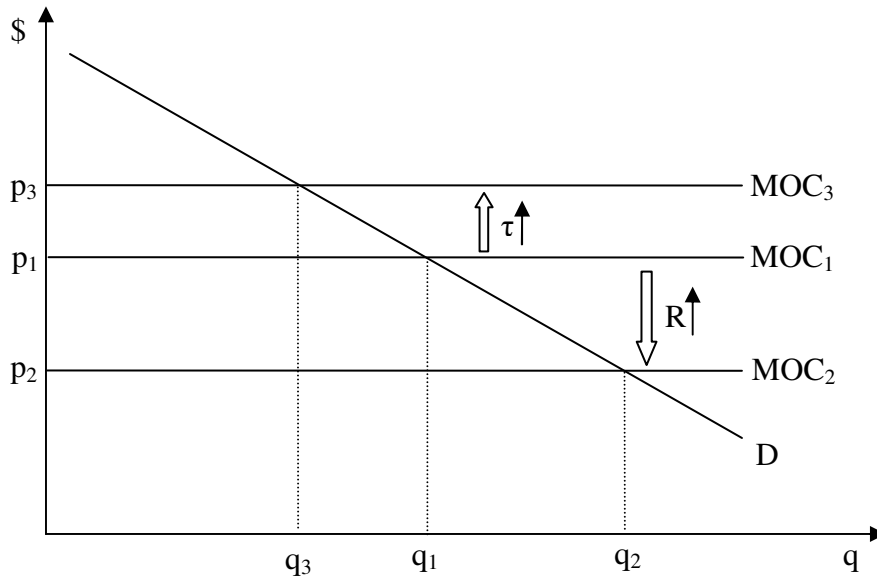

Figure 3. Volumetric conservation surcharge

3.1 Lump-sum watershed conservation surcharges

In the context of public utilities, a conservation surcharge is generally understood to be a volumetric charge that integrates marginal and average costs in price structure

design (see e.g. Mann and Clark, 1993). The charge is determined according to the avoided-cost principle. Demand-side conservation is induced by incorporating capacity expansion costs into the price for discretionary usage. This type of conservation surcharge may be roughly correct for electric utilities, however inasmuch as groundwater is a renewable resource, the optimal pricing structure for water should include marginal user cost. A lump-sum conservation surcharge appended to the efficiency price of groundwater is a means of financing investment in watershed conservation while accounting for the marginal user cost of groundwater.

One approach to benefit taxation, and the one used in the lump-sum tax scheme detailed in the remainder of this section, is to set the costs of conservation investment proportional to the benefits. The idea of proportional benefit taxation is sometimes attributed to Wicksell (1958),[9] although technically the only requirement of Wicksell's political model is unanimity, which guarantees Pareto-improvement[10] – some individuals must be made better off and nobody can be made worse off. Inasmuch as Wicksellian taxes can be anything less than benefits, as established by the political process, proportional benefit taxation can satisfy the criteria for Wicksellian taxation, but a Wickellian tax need not be proportional to benefits. In general, the cooperation induced by unanimity need not lead exactly to proportional benefit taxation. Other possibilities include concepts from cooperative game theory such as the Shapley value (Shapley, 1953), as well as concepts from the theory of public goods such as Lindahl pricing (e.g.,

[9] See e.g., Backhaus and Wagner (2004) and Shughart and Razzolini (2003).
[10] The lump-sum tax ensures Pareto-improvement across generations, i.e., each generation t as a whole is made better off with the program, but not within generations. An instrument that leaves every single individual (within and across generations) better off would require a higher level of sophistication as well as more individualized information. See Pitafi and Roumasset (2009) for an application of (Pareto-improving) proportional benefit taxation to finance pricing reform in a spatial and intertemporal context of groundwater management.

Lindahl, 1919; Hines, 2000), according to which public good provision is supported by individual-specific prices set equal to marginal valuations.

In anticipation of future scarcity, it is optimal in some cases to incur large investment costs at the outset, even though benefits may be concentrated further off into the future. If the project runs a deficit initially and a surplus later, a bond will be required, such that the present value of collections is equal to the present value of investment costs. Although we assume a representative consumer in every period, water users are differentiated across time by the benefits they receive. The benefit from water use obtained by a representative generation-t consumer when the aquifer and watershed are jointly optimized is calculated as:

$$(9) \qquad \hat{V}_t = \int_0^{\hat{q}_t+\hat{b}_t} D^{-1}(x_t)\,dx_t - [c_q(\hat{h}_t) + c_d]\hat{q}_t - [c_b + c_d]\hat{b}_t \;.$$

Similarly, the generation-t benefit obtained by optimizing groundwater extraction, taking the status quo conservation as given[11] can be calculated as:

$$(10) \qquad \tilde{V}_t = \int_0^{\tilde{q}_t+\tilde{b}_t} D^{-1}(x_t)\,dx_t - [c_q(\tilde{h}_t) + c_d]\tilde{q}_t - [c_b + c_d]\tilde{b}_t \;.$$

The period-t welfare gain from the conservation program is therefore $\hat{V}_t - \tilde{V}_t$.

In order to solve for the proportion of welfare gains that balances the intergenerational budget, it is also necessary to calculate the PV cost of investment:

$$(11) \qquad \hat{C} = \int_0^{\infty} e^{-rt} c_I \hat{I}_t\,dt \;.$$

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[11] The benchmark could be measured in a variety of different ways. For example, one could also consider the trajectory of capital stock for zero investment or require just maintenance for a chosen benchmark year. The methodology is applicable to whichever benchmark is most appropriate for the particular application.

Since the present value of collections must be sufficient to cover the investment costs (Eq. 11), and the per-period tax is calculated as a proportion (α) of the periodic welfare gain, the following condition must be satisfied:

(12) $\quad \hat{C} = \int_0^\infty e^{-rt} [\alpha(\hat{V}_t - \tilde{V}_t)]dt \quad \Rightarrow \quad \hat{\alpha} = \hat{C} / \int_0^\infty e^{-rt} [(\hat{V}_t - \tilde{V}_t)]dt$.

The efficient lump-sum tax for the representative generation-t consumer is:

(13) $\quad \tau_t = \hat{\alpha}(\hat{V}_t - \tilde{V}_t)$.

If one has reason to believe that the political process would yield a tax system that is not proportional, e.g. one in which certain generations bear a larger proportion of the costs, then the tax formula (Eq. 13) can be adjusted by replacing $\hat{\alpha}$ with α_t, where α_t varies between generations and is determined by the political process. Proportional benefit taxation is used in this analysis, however, because it is a defensible principle in the sense that it theoretically limits rent-seeking behavior. A group of beneficiaries cannot alter its relative tax share; an increase or decrease for one group means an increase or decrease for all. With a progressive tax structure, the degree of progression is open to rent-seeking.

3.2 Conservation financing with negative beneficiaries

Proportional benefit taxation makes sense as long as $\hat{V}_t > \tilde{V}_t$ for all t, i.e. consumers in every period gain from the watershed conservation plan. If there are negative beneficiaries, however, proportional payments (even if negative) may leave some consumers worse off. A Pareto-improving outcome can still be achieved with a slight modification of the previously discussed lump-sum tax program. The most straightforward way of doing so is to increase the proportional collection of benefit taxes

from the *winners* (those consumers for which $\hat{V}_t > \tilde{V}_t$) in order to leave the *losers* (those

consumers for which $\hat{V}_t < \tilde{V}_t$) just as well off as they were without the watershed

management plan. The tax collection would be higher per household in this scenario,

inasmuch as the *winners* must compensate the *losers* in addition to financing investment

in conservation.

3.3 Conservation financing under alternative property rights regimes

The model and discussion up until now have proceeded on the assumption that the

watershed overlies publicly owned land that is protected for environmental and/or

cultural reasons. In such cases, the government need not worry about private landowners,

who may object to using the land for conservation purposes. If private landowners own

the watershed, however, they likely already enjoy profits from other uses of the land,

such as logging or agriculture. In this section, we consider how the analysis should be

modified to incentivize private landowners to optimally conserve the watershed.

One possibility is for the government to pass a law mandating the landowner to

conserve at least enough to maintain a percentage of the current level of recharge or some

other benchmark. If the landowner conserves beyond the benchmark level, then he must

be paid the value of additional recharge services yielded by the investment in

conservation capital. If he fails to preserve at least the benchmark level of recharge, then

the government charges him the value of the recharge lost. Such payments for ecosystem

services can leave landowners better off than they otherwise would be if the payments

exceed the sum of conservation investment costs and forgone profits from the most

profitable alternative land use.

Alternatively, the government can pay the landowner just enough to make him exactly as well off as he was before the watershed program was implemented, while inducing the optimal level of conservation. In that scenario, the payment of the investment costs would still be proportional to the benefits, and accordingly each water user would still be made at least as well off as in the benchmark case. The solution would emulate the public case, except that private landowner would receive a transfer to leave him at least as well off, ensuring that the program is still Pareto-improving.

Whether private landowners would be allowed to make a profit from ecosystem services or would be left only as well off as they were before implementation of the conservation program is a question we leave to the political process. In either case, the government would not need to finance the program if capital markets were perfect. Inasmuch as capital markets are not perfect, however, implementing such a conservation program would be greatly facilitated by a watershed partnership.

3.4 Discussion

Investing in watershed conservation lowers the marginal user cost of groundwater and consequently the efficiency price. Volumetric user charges that increase the price of water thus impede efficiency. Lump-sum financing of investment, on the other hand, is win-win. Every generation of water users is better off after implementing and financing the conservation project than if groundwater is optimized without watershed conservation. The lump-sum tax structure is simple and transparent, yet preserves efficient incentives. A "watershed conservation tax" would appear as a separate charge on a typical user's water bill, much as sewerage fees do in many localities. The fixed

charge would be explained as representing a proportion of expected benefits from the watershed conservation plan.

Whether the watershed conservation surcharges can be truly classified as "lump-sum" depends on consumers' elasticity with respect to the fixed fee. The analysis thus far has maintained the assumption that consumers are perfectly inelastic, but the literature on other types of public utilities suggests that this is not always necessarily the case. Rodini et al. (2003) find that mobile phone services exhibit some substitutability with telephone landlines, particularly with a second fixed line. In that example, an increase in the monthly fixed charge for a landline might induce a consumer to switch over to a mobile phone service. Such a fee increase, while not volumetric, is also not lump-sum, inasmuch as it affects the user's landline consumption decision. Although there are few analogous alternatives for potable water, a conservation surcharge may affect things like household formation, thus making consumers less than perfectly inelastic.

Implementing the watershed conservation tax would require enabling legislation for water utilities to change their principles of finance in localities such as Hawai'i, where the utility is allowed to finance construction and maintenance of groundwater infrastructure but not for maintaining nature's infrastructure for aquifer recharge. Inasmuch as investment costs are concentrated in the initial periods and benefits concentrated in future periods, financing a watershed conservation program requires borrowing. One way to borrow the requisite funds is a state-issued bond. Since the Department of Land and Natural Resources (DLNR) has the authority to designate forest reserves for the protection of the state's water resources, while the Honolulu Board of Water Supply (BWS) provides groundwater to most users on O'ahu, the envisioned plan

of finance would require interagency coordination. Legislation would be required to enable the HBWS to collect conservation surcharges from water users on behalf of the state. DLNR would ultimately carry out the watershed conservation project, while the state pays off the bond using the surcharges collected by HBWS.

The problem becomes slightly more complicated, when multiple types of users are considered. The analysis thus far has proceeded on the assumption that each generation can be sufficiently characterized by a representative consumer. The benefit principle should still extend to various types of users, provided that welfare gains can be differentiated by user, i.e. there is sufficient information regarding the preferences or demand functions of every household.

4 Watershed conservation as climate adaptation

Available research indicates that climate change will affect groundwater recharge rates and levels in a multitude of ways, although the regional magnitude, and in some cases the direction, of such impacts remain uncertain (IPCC, 2007b). Climate change may lead to changes in vegetation, and hence evapotranspiration (ET), which affects recharge to groundwater aquifers. An increase in temperature would also affect ET and consequently recharge, inasmuch as more water would evaporate before having the opportunity to infiltrate back into the ground. In addition, increased ET and associated sea level rise lead to intrusion of saline water into coastal aquifers, reducing the usable portion of coastal groundwater resources. Climate change models predict a considerable future increase in heavy rainfall events in many areas, including Hawai'i (IPCC, 2007a),

in which wet-season mean rainfall may decline (Timm and Diaz, 2009).[12] A higher

frequency of extreme events increases the risks of floods, adversely affects the quality of

groundwater resources, and may negatively affect recharge depending on how much of

the concentrated rainfall is lost as runoff. In many regions, aquifer recharge is likely to

decrease (IPCC, 2007a) unless the quality of watersheds is improved. The analysis that

follows focuses on such areas in which the decline in recharge dominates a possibly

higher level of average annual rainfall.

In addition to climate change, there are other reasons why the watershed may not

be in a steady state condition. In some locales, logging is a source of livelihood for

residents and the forest stock acts as a natural asset which can be quickly liquidated

should the need arise. Events such as landslides, which cause catastrophic damage to

delicate watershed ecosystems, naturally occur and climate change will likely increase

the frequency of such occurrences. Watersheds are also constantly being threatened by

new and existing invasive species. Invasive species alter existing land cover in otherwise

balanced ecosystems, which results in increased runoff, decreased evapotranspiration, or

both. Consequently, without watershed conservation, recharge decreases over time.

Declining recharge creates an even stronger case for investment in conservation

capital. As depicted in Figure 4, climate change causes the recharge function to shift

downward over time. Thus for a given level of capital stock (N_1), the recharge rate is

lower ($R_1 < R_2$). The excess burden of not properly managing the watershed is higher for

more substantial declines in recharge. The intuition is that as water scarcity increases, so

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[12] Regional climate predictions made by global climate models are highly uncertain, however, inasmuch as local topography is not sufficiently characterized at the global scale. Recent attempts to design regional climate models using statistical downscaling techniques require further refinement but provide a step in the right direction.

does the value of the marginal groundwater unit. Consequently, it is optimal to actually

maintain a higher capital stock with climate change ($N_{opt}^{cc} > N_{opt}^{ncc}$), even though the

resulting recharge rate is lower ($R_{opt}^{cc} < R_{opt}^{ncc}$). Figure 5 illustrates the result in terms of the

MOC of groundwater. Since a higher capital stock is optimal for declining recharge, the

downward shift of the MOC starting from the status quo is actually larger than the shift

for the case of no climate change. Thus, the change in quantity consumed is also larger,

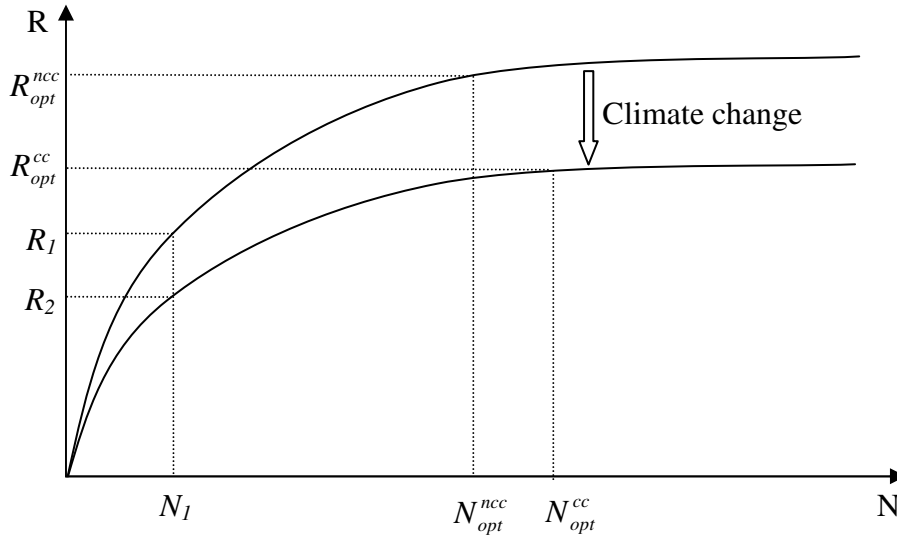although the absolute amount of total consumption is lower.

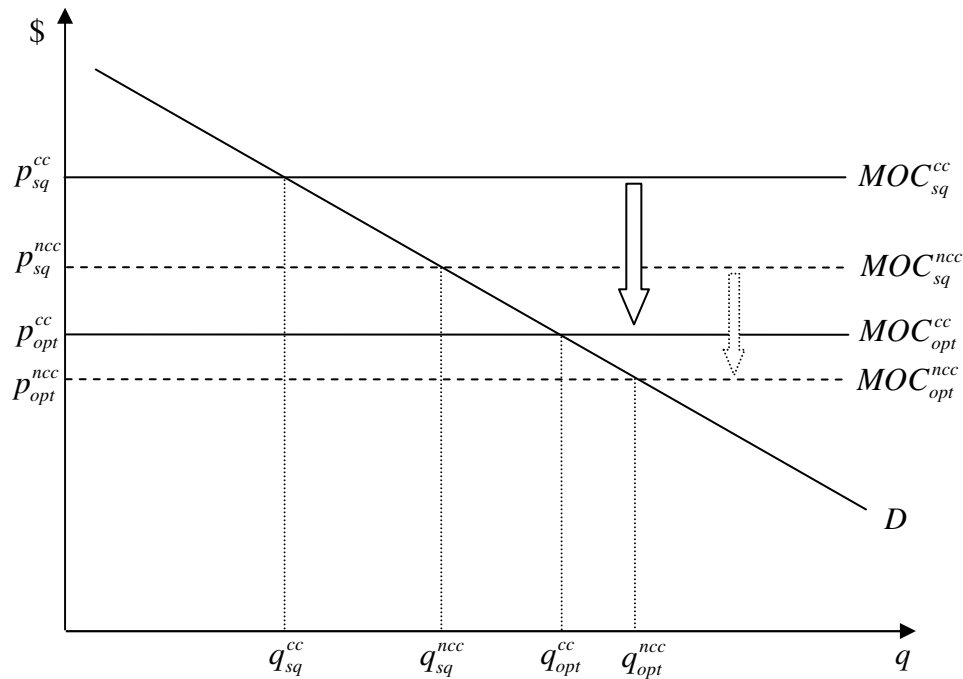Figure 4. Declining recharge resulting from climate change

Figure 5. Climate change increases excess burden of non-optimal watershed management

5 Conclusion

Ecosystems are a form of natural capital that produces a flow of benefits over time, much as natural resources do. Valuing ecosystem services requires investigating many aspects of complex and intertwining systems, including but not limited to geophysical, ecological, and economic systems. In this paper, we develop a methodology for valuing benefits to groundwater consumers resulting from optimal conservation of an up-gradient watershed. Upon solving the dynamic optimization problem, we find that accounting for declining recharge capacity increases the marginal user cost and hence the efficiency price of groundwater. At the same time, implementing a conservation project reduces the shadow price of groundwater. The PV gain in consumer surplus created by

the groundwater price differential serves as a lower bound to the benefits of forest conservation. Other non-measured values include, for example, recreation, biodiversity, and cultural values.

Since consumers receive the benefits from investment in maintaining the watershed, benefit taxation requires them to be responsible for the costs. A lump-sum watershed conservation surcharge is transparent, as it requires each generation of users to pay a proportion of its benefit to fund watershed conservation. Unlike a volumetric conservation surcharge in the public utilities context, whose purpose is to induce demand-side conservation in order to avoid capacity expansion costs, the efficient watershed conservation surcharges are lump-sum. Inasmuch as investment in watershed conservation actually reduces the price of groundwater, a volumetric groundwater charge would induce inefficient consumption.

Investment follows a most rapid approach path to the steady state, and much of the cost is concentrated in the initial periods of the program. Accordingly, it is as if the government issues a bond to finance the conservation program, and the bond is paid off by future beneficiaries. This may require enabling legislation for water utilities to change their principles of finance. In states such as Hawaii, the utility is allowed to finance the construction and maintenance of the infrastructure for groundwater extraction and delivery, but not for maintaining nature's infrastructure that recharges the aquifer.

The theoretical framework developed is generally applicable to other instances of an upstream watershed providing ecosystem services to a downstream resource. Consider, for example, the case of hydroelectric power. If the watershed is allowed to deteriorate, runoff increases as less permeable land-cover replaces the healthy forest

system. Increased runoff creates more sediment flow into the downstream reservoir, and consequently decreases the capacity of the reservoir over time. The decline in reservoir capacity decreases the power generating capacity of the hydroelectric plant. Therefore, a resource planner should invest in watershed conservation until, at the margin, the costs of investment are exactly equal to the benefits, which are measured as the value of electricity capacity saved by the reduction in sediment flow. Assuming the utility generates its electricity primarily from the hydroelectric plant, a lump-sum tax system can be implemented to distribute watershed project costs in accordance with benefits obtained by electricity users. More generally, the framework can also be applied to other situations where resource management includes investment in the growth of a resource. Examples include fisheries, forest stands, and pastures for cattle grazing.

The analysis is a first step toward the optimal management of a groundwater aquifer and its associated watershed. Many simplifying assumptions are made to facilitate clearer understanding of the model's outcomes and resulting policy implications. Consequently, many possible research extensions could improve on and extend the basic model. Inasmuch as water balance, and hence groundwater infiltration, depends on many factors other than precipitation and forest stock, e.g. type of land cover, soil porosity, ground slope, the characterization of the state of the watershed should depend on vector of these factors in a real world application. In addition, these factors also vary over space, which means that application of a spatial version of the model would require detailed information provided, for example, by GIS. A more advanced framework might also take into account other flows of benefits generated by the watershed. In addition to the consumption benefits of increased groundwater recharge,

investment in watershed conservation also mitigates sedimentation, potentially increases

biodiversity, and adds cultural value when reforestation is primarily native flora.

Appendix A. Current Value Hamiltonian

The corresponding Current Value Hamiltonian is:

$$\text{(A1)} \quad H = \int_0^{q_t + b_t} D^{-1}(x_t) dx_t - [c_q(h_t) + c_d] q_t - [c_b + c_d] b_t - c_I I_t$$
$$+ \lambda_t \gamma^{-1} [R(N_t) - L(h_t) - q_t] + \mu_t [I_t - \delta N_t]$$

The Maximum Principle requires that the following conditions hold:

$$\text{(A2)} \quad \frac{\partial H}{\partial q_t} = D^{-1}(q_t + b_t) - c_q(h_t) - c_d - \gamma^{-1}\lambda_t \leq 0 \qquad q_t \geq 0, \; q_t \frac{\partial H}{\partial q_t} = 0$$

$$\text{(A3)} \quad \frac{\partial H}{\partial b_t} = D^{-1}(q_t + b_t) - c_b - c_d \leq 0 \qquad b_t \geq 0, \; b_t \frac{\partial H}{\partial b_t} = 0$$

$$\text{(A4)} \quad \dot{\lambda}_t - r\lambda_t = -\frac{\partial H}{\partial h_t} = c_q'(h_t) q_t + \gamma^{-1}\lambda_t L'(h_t)$$

$$\text{(A5)} \quad \dot{h}_t = \frac{\partial H}{\partial \lambda_t} = \gamma^{-1}[R(N_t) - L(h_t) - q_t]$$

$$\text{(A6)} \quad \dot{\mu}_t - r\mu_t = -\frac{\partial H}{\partial N_t} = -\gamma^{-1}\lambda_t R'(N_t) + \mu_t \delta$$

$$\text{(A7)} \quad \dot{N}_t = \frac{\partial H}{\partial \mu_t} = I_t - \delta N_t$$

Appendix B. Comparative Statics

Since the system is assumed to be in a steady state, time subscripts have been omitted to avoid notational clutter. Starting with Eq. 7, define the function G:

(B1) $\quad G \equiv c_b - c_q(h) - c_d + \dfrac{c_q'(h)[R - L(h)]}{\gamma r + L'(h)} = 0.$

Then, applying the implicit function theorem:

(B2) $\quad \dfrac{\partial h}{\partial R} = \dfrac{\partial G / \partial R}{\partial G / \partial h} < 0,$

where

(B3) $\quad \dfrac{\partial G}{\partial R} = \dfrac{c_q'(h)}{\gamma r + L'(h)},$ and

(B4) $\quad \dfrac{\partial G}{\partial h} = -c_q'(h) + \dfrac{[\gamma r + L'(h)]\{c_q''(h)[R - L(h)] - L'(h)c_q'(h)\} - c_q'(h)[R - L(h)]L''(h)}{[\gamma r + L'(h)]^2}.$

The assumptions about the leakage and extraction cost functions imply that $\partial G / \partial R < 0$ and $\partial G / \partial h > 0$, resulting in inequality B2.

From Eq. A5 and result B2, it is straightforward that

(B5) $\quad \dfrac{\partial q}{\partial R} = 1 - L'(h)\dfrac{\partial h}{\partial R} > 0.$

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