Coastal Groundwater Management in the Presence of Positive Stock Externalities

Problem and Research Objectives

The nearshore marine environment of Hawai‘i is a major recreational and ecological resource that supports indigenous fish and marine vegetation. Freshwater discharge from groundwater aquifers mixes with seawater along the coast to create an ecological system with salinity less than that of the ocean water. Onshore extraction of freshwater affects the salinity of the nearshore ecosystem since lower aquifer-head levels produce less freshwater discharge into the ocean. In other words, the state of the aquifer is directly linked to the cultural, recreational, and economic values of the community.

Thus our research objective was to determine the optimal management scheme in Hawai‘i for groundwater resources—taking into consideration both the benefits of water consumption and the environmental consequences of freshwater extraction.

Understanding the environmental consequences of freshwater extraction requires an assessment of the linkages between submarine discharge and the nearshore ecosystem. Native marine algae, identified by the Hawaiian word *limu,* play an important role as primary producers in a food web of endemic and other organisms. They can therefore serve as an appropriate indicator of the surrounding environment's overall health.

To gain a better understanding of how groundwater discharge affects the nearshore marine environment we monitored, in a controlled laboratory environment, the physiological response of a selected species of *limu* to varied levels of salinity and nutrients. We chose to use the edible endemic species of marine algae *Gracilaria coronopifolia* for our study.

Methodology

Our research agenda is inter-disciplinary and involves two sub-programs. The first uses a bio-hydro-economic model to solve for optimal levels of groundwater use and *G. coronopifolia* production. The second is a laboratory study of the relationship between salinity and the biological productivity of *G. coronopifolia*.

Bio-hydro-economic Model

The model is an application of optimal control theory and follows the framework laid out in Krulce, Roumasset, and Wilson's (1997) study of the Pearl Harbor aquifer. The objective is to choose the paths over time of groundwater extraction and desalinated-water production to maximize the present value of net social surplus from water. For this purpose social surplus includes both traditional water-use benefits as well as external benefits (or costs) of freshwater extraction on the nearshore ecosystem. Our particular study focuses on *G. coronopifolia* as the nearshore resource affected by submarine discharge but the model is general and can therefore be applied to any other nearshore resource.

Mathematically, the problem is to

$$\max_{q_t, b_t} \int_0^{\infty} e^{-rt} [\int_0^{q_t + b_t} p(x)dx + \int_0^{m_t} p_m(y)dy - c(h_t)q_t - \bar{p}b_t - c_m(S_t)m_t]dt$$

subject to
$$\dot{h}_t = a[R - l(h_t) - q_t]$$
$$\dot{S}_t = g(S_t, h_t) - m_t$$

where the social surplus is defined as the consumer surplus associated with water and *G. coronopifolia* consumption (the first two terms) less the producer costs of freshwater extraction and ocean-water desalination as well as the cost of harvesting *G. coronopifolia* (the last three terms). The aquifer-head level evolves over time according to changes in natural inflow, leakage, and extraction. The evolution of the *G. coronopifolia* stock depends on harvesting and on the resource's intrinsic growth function (which is itself dependent on the stock and on freshwater discharge).

Manipulation of the first-order conditions for this problem yields the following expression for price:

$$p = c(h) + \frac{\dot{p} - a(R - l(h))c'(h)}{r + al'(h)} + \frac{ag_h(S,h)\theta}{r + al'(h)}$$

The usual expression for the efficient price of a renewable resource includes the first two terms on the right hand side of the equation; price is equal to extraction cost plus marginal user cost. There is a third term, however, when a stock externality exists. In this case the term captures how the stock of groundwater (and hence discharge) affects the growth rate of *G. coronopifolia*.

Freshwater-carried nutrients and algae growth

G. coronopifolia was chosen for this investigation in order to assess the impact of varied levels of submarine groundwater discharge on the nearshore environment. The physiological parameters measured in this investigation include growth rate, branch development, and in vivo pigment absorption. Growth rate is measured as changes in wet-tissue mass over time and branch development is measured by quantifying the rate at which new growing tips are formed in reference to the initial tips and initial mass. To accurately measure these physiological responses to isolated variables a digital growth chamber was modified to support a unidirectional flow-through saltwater system.

In order to quantify changes in wet weight and morphology, three variables were calculated. The specific growth rate was calculated [(final wet mass – initial wet mass) / initial wet mass] / sixteen days. The percent change in apical-tip number relative to initial-tip number was calculated in a similar manner: 100*[(final apical-tip number – initial apical-tip number) / initial apical-tip number] / sixteen days. In order to quantify the number of apical tips in reference to initial weight, apical-tip number / mass is calculated as the tip score. The change in tip score can then be calculated [(final tip score – initial tip score) / initial tip score] / sixteen days.

Principal Findings and Significance

Native algae growth and nutrients

In order to simulate submarine discharge in a controlled environment, we ran trials with four levels of salinity (11‰, 19‰, 27‰, and 35‰) and corresponding levels of other nutrients, the proportional relationship of which others have estimated for the North Kona Coast. The mean growth rate, percentage change in apical-tip number, and apical-tip number/mass were calculated for each level of salinity. Only the 11‰ treatment differed significantly in both mean specific growth rate (lower than the others) and in vivo pigment absorption (higher than the others). Nearly half of the samples in the 11‰ treatment group died rapidly while the other half grew at rates similar to the other treatment groups. Therefore it is likely that the lower salinity concentration threshold for the viability of *G. coronopifolia* is close to 11‰.

Significant results were obtained for both measures of tip development. The 27‰ salinity-level treatment showed at least twice the branching rate of any of the other treatments. Since most growth of marine algae occurs at the apical tips, it is clear that those samples with more tips per mass will have higher growth rates.

In the botanical experiment, maximal *G. coronopifolia* growth rate increased with increasing salinity, within the 11‰–27‰ range. Within the 27‰–35‰ salinity range, however, the maximal growth rate actually decreased with increasing salinity from 3% per day for the 27‰ treatment to 1% per day for the 35‰ treatment (ocean salinity), i.e. the growth rate declined by about 67%.

This study demonstrates that the calculation of tip scores and the percent of new apical tips are valid and useful methods for quantifying changes in morphology of marine algae. Water chemistry conditions which simulate moderate amounts of freshwater discharge maximize the growth rate of *G. coronopifolia* when compared to ambient ocean-water controls.

Bio-hydro-economic Model

We use data from the Kūkiʻo area located along the North Kona Coast of the island of Hawaiʻi to numerically solve for the optimal groundwater-management program. The *G. coronopifolia* growth curve estimated in the lab likely overstates the true intrinsic growth rate, inasmuch as the controlled experiments do not simulate fish herbivory, competition with invasive algae or other plant species, and human harvesting. The bio-hydro-economic analysis takes these factors into account by adjusting the growth rate downward and explicitly including harvest as a subcomponent of the model.

Upon establishing a functional relationship between *G. coronopifolia* growth and submarine groundwater discharge, we are then able to proceed with numerical simulations of the model. In the first of three approaches, we use the actual market value of *G. coronopifolia* and find that optimal water extraction is less than extraction when *G. coronopifolia* is ignored, although the difference is slight. This is likely due to the fact that the value of *G. coronopifolia* is small relative to the value of water. Market value accounts for only the consumptive value and ignores other potentially significant cultural and ecological values.

We address cultural and ecological value by imposing a “safe-minimum standard” on the *G. coronopifolia* stock in the second approach. When a stock constraint is imposed, the optimal paths of water extraction, aquifer-head level, and price for water are non-monotonic. The aquifer is optimally depleted below its steady-state level initially and is then built back up to the steady-state level in the period that follows. This contrasts with conventional management according to maximum sustainable yield. While the backstop technology (desalination) is never required in the market value scenario (due to the assumption of a stationary demand function), it is implemented for all stock constraints that meet or exceed 75% of the current stock. Maintaining a tight stock constraint requires substantial water conservation—which could be implemented by higher consumer prices at the margin.

The growth function of the stock of *limu* is difficult to estimate in situations where the stock is small relative to its size without predators. Thus in the third approach, we impose a constraint on the intrinsic growth rate, equivalently, a constraint on the salinity level achieved by a minimum discharge level. This minimum discharge is associated with a particular head level, so the constraint is ultimately imposed on the head level of the aquifer. For head constraints that represent a reasonable range of growth rates given the ocean salinity at the study site (1.8%–2%), the optimal approach paths for head, pumping, and price are monotonic. The head level rises over time in all scenarios as the optimal rate of extraction declines over time. With the growth constraints, desalination is never used. Again, the stricter the constraint, the more water conservation is required.

Publications Cited in the Synopsis

Krulce, D.L., J.A. Roumasset, and T. Wilson. 1997. Optimal management of a renewable and replaceable resource: The case of coastal groundwater. *American Journal of Agricultural Economics* 79 (4): 1218–1228.