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**OPTIMAL MANAGEMENT OF A
HAWAIIAN COASTAL AQUIFER WITH
NEAR-SHORE MARINE ECOLOGICAL
INTERACTIONS**

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Abstract

We optimize groundwater management in the presence of marine consequences of submarine groundwater discharge (SGD). Concern for marine biota increases the optimal steady-state head level of the aquifer. The model is discussed in general terms for any coastal groundwater resource where SGD has a positive impact on valuable near-shore resources. Our application focuses on the Kona Coast of Hawai'i, where SGD is being actively studied and where both near-shore ecology and groundwater resources are serious socio-political issues. To incorporate the consequences of water extraction on nearshore resources, we impose a safe minimum standard for the quantity of SGD. Efficient pumping rates fluctuate according to various growth requirements on the keystone marine algae and different assumptions regarding recharge rates. Desalination is required under average recharge conditions and a strict minimum standard, and under low recharge conditions regardless of minimum standards of growth.

Index terms: 0476 Plant ecology (1851), 1813 Eco-hydrology, 1829 Groundwater hydrology, 1880 Water management (6334), 6334 Regional planning (1880)

Keywords: groundwater management, marine ecology, dynamic optimization, safe minimum standard, sustainability science.

1. Introduction

With a majority of population centers located near coastlines, sustainable management of coastal aquifers is a priority water resource issue worldwide (Postel 1997, 1999). The ecological importance of these same coastal aquifers to near-shore marine ecosystems, via submarine groundwater discharge (SGD), is a rising topic of interest among researchers, managers and policymakers (Johannes 1980, UNESCO 2004). As such, there is a need to jointly study the optimal management of coastal water resources with explicit consideration of the potential effects on important marine ecological resources.

Groundwater management is examined extensively by many resource economists including, for example, Renshaw (1963), Burt (1964), Brown and Deacon (1972), and Gisser and Sanchez (1980). These pioneering works address the groundwater allocation problem in the context of the theory of the mine and simplify what are often very complicated hydrogeological situations. However they offer valid analytical tools if used properly with their limitations clearly stated. The problem of groundwater management becomes more complicated when dealing with a coastal aquifer. First, the discharge depends on the amount of groundwater storage and head; the higher the head/storage, generally the higher the discharge, due to an increased flow gradient from land to ocean. Second, seawater desalination may be added as an additional, albeit high-cost source of freshwater, commonly known as a “backstop” resource. The coastal groundwater problem, then, is analogous to the prototypical renewable resource problem where natural growth is a function of its own stock. This special characteristic requires a model that allows for endogenous net recharge, such as introduced by, for example, Tsur and

Graham-Tomasi (1991). However, existing endogenous recharge models of groundwater management focus only on the effects of groundwater storage on the change in net recharge to the aquifer. The external, ecological effects of groundwater discharge have not been examined in the economic literature.

Within the hydro-geological community, numerous papers exist on the physical and chemical processes surrounding basal aquifers, saltwater intrusion and upconing, optimal coastal well design, groundwater discharge to the ocean, and related coastal water resource phenomena. Bear et al. (1999) and Cheng and Ouazar (2003), and Ukarande 2009 provide an excellent overview of the state of knowledge on the subject. Hydrologic-economic models build upon this strong scientific foundation to address social and economic concerns. Several look specifically at the important issue of seawater intrusion in regional groundwater systems (Willis and Finney 1988, Benhachmi et al. 2003, Hallaji and Yazicigil 1996, Das and Datta 1999). Shamir et al. (1984) determine optimal annual operation of a coastal aquifer by using a multiple objective model. The uncertainty of a coastal aquifer's input parameters such as hydraulic conductivity, freshwater outflow, and pumping rate has been examined by Naji et al. (1999). Dasgupta and Amaraweera (1993) use recharge estimates from a water balance study and consider the variations of factors affecting the soil moisture balance to assess the sustainability of continuous water withdrawal in the future. Though the discharge of water to the ocean is a necessary part of water/mass balance in all of the above efforts, the ecological effects of SGD have not been explicitly considered in many of these coastal water management models.

The ecology of coastal brackish environments has been studied worldwide for many decades. While more is known about the effect of freshwater inputs to coastal ecosystems such as estuaries and river mouths, the effect of SGD on marine organisms has only recently become a topic of interest. SGD input to marine ecosystems decreases the salinity and increases the nutrient content of the surrounding marine waters in a way similar to estuaries and river systems (Li et al. 1999, Moore et al. 2009, Burnett et al. 2006, Bratton et al. 2009). The organisms which inhabit these brackish environments must be able to maintain high productivity while withstanding rapid fluctuations in water column nutrients and salinity. Although nutrient concentrations have long been known to determine the productivity of primary producers, salinity has been shown to influence the growth and distribution of marine photosynthetic organisms (Koch and Lawrence 1987, Dawes et al. 1998, Israel et al. 1999). Many studies have shown a relationship exists between SGD and algal biomass worldwide (Smith et al. 2005, Lapointe 1997, Herrera-Silveira et al. 1998, 2004, Hwang et al. 2005, Lee and Kim 2007, Tse and Jiao 2008, Leote et al. 2008). Tropical regions in particular have been a hot spot for research on this topic in the last decade due to the oligotrophic (nutrient deplete) nature of marine waters. Evidence has been accumulating in the literature that certain species of tropical marine algae have increased productivity in brackish water relative to ambient oceanic salinity. Numerous studies have shown that the growth rate, for example, of *Gracilaria spp* increases as salinity decreases from ambient oceanic levels with optimal conditions occurring between 20-30‰ salinity (Causey et al. 1946, Hoyle 1976, Glenn et al. 1999, Israel et al. 1999, Yokoya et al. 1999, Choi et al. 2006). From these studies, it is likely that certain marine primary producers have adapted to and rely on SGD as a natural

source of terrestrial nutrients and freshwater. Therefore, excessive extraction of groundwater has the potential to limit the productivity and distribution of these species as SGD flux to the coastal environment decreases. This effect may be magnified in arid tropical regions where terrestrial runoff is minimal and SGD represents the only source of freshwater and “new” nutrients to marine ecosystems.

The hydrologic-economic-ecologic model presented here builds upon prior natural resource management models but focuses on the interaction between groundwater use and consequences to the near-shore ecosystem. Generalized to be applicable to most any coastal aquifer system with valuable near-shore resources, the model is applied here to the Kona Coast of Hawaii where SGD is being actively studied (e.g., Johnson et al. 2008, Peterson et al. 2009), and where both near-shore ecology and groundwater resources are serious socio-political issues.

2. Methods

The water management model presented here is similar to many past hydrologic-economic coastal aquifer models (Krulce et al. 1997, Koundouri and Christou 2006) in that it mimics the welfare-maximizing behavior of a single planning entity. It differs from others in that it allows the planning entity to explicitly consider the welfare of the near-shore marine ecosystem, and hence weigh the ecological and economics costs of different long-term pumping strategies under varying ecological regimes and recharge scenarios. It incorporates standard hydrologic and economic equations; with the addition of constraints linking pumping of a basal aquifer to changes in growth rate or productivity of a keystone marine species, in this case macro-algae. Figure 1 depicts the

relationships between inland recharge, pumping of coastal wells, SGD, and marine algae productivity.

The goal here is to take a practical first look at the potential effects of coastal pumping activities on the near-shore marine ecosystem of Hawaii, or, vice versa, how hard ecological constraints may impact water management strategies and economics. Actual empirical data is used for each part of the model, which necessitates simplification of the hydrology, ecology, and economics.

<<Figure 1 here>>

2.1. Hydrology: Coastal Aquifers and Submarine Groundwater Discharge (SGD)

Submarine groundwater discharge is a widespread phenomenon which can occur wherever an aquifer, with a head level above sea level, is hydraulically connected to permeable marine sediments (Burnett et al. 2003).¹ Submarine springs have been located in coastal waters worldwide including those of the United States, Cuba, Mexico, Chile, Jamaica, Australia, and Japan, although the majority have been found in the Mediterranean basin: Libya, Israel, Lebanon, Syria, Greece, France, Spain, Italy, and Yugoslavia (Bonem 1988). It is a well-known phenomenon in Hawaii, and has been documented on the West Hawaii coastline, including the area studied here (Kaneshiro and Peterson 1977, Lepley and Palmer 1967, Young et al. 1977, Adams and Lepley 1968, Duarte et al. 2006). In addition to point-sources of discharge such as springs, groundwater may also enter the marine environment in a diffuse manner through benthic

¹ While submarine groundwater discharge can be freshwater or brackish recirculated seawater, for the purposes of this study we are focusing on fresh SGD.

sediments (Gallerdo and Marui 2006). As terrestrial groundwater enters the marine environment, mixing results in water which may have a chemical signature which is quite different than either source. Concentrations of nutrients, trace metals, organic carbon, methane, CO₂ may be considerably higher than surface ocean waters (Burnett et al. 2003). The effect of SGD on marine waters may be variable over large spatial scales as this is expected to be relative to local and regional, geologic, tidal and climatic conditions.

With renewed interest and advances in detection techniques, many studies have recently concluded that SGD is a significant source of nutrients to numerous coastal environments (Burnett et al. 2001, 2003, Giblin and Gaines 1990, Johannes 1980, Lapointe 1997, Paerl 1997, Simmons 1992, Corbett et al. 1999, D'elia et al. 1981). Groundwater nutrient concentrations are typically high relative to seawater and even small groundwater fluxes may make large contributions to coastal nutrient budgets (Li et al., 1999, Stieglitz 2005). The pore waters of coastal sediments have repeatedly been found to contain dissolved inorganic nitrogen (DIN) and phosphate concentrations several orders of magnitude greater than that of the overlying water column (Valiela et al. 1990, Valiela et al. 1992). Many studies suggest that SGD flux may rival rivers and the atmosphere as a source of nutrients to coastal environments (Paerl, 1997, Garrison et al. 2003). For example, on the island of Oahu, Hawaii, total nutrient loading in Kahana Bay from SGD, was equal or greater than that carried by surface runoff (Garrison et al. 2003). In another example, total SGD flux (total flux / bottom area) to Yeosu Bay, Korea is 26 mM DIN m⁻²d⁻¹ and 0.11 DIP mM m⁻²d⁻¹, an order of magnitude greater than measurements from both stream water and ocean sediments (Hwang et al. 2005).

In addition to increasing nutrient levels, SGD has been shown to decrease the salinity of local waters compared to ambient oceanic conditions. Many studies have found significant inverse relationships between nutrients and salinity suggesting SGD as a source. In Discovery Bay, Jamaica, a highly significant negative relationship between nitrate and salinity with nitrate concentrations typically near 80 μM was found for SGD (D'Elia et al. 1981). In Cape Cod, MA, Giblin and Gaines (1990) observed a negative relationship between salinity and nitrate in sandy sediments. Lewis (1987) found a strong inverse relationship with salinity and nitrogen ($\text{NO}_2 + \text{NO}_3$). Phosphate has also been shown to be negatively related to salinity in regions of SGD (Knee et al. 2008, Johnson et al. 2008). In Great South Bay, New York, nitrate and salinity in sediment cores were negatively correlated and both variables were related to the amount of rainfall (Capone and Bautista 1985). Along the Kona coast, studies have demonstrated similar relationships, clearly showing decreases in salinity and increases in nutrients (Johnson et al. 2008; Duarte et al. 2006).

The nature of a coastal aquifer can be very complicated given the complexity of density-dependent flow dynamics and geology. The simplest model used to describe coastal aquifers is that of two immiscible fluids existing in the form of a basal lens or Ghyben-Herzberg lens. Though this model may not be appropriate for understanding the detailed flow dynamics of some coastal aquifer systems, it is sufficient for tracking average volumes of water in the aquifer and associated average head levels as required in this paper. For the western coast of the Big Island, this model is reasonable given the relatively calm sea conditions, homogeneous coastline geology, buffering effect of the high-level aquifer on basal inputs, lack of surface water inputs or outputs, and

unidirectional flow to the ocean along the coastline of study. While the actual transition zone itself is likely not completely sharp, the volume of recharge from the high-level aquifer via rainfall minus groundwater pumping must equal discharge to the ocean when a steady-state is reached. Assuming average ocean conditions are not changing, an increase in recharge will lead to a higher head levels and hence basal lens thickness.

Assuming Ghyben-Herzberg principles apply the change in the head level of the aquifer can be explained by natural recharge (R), amount of water extracted (q), and the submarine groundwater discharge/leakage of water to the ocean (l). The recharge is assumed constant. The aquifer state equation (1) is:

$$\boxed{} \tag{1}$$

where \square is a conversion factor converting volume to height of water based on the Ghyben-Herzberg principle.²

As a first-order approximation, we assume a linear relationship between the magnitude of discharge and the near-shore salinity at a given point along the coastline. Groundwaters discharging from West Hawaii into the coastal zone tend to be nearly fresh (salinity ~2-5) with reasonably good relationships between discharge, temperature and salinity (Peterson et al., 2009). While both salinity and discharge vary considerably over a tidal cycle (high discharge and low salinity at low tide), they tend to vary with a clear inverse linear relationship.

$$\boxed{} \tag{2}$$

² \square is specific to the site. Besides the Ghyben-herzberg relationship, it depends on the shape (e.g. length and width), and the porosity of the aquifer. Time subscripts are suppressed for the remainder of the paper for notational clarity.

where s is near-shore salinity, s_{sw} is average salinity of ocean water (not diluted by SGD), and d is a constant determined from local conditions. Equation 2 assumes that tidal influence, currents and other mixing phenomena remain roughly constant when integrated over time scales of days or longer. Since SGD is the only significant source of fresh water along this coastline, it is reasonable to assume that increases in SGD are directly proportional to decreases in near-shore salinity (Johnson et al. 2008, Peterson et al. 2009). This model does not attempt to resolve short time scale fluctuations in the water column which would require detailed coastal mixing models. We feel this assumption is appropriate given that near-shore marine algae would be most affected by changes in fresh water discharge in a relatively narrow boundary layer near-shore; prior to any open ocean mixing phenomena.

2.2. Ecology Matters: Importance of SGD to the Near-Shore Marine Ecosystem

Nutrient addition to near-shore marine ecosystems via SGD is of primary importance because nutrient availability largely controls primary productivity. Although inorganic forms of nitrogen are generally found to be the primary limiting nutrient in coastal ecosystems (Lapointe and Oconnell 1989, Littler et al. 1991, McGlathery 1992, Larned 1997), some studies suggest phosphate may limit algal growth (Lapointe 1987, Lapointe et al. 1987, Lapointe et al. 1992, Larned 1998). Changes in salinity due to SGD may also affect productivity as salinity is one of the most critical chemical factors affecting the growth rate, development, and distribution of seaweeds (Dawes et al. 1998, Israel et al. 1999, Koch and Lawrence 1987). The distribution and abundance of heterotrophic marine fauna may also be directly effected by changes in salinity due to

narrow ranges in osmotic tolerance for some organisms. Porewater salinity was found to be related to the composition of marine microphytes (Smith 1955, Moore 1979), of overlying algal mats, of the presence of a burrowing crab, of seagrass beds and associated fauna (Kohout and Kolipinski 1967), and density of polychaete worms. Commercial fish and lobster yields have also been positively correlated with the rate of discharge of land-based nutrients (Sutcliffe 1972). Recent studies have suggested SGD plays a major role in large scale increases of algal biomass in Hawaii (Smith et al. 2005), New York, Jamaica (Lapointe 1997), Mexico (Herrera-Silveira et al. 1998, 2004), Korea, (Hwang et al. 2005, Lee and Kim 2007), China (Tse and Jiao 2008), and Portugal (Leote et al. 2008).

Decreases in SGD over time could have serious implications ranging in scale from that of individual organisms to entire ecosystems. These disturbances may significantly alter the chemical properties of coastal waters endangering unique plants and animal species with ecological, cultural, and economic value. In this paper, we are interested particularly in the effects of water quality on Hawaiian indigenous marine algae (also called “limu” in Hawaiian), which are known to be a keystone species of the Hawaii’s coastal ecosystem (Abbott 1978).

To incorporate the effects on marine algae, a relationship is developed to link changes in SGD (or leakage), l , with changes in important water quality parameters,

$$\boxed{} \quad (3)$$

where $\boxed{}$ is the concentration of a given environmental parameter such as salinity, nitrogen or phosphorus. These relationships can be determined via direct field measurements

and/or estimated via numerical flow and transport models. We use salinity, nitrate and phosphate as the environmental parameters of interest in the case study.

The changes in \square are related to changes in a metric which correlates with productivity of the near-shore marine ecology,

$$\square \quad (4)$$

where \square could be stock of a given key species, growth rate, or any other ecological metric deemed important for the system of concern. We use growth rate as the indicator variable for productivity in the case study. Equation (4) may be incorporated into the management model as a minimum or maximum constraint, as done here, or be dynamically linked to a related resource stock, as done by Pongkijvorasin et al. (2010).

2.3. Management Model: Optimal Pumping Strategies with Ecological Constraints

The model structure applied here follows closely to the one in Krulce et al. (1997). Let $p(q)$ represent the price of water, which depends on the total amount of water used (q). At any time t , q amount of water is extracted from the aquifer. The extraction cost increases when the head level is lower because the water must be pumped a farther distance. The marginal cost of water extraction is assumed to be a positive, decreasing, and convex function of the head level, i.e., \square, \square .

We assume that an abundant but expensive alternative freshwater source exists, i.e., freshwater can be produced by seawater desalination. This is a special feature when dealing with coastal groundwater management, as seawater is abundant in the area. We denote \square as the fixed cost of producing water from desalination, and b is the amount of water produced by desalination technology at time t .

Head level of the aquifer varies as a function of natural recharge (R), amount of water extracted (q), and SGD (or leakage) to the ocean (l). As the head level increases, both the hydraulic gradient to the ocean and surface area from which water can leak increase. Thus, there is more water discharging from the aquifer into the ocean when the head level is high. We model SGD as a positive, increasing, convex function of head level, i.e., $l = l(h)$.

Examples of water quality parameters μ , which may affect the productivity of limu are salinity, nutrients, and temperature. For the case study, water quality μ will be represented by salinity, s_{sw} and, by empirical correlation, nitrate and phosphate.

Productivity, ψ , will be represented by growth rate, g , which is percent growth per day.

Therefore, natural growth rate of limu depends on nearshore salinity, nitrate, and

phosphate, $g = f(s_{sw}, \text{nitrate}, \text{phosphate})$. These indicators are related to the amount of

freshwater discharged, $l(h)$. From these relationships, the natural growth rate of limu is therefore dependent on the aquifer's head level, h , as well as other ecological factors not considered here (light, temperature, etc.).

The social planner's problem is to choose the paths of groundwater extraction and desalinated water in order to maximize social net benefit, which is equal to consumer surpluses, derived from water consumption, minus the costs of obtaining the water. To integrate ecological considerations, we impose a constraint on the intrinsic growth rate of limu, e.g., $g \geq \bar{g}$, which can be also expressed in terms of head level, e.g., $l \leq \bar{l}$, as described above. Given discount rate r , the problem can be written as:

$$\max_{\{q, l\}} \int_0^{\infty} e^{-rt} [B(q, l) - C(q, l)] dt \quad (5)$$

$$\boxed{\hspace{10em}} \tag{6}$$

$$\boxed{\hspace{2em}} \tag{7}$$

If the constraint (equation 7) is non-binding, the condition for the optimal trajectories can be expressed as:

$$\boxed{\hspace{10em}} \tag{8}$$

The optimal condition in equation (8) requires the equality between the marginal benefit of water extraction and the marginal cost, which consists of the extraction cost and the marginal user cost (MUC).³ The MUC is composed of the forgone benefit from the higher future price and the higher extraction cost in the future.

When the constraint is binding, the steady state head level is higher than in the previous case. The optimal condition can be expressed as:

$$\boxed{\hspace{10em}} \tag{9},$$

where θ is the Lagrange-multiplier for the head level constraint (equation 7) or in other words, the scarcity value of the head level. Equation (9) indicates that the optimal condition requires the marginal benefit of extracting water equal to the marginal cost. In this case, the marginal cost consists of the extraction cost, the forgone benefit from the higher future price, the higher extraction cost in the future, and additionally, the cost of meeting the minimum growth requirement. This implies that, at a certain head level, the optimal water extraction with a binding constraint is less than when the constraint is not binding.

³ Time as a function argument has been ignored in some places to avoid notational clutter. Variables with a dot indicate their first-derivative with respect to time.

3. Application to the North Kona Coast, Hawai'i

The model is applied to the Kona Coast of the Island of Hawaii (a.k.a. the Big Island). North Kona was chosen for (1) its dependence on groundwater for virtually all water supply; (2) lack of any surface water systems to complicate the terrestrial-marine connection; (3) availability of field data; and (4) local political attention focused on both water resource scarcity and marine ecosystem degradation.

3.1. Coastal Water Resources of West Hawai'i

Virtually all water supplies on the west coast or leeward side of the Island of Hawaii are from groundwater; the small remainder being catchment water. Due to the young, highly porous volcanic geology of the region, there are no surface water features of significance (Giambelluca et al. 1986). The region receives much less rainfall than the windward side, with average rainfall ranging from 38 to 203 cm per year (versus 254 to 610 cm per year on the east coast of the Big Island).

In the inland/upland regions high-level aquifers exist, acting as a primary source of recharge to the thin basal aquifers. These unique aquifers are the result of groundwater held up to unusually high levels above sea level due to the presence of relatively impermeable geologic features that retard the flow of groundwater and build up water levels. While there is more than one form of high-level aquifer, in Kona they are due to geologic features, such as dikes and/or faults that cut perpendicularly across the semi-horizontal lava layers that make up the majority of the region's subsurface geology. The number of dikes is densest toward the center of the mountain and diminishes towards the

coast. As such, you will generally find high-level aquifers inland and basal aquifers towards the coastline. Though the physical and chemical dynamics linking these two aquifer systems are still poorly understood, if the high-level aquifers are in an equilibrium state and storage is not changing significantly, all upland “deep recharge” must be leaking to the lower coastal aquifer and out to the ocean. In essence, the high level aquifer acts as a fairly discrete recharge source to the basal aquifer. As such, it is reasonable to only model the coastal, basal aquifer when investigating SGD phenomena.

Basal aquifers in the region are thin, with coastal heads averaging 0.6-1.5 meters above sea-level. There is little to no caprock to increase head levels. Many aquifer areas are brackish even prior to pumping, and many wells have had to be shut down or pumping reduced due to salinization issues.

The dry, sunny nature of Kona has also made it an attractive destination for travelers and for residential and resort development. The increase in resident and visitor population is taxing water supplies, with affordable water often being the limiting factor for projects. As such, there is much discussion and debate concerning the sustainable yields of Kona’s aquifers and development of best management practices suitable to the unique circumstances of the area.

The data used in the test scenarios presented are from the Kaupulehu-Kukio area, which is a particularly dry and water-limited area of the North Kona coastline. Wells here penetrate the Kiholo Aquifer and, under virgin conditions, are sometimes brackish even a kilometer or more inland. Recharge is primarily on the inland-upland slopes, the vegetative land-cover is sparse and simple to account for, there is no surface water, and

good data exists for existing wells (Duarte 2002). Furthermore, the coastline is fairly calm with data existing on near-shore seawater salinities.

3.2 SGD in West Hawai'i and Selection of a Hawaiian Indicator Species

For the past three decades, the west coast of Hawaii Island has been a hot spot for SGD research due to its arid climate and unique hydrogeological properties as previously stated. Recent research in this area, employing a variety of techniques, has revealed more than 50 point-source and diffuse discharge sites which primarily occur or are amplified in coastal embayments (Johnson et al. 2008). More than 30% of the volume of coastal ocean water in the Kona coastal area may be due to SGD (Knee et al. 2008). SGD is the primary source of nitrate, phosphate and silica to this coastal marine environment.

Highly significant inverse relationships have repeatedly been found between salinity and nitrate, phosphate, silica and Ra-isotope activity indicating that salinity is a good indicator of SGD in this region (Johnson et al. 2008, Knee et al. 2008, Street et al. 2008). The coastal waters of Kona, as well as most tropical marine ecosystems, are classified as oligotrophic (nutrient deplete), and thus any addition of nutrients will increase primary productivity (Fong et al. 1996, Kamer and Fong 2001, Larned 1998, McGlathery, 1992, Peckol et al. 1994, Valiela et al. 1997, Fong et al. 1993). At near-shore SGD sites with low salinity, nutrient concentrations may be two to three orders of magnitude greater than off-shore ambient oceanic conditions (Johnson et al. 2008, Knee et al., 2008, Street et al. 2008).

In marine ecosystems, photosynthetic organisms ultimately sustain the entire oceanic food web through the use of sunlight energy to fix carbon. They are responsible

for 48% of global net primary productivity (Field et al. 1998) and produce between 30-60 Pg of organic carbon each year (Charpy-Robaud and Sournia 1990, Martin et al. 1987, Smith and Hollibaugh 1993, Carr et al. 2006). In order to quantitatively measure the potential impacts of groundwater on near-shore marine communities, marine macroalgae were chosen as a biological indicator. In Hawaii, macroalgae are of major importance to the local economy, cultural practices, and reef biology. Macroalgae are not used as extensively anywhere else in the Pacific. In particular, species in the genus *Gracilaria* are highly sought after as source of fresh food and agar worldwide.

In this case study, the Hawaiian endemic red edible limu manaua (*Gracilaria coronopifolia*) was chosen as a keystone indicator species. Limu manaua is native to the Kona coast and is economically, ecologically and culturally significant in Hawaii. This species is one of the three most sought after seaweeds for food in the Hawaiian Islands (Abbott 1984). While this alga is one of the ten most common macroalgae in Hawaii, its distribution and abundance in recent years has seen serious decline due to over harvesting and other important understudied factors. Limu manaua is known to tolerate a wide range of salinity and nutrient regimes (Hoyle 1975) making it a good candidate for physiological measurements at various levels of SGD.

In order to characterize the relationship between SGD influenced water quality and algal growth, we conducted two replicate experiments with *Gracilaria coronopifolia* using a highly controlled unidirectional algae growth chamber. This experimental design allows simultaneous variation of nitrate, phosphate and salinity in order to simulate varied levels of SGD. Four treatments were chosen using empirical relationships on SGD from the Kona coast (Johnson et al. 2008) to determine nutrient and salinity

concentrations. Treatments ranged from low salinity / high nutrients to high salinity / low nutrients with 12 replicate thalli per treatment. The results of this experiment allow us to plot changes in algal growth rate as a function of SGD (Figure 2). A significant quadratic regression relationship ($R^2=0.39$, $P=0.000$; Figure 2) was found for SGD treatment vs. growth rate. A maximal growth rate of 3.0% per day was observed in the 27‰ SGD treatment (27‰ salinity, 7.51 μM Nitrate, 0.15 μM Phosphate) which was ~ three-fold greater than ambient oceanic controls (35‰ salinity, 0.22 μM Nitrate, 0.05 μM Phosphate). Significant increases in apical tip development and photosynthetic performance were also greater in 27‰ SGD treatment compared to controls. For more information regarding the methodology and results of this experiment, please see Amato 2009. These result suggests that moderate levels of SGD influx to an oligotrophic environment may increase the growth rate of *Gracilaria coronopifolia* . For samples accustomed to SGD flux, reduced growth rates may result from decreased discharge. The relationship between SGD and growth is illustrated in Figure 2.

<<Figure 2 here>>

3.3. Management Model for Case Study Site

The coastal areas of the Kiholo aquifer is a thin basal lens. For a one-dimensional, sharp-interface case, the aquifer is modeled as a lens of less-dense freshwater floating on an underlying lens of denser saltwater. The state equation of head level for a thin basal lens can be approximated by:
$$h = \frac{W}{L} \left(\frac{1 - \theta}{\theta} \right) \left(\frac{L^2}{2} - x^2 \right)$$
, where θ is the porosity; W is the aquifer width; L is the aquifer length and $\frac{1}{2}$ simply converts to appropriate units.

For a more detailed explanation see Duarte (2002). In order to focus on the long-run optimal extraction path, we disregard three-dimensional issues wherein cones of depression and disequilibrium spatial relationships are allowed in the short run.⁴

For the Kiholo aquifer, the porosity is 0.3; the aquifer unit width is 6,000 m.; and the aquifer length is 6,850 m. Thus, the state equation for the Kiholo aquifer can be written as $Q = k(h - h_0)$. The water (e.g., recharge, discharge, or extraction) and head level are presented in units of “thousand cubic meters per year” (tm^3/y) and “meters” (m), respectively.

Mink (1980) derived the structural expression for discharge as a function of the head level, assuming a sharp interface between fresh and saltwater. He shows that the relationship can be expressed by: $Q = k(h - h_0)$, where k is a coefficient specific to an aquifer. In this paper, two assumptions are made in order to estimate the parameter k . First, we assume that under the current extraction rate, aquifer head level is being drawn down. Second, if there is no extraction, head level will be increasing to a new equilibrium. The current average net recharge for the Kukio aquifer is estimated to be $15,114 \text{ tm}^3/\text{y}$, while the current extraction rate is $1,074.4 \text{ tm}^3/\text{y}$. Under these assumptions, current leakage ranges from $14,039.6$ to $15,114 \text{ tm}^3/\text{y}$. With a current head level of 1.75 m, our k parameter is estimated to be between 4,584 and 4,935. In this simulation, we use a value of 4,800 for k , thus, the discharge function is estimated as: $Q = 4,800(h - h_0)$.

⁴ The wells in our model are substantially above the area of potential saltwater intrusion. Indeed the coastal hotels are already pumping groundwater from inland wells and using gravity to pipe it back to the points of consumption. And the predominantly-public wells in the area are typically spaced such that cones of depression have little or no impact on neighboring wells.

The costs of extracting groundwater are primarily due to the cost of energy needed to lift water to the ground level. Duarte (2002) estimates the unit cost, c , of water extraction for the Kiholo aquifer as a function of head level and ground elevation of the well for which data was collected, h_g : $c = 0.00083(h_g - h)$. Pitafi (2004), using 2001 data, estimates the unit cost of desalination and transportation of the desalted water to the existing water distribution system at \$7.00 per thousand gallons. Adjusted for inflation (Department of Business, Economic Development, and Tourism, 2006), we estimate the current cost of desalination to be \$7.70 per thousand gallons in 2005 dollars (\$2/m³).

We model the demand for water with a linear demand function: $p = \alpha - \beta q$. The Public Utility Commission price (retail price) for water in the region is \$1.27 /m³ (\$ 4.80 / 1000 gallons). We assume that the price elasticity of water demand is -0.7 (based on Griffin 2006 and Dalhuisen et al. 2003). The demand for water can be estimated as: $p = 3.1 - 0.00048q$ accordingly.

At the current level of discharge, the average near-shore coastal salinity in the area is approximately 31 ppt (State of Hawaii 2006). We assume that if there is no discharge, the salinity level would be at the average level of seawater (36 ppt). Assuming that salinity is linearly related to discharge, the relationship can be expressed as: $s_{sw} = 36 - 0.00033 * l$.

The growth rate of the marine algae is based on the growth curve presented in Figure 2 above. Assuming that growth is linearly related to salinity over the range of 29 – 36 ppt, this relationship can be expressed as $g = 10.2975 - (0.2625 * s_{sw})$.

A summary of key equations and parameters are presented in Tables 1 and 2.

<<Table 1 here>>

<<Table 2 here>>

4. Results of Modeling Scenarios

The model is first tested without any ecological constraints to generate a set of optimal pumping strategies which considers welfare based only upon water extraction. The model is then run with constraints on marine algae. This scenario demonstrates the effects of an ecological externality on water resource supply and system economics. We then test the model's sensitivity to recharge, which is a critical forcing flux in the system.

4.1. Unconstrained Case

We first solve for optimal extraction rates without regard for the ecology of nearshore resources. To reap maximum net benefit from water, extraction will be right above 5,770 tm^3/y and decreasing only very slightly over time to a slightly smaller steady state level. If the aquifer is depleted optimally, the steady state head level will be brought down to 1.4 m. The unconstrained case is illustrated alongside the minimum growth rate scenarios in Figure 3.

<<Figure 3 here>>

4.2. With Ecological Constraints

In order to integrate the importance of the keystone marine species into the economic model, constraints on the growth rate of the algae were imposed. The selected constraints represent a reasonable range of growth rates given ocean salinity levels at our

study site: 1.8% growth per day (hereafter, the “soft constraint”) and a 2% growth per day (“hard constraint”). These growth rates correspond to the desirable ranges of salinities for our species of interest in the Kaupulehu region, 29-33 ppt.

Minimum growth requirements reduce the optimal level of extraction over time, increasing aquifer head level. Under the hard constraint, optimal pumping will begin around 4,200 tm^3/y and decrease to a steady state level of 1,800 tm^3/y . Under this scenario, 482 tm^3/y of water would have to be desalinated. The steady state head level increases to 1.7 m due to lower groundwater extraction. Under the soft constraint, pumping increases to 5,600 tm^3/y and will decrease less rapidly to 4,100 tm^3/y . No water would have to be desalinated. Head level under the 1.8% per day constraint will fall to 1.5 m.

4.3. Sensitivity to Regional Recharge

One challenge with generalizing water management recommendations across aquifers or decision units is the variability in key parameters of the model. One particular parameter that may influence the transferability of our results, even within Hawaii, is the estimate of aquifer recharge. How much additional water is entering the system will undoubtedly influence optimal groundwater pumping recommendations. To address this issue, we performed a simple sensitivity analysis with respect to regional recharge.

To approximate recharge variation, we calculate the percentage deviation of rainfall in our study site from its mean. Rainfall in the Kaupulehu-Kukio region fluctuates roughly 10 cm from the annual mean (Bauer 2003). Average rainfall in the region is 50

cm, therefore plus and minus 10 cm is approximately 20 percent variation. We thus test the sensitivity of our results to variations of recharge of plus and minus 20 percent.

For the ecologically-unconstrained case, variation in recharge does not have a strong influence on optimal pumping. Steady state water extraction increases only about 400 m³ per year with 20% more recharge, and extraction falls by only 400 m³ per year with 20% less recharge. Head level drops a mere 24 cm with low recharge and increases by 21 cm with higher annual recharge. It thus does not appear that pumping under the unconstrained scenario is particularly sensitive to variations in recharge in the Kaupulehu region.

Recharge has a much more pronounced influence on optimal groundwater extraction when the effect of aquifer drawdown on the ecology of the nearshore limu resource is considered. We begin with the hard growth constraint. Under the low recharge scenario, withdrawal of groundwater from the aquifer is not possible. With 20 percent less rainfall, the algae are not able to sustain the 2% daily growth, even with no groundwater extraction. Therefore the alternative resource will be used exclusively, and 2,292 tm³/y of desalinated water will be provided to meet demand. However under the high recharge scenario, optimal pumping will be allowed to more than double that of average recharge conditions, starting at 5,600 tm³/y and decreasing gradually to a high steady state level of 4,800 tm³/y.

When we consider the soft growth constraint, optimal groundwater extraction under the low recharge assumption will drop significantly to a steady state just above 1,000 tm³/y. Furthermore, more water would need to be desalinated annually than withdrawn from the aquifer, approximately 1,196 tm³/y. However under the high

recharge scenario, the soft constraint is not binding. The water manager would be able to pump 20 percent more water without regard to the ecological constraint. Growth will remain higher than 1.8% per day while quantities equal to the unconstrained case are extracted. Under these wet conditions, extraction rates could increase significantly, to more than 1,500m³/year in the long-run compared to average recharge conditions.

<<Figure 4 here>>

The influence of the growth constraints under the three recharge scenarios are illustrated in Figure 4. Under average assumptions about recharge, the stricter the ecological constraint, the less water can be extracted in the steady state. However, if the water manager's region receives enough precipitation and thus high levels of recharge, the ecological constraint will not limit pumping except under the hard constraint, and by only about 900 tm³/y in this case. Caution is advised when recharge rates are low, however. It is not possible to sustain more than 2% daily algal growth under dry conditions, therefore the alternative (and expensive) desalination technology will be used exclusively. Furthermore, pumping will have to drop appreciably to sustain 1.8% daily growth. These scenarios are summarized in Table 3.

<<Table 3 here>>

The economic implications of differences in rainfall (thus recharge) and the severity of the ecological constraint are intuitive. No constraints and high recharge lead to

the highest net present values.⁵ Because we do not attempt to value the ecological services maintained and perhaps accentuated through the ecological constraints, increasing restrictions on growth reduces this benefit, as do lower recharge rates. Net present values for all scenarios are presented in Table 4.

<<Table 4 here>>

5. Discussion and Conclusions

It has long been understood that terrestrial and oceanic processes are not independent phenomenon. For thousands of years, Hawaiians and other coastal peoples have known that the health of the ocean is dependent on the health of the land. As the human population continues to rise, especially in coastal areas, our potential to negatively impact the coastal marine environment also rises. Controlling pollution and sustainable harvesting of oceanic resources is not enough to ensure the persistence of diverse healthy seas. In this paper, we attempt to change the paradigm that groundwater resources are primarily of importance for terrestrial applications. It is crucial that we begin to consider groundwater as a resource equally valuable to both terrestrial and marine ecosystems.

This paper develops the resource economics of groundwater pumping from a coastal aquifer, explicitly considering the potential effects of submarine groundwater discharge on important marine ecological resources. We model coastal groundwater management as a renewable but replaceable resource. Net aquifer recharge is a function of the current head level, and an abundant but expensive alternative resource (desalination) is available.

⁵ Where net present value is defined as the total stream of future benefits minus costs, evaluated in today's dollars.

When we consider the effect of pumping on a keystone marine species, a lower trajectory of water extraction is indicated. The backstop resource will be used only when the efficient price of water in the absence of desalination exceeds the cost of desalination.

We numerically illustrate the model using hydrologic data from the North Kona Coast of the island of Hawaii. To incorporate the ecological effect of groundwater extraction, we impose an ecological constraint on head level to preserve sufficient SGD leakage and thus a minimum growth rate for the marine algae of interest.

Efficient pumping rates fluctuate according to various growth requirements on the keystone marine algae and different assumptions regarding recharge rates. In very wet areas, the water resource managers may not have to adjust pumping (under the soft growth requirement) or may only have to decrease pumping very slightly (under the hard growth constraint). In drier areas with low recharge inputs, optimal pumping is sensitive to the level of caution implied by the ecological constraint. In these arid regions, no level of pumping is possible under the hard growth constraint and exclusive use of the alternative desalination technology is required. If managers are less cautious regarding minimum algal growth and impose the softer constraint, pumping can proceed at a low pumping rate. In summary, desalination is required under average recharge conditions using a hard constraint, and under low recharge conditions using either hard or soft constraints.

Specific to the issue of SGD impacts on near-shore ecosystems, the results are unique in that they focus purely on changes in the quantity of *naturally* occurring SGD and do not consider effects of contamination as studied by others (Herrera-Silveira and Morales-Ojeda 2009, Lapointe et al. 2005, Lapointe and Bedford 2007, Smith et al.

2005). Given the fact that marine algae have evolved to survive over a range of water quality conditions, there was a distinct possibility at the onset of this study that no differences would be observed by reasonable pumping rates. Such a null result, however, would have been equally important to management and policy.

In Hawaii and around the world, SGD is an emerging and exciting field that has the potential to help us understand the complex linkages between terrestrial and marine fluid dynamics and associated ecological systems. At the same time, serious socio-political battles are already raging with respect to terrestrial anthropogenic impacts on near-shore environments. In Hawaii, on one end of the spectrum are parties arguing that groundwater wells will diminish SGD and thus seriously degrade or destroy marine ecosystems. On the other end, landowners and developers insist that the effects are small and/or insignificant relative to other activities such as over-fishing and pollution in general. In the midst of these battles, new and emerging SGD data and analyses are being wielded as weapons. In most cases the science is in its infancy or there is no definitive analysis available. This may be leading to, in our opinion, very dangerous legal and policy precedent.

In the case of Hawaii, we hope that this research and results such as Figure 4 will provide some guidance on the issue. It seems clear that for the very wet, windward sides of the islands, it would take a tremendous amount of pumping to significantly affect SGD fluxes and net impact on the near-shore water quality. Of course, the locating of a well or well field can heighten or lessen impacts. For drier, leeward areas there is a greater chance of near-shore effects. However, it is possible that the impact could be on the order of or less than that of naturally occurring weather pattern and seasonal fluctuations. As

such, we advise communities in these dry regions to adopt general standards or BMPs for their near-shore environment and conduct high-level assessments using tools such as developed here. If there is a potential for concern, more detailed hydrologic and ecologic analysis can be done as a next step.

Our goal in this paper was to explore some basic ideas and consider methodologies for future integration of economic, hydrologic and ecologic management systems. While neither the economic or hydrologic components of the management model presented are original contributions in and of themselves, to our knowledge this is a first attempt to quantitatively link these three disciplines in a management model. The framework developed is generic and may easily be amended to suit a variety of management questions; with much room for greater advancement and detail in any one of the three principal model components. A number of opportunities exist for expanding this economic model. For example, pumping cost could depend on extraction rate in addition to the aquifer head level. Another extension would account for competition and predation among nearshore organisms. A third possibility could incorporate the long run optimization problem of location, capacity, and timing of well construction.

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Figure Captions

Figure 1: Flowchart depicting the hydrologic-economic-ecologic components of the modeling framework

Figure 2. Pooled mean Growth Rate (% growth per day) vs. SGD treatment of *Gracilaria coronopifolia*. Error bars indicate ± 1 standard deviation of the mean. The solid line represents the best-fit line from quadratic regression ($R^2=0.39$, $P=0.000$).

Figure 3: (a) Extraction, (b) Head Level, and (c) Algal Growth Rate for Unconstrained Optimum and Two Ecological Constraints on the Marine Algae

Figure 4: Optimal Pumping Depends on Growth Requirements and Recharge

Tables

Table 1. Summary of key equations

Function	Equation
Aquifer state equation	
Discharge function	
Unit cost of water extraction	$c = 0.00083(403.2 - h)$
Water demand	$p = 3.1 - 0.00048q$
Salinity level	$s = 36 - 0.00033 l$
Growth	$g = 10.2975 - (0.2625 * s)$

Table 2. Parameters used in the model

Parameter	Explanation [units]	Value
θ	Porosity [-]	0.3
W	Aquifer width [m]	6,000
L	Aquifer length [m]	6,850
R	Net Recharge [tm^3/y]	15,000
L_0	Current discharge [tm^3/y]	14,700
h_0	Initial head level [m]	1.75
h_{grd}	Ground elevation [m]	403.2
EC	Energy cost of lifting 1 m^3 of water 1 m. [$\$/\text{m}/\text{m}^3$]	0.00083
	Desalination cost [$\$/\text{m}^3$]	2
Q_0	Current water extraction rate [tm^3/y]	1,075
P_0	Current water price [$\$/\text{m}^3$]	1.27
η	Long-term elasticity of demand for water [-]	-0.7
S_l	Initial coastal salinity level [ppt]	31
r	Discount rate [%]	3

Table 3: Steady State Pumping Summary

Scenario	Average recharge (tm^3/y)	High recharge (tm^3/y)	Low recharge (tm^3/y)
Unconstrained Optimum	5,763.1	5,763.5	5,762.5
Soft constraint	4,118.3	5,763.5	1,095.5/ 1196 desal
Hard constraint	1,809.5/ 482 desal	4,832.3	2,292 desal

Table 4: Net Present Value of All Scenarios

Scenario	Average recharge	High recharge	Low recharge
Unconstrained Optimum	\$259.1 m	\$259.5 m	\$259.0 m
Soft constraint	\$248.7 m	\$259.5 m	\$147.1 m
Hard constraint	\$159.7 m	\$255.4 m	\$41.3 m