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OPTIMAL GROUNDWATER MANAGEMENT WHEN RECHARGE IS DECLINING: A METHOD FOR VALUING THE RECHARGE BENEFITS OF WATERSHED CONSERVATION

BY

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Abstract

Demand for water will continue to increase as per capita income rises and the population grows, and climate change can exacerbate the problem through changes in precipitation patterns and quantities, evapotranspiration, and land cover – all of which directly or indirectly affect the amount of water that ultimately infiltrates back into groundwater aquifers. We develop a dynamic management framework that incorporates alternative climate-change (and hence, recharge) scenarios and apply it to the Pearl Harbor aquifer system on O‘ahu, Hawai‘i. By calculating the net present value of water for a variety of plausible climate scenarios, we are able to estimate the indirect value of groundwater recharge that would be generated by watershed conservation activities. Enhancing recharge increases welfare by lowering the scarcity value of water in both the near term and the future, as well as delaying the need for costly alternatives such as desalination. For a reasonable range of parameter values, we find that the present value gain of maintaining recharge ranges from $31.1 million to over $1.5 billion.

Keywords Groundwater management, Climate change adaptation, Watershed conservation

JEL Codes Q25, Q54

1 Introduction

General circulation models (GCMs) predict that annual precipitation will decline in many regions across the globe over the next century as the climate changes. In some areas such as Hawai‘i, water tables and streamflow have already been declining as a result of both increased groundwater withdrawals and the warming climate (Bassiouni and Oki, 2012). Demand for water will continue to increase as per capita income rises and the population grows, and climate change can exacerbate the problem through changes in precipitation patterns and quantities, evapotranspiration, and land cover – all of which directly or indirectly affect the amount of water that ultimately infiltrates back into groundwater aquifers. If the climate becomes less favorable to groundwater recharge as preliminary projections suggest, the importance of efficient management of both water supply and demand options will be paramount.

The Ko‘olau Watershed on the island of O‘ahu, Hawai‘i, is a focal point of several impending environmental crises and is ideal for the development of a comprehensive research program that focuses natural and decision sciences on the problem of water resource management in the face of climate change. The watershed spans almost the entire windward side of the island and is diverse in its economic uses, including conservation land, agricultural, military, and urban users. In addition to the decline of biodiversity, ecological services that have been sustained for many centuries are increasingly at risk. While our focus is on groundwater services – which depend primarily on precipitation trends and the distribution of various types of land cover throughout the watershed such as native forests, invasive plants, or feral ungulate induced areas of bare soil – forested watersheds provide a variety of additional benefits, including those related to species habitat, subsistence, hunting, aesthetic value, commercial harvest, protection against flooding and sedimentation, and ecotourism (Kaiser et al., 1999).

Groundwater recharge services are of particular interest because groundwater provides nearly 99 percent of Hawaii's domestic water and roughly 50 percent of all freshwater used in the state (Gingerich and Oki, 2000).

We develop a model to optimize groundwater extraction over time for several plausible climate-change (and hence, recharge) scenarios. The model, which is applied to the Pearl Harbor aquifer in Southern O‘ahu, extends traditional groundwater economic models by explicitly allowing recharge to vary over time. Key quantitative results include projected trajectories of the efficiency price of water (i.e. the price that induces optimal consumption), the aquifer head level, and the optimal time to incorporate a backstop alternative such as desalination.

By calculating the net present value of water for a variety of plausible climate scenarios, we are able to estimate the indirect value of groundwater recharge that would be generated by watershed conservation activities – e.g. invasive non-native plant removal, installation of fencing to control feral ungulates such as wild pigs, or reforestation of recharge-augmenting native plant species – many of which are already being undertaken to some extent (Sumiye, 2002). Historical conservation data for O‘ahu suggests that the benefit-cost ratio of integrated watershed management has been positive and in the range of 2.7-15.3 (Kaiser, 2012). Enhancing recharge increases welfare by lowering the scarcity value of water in both the near term and the future, as well as delaying the need for costly alternatives such as desalination. For a reasonable range of parameter values, we find that the present value gain of maintaining recharge ranges from $31.1 million to over $1.5 billion. The range of values serves as a lower bound to the true value of watershed conservation, however, inasmuch as preservation activities generate additional unmeasured benefits such as scenic amenity, increased biodiversity, protection from flooding, carbon sequestration, and cultural value.

2 Model

In this section, we build on the conventional single-aquifer economic-hydrologic optimization model (e.g. Brown and Deacon, 1972; Gisser and Sanchez, 1980; Feinerman and Knapp, 1983) by adjusting the hydrology to accommodate a coastal aquifer and allowing recharge to decline over time. A coastal groundwater aquifer is typically characterized as a lens of freshwater floating on underlying seawater (Mink, 1980). Due to the difference in density of freshwater and saltwater, the upper surface of the lens is buoyed above sea level. The volume of freshwater in storage at any given point in time is dependent on the aquifer's boundaries, its porosity, and the head level (h), defined as the distance between mean sea level and the top of the lens. As the stock of freshwater declines, the lens contracts, the head level falls, and water extraction becomes more costly. At a lower head level, groundwater must be lifted further, which requires more energy. Eventually, the lower surface of the lens rises to the bottom of wells nearest the coast, and deeper inland wells must increase their shares of extraction at a higher unit cost. To capture these effects, the unit extraction cost is modeled as a non-negative, decreasing, convex function of the head level, i.e. $c(h_t) \geq 0$, $c'(h_t) < 0$, and $c''(h_t) \geq 0$.

Freshwater can also flow out of the aquifer naturally. Pressure from the lens causes groundwater to discharge into the ocean as springflow and diffuse seepage through low permeability caprock—coastal plain deposits such as marine and terrestrial sediments, limestone, and reef deposits—that bounds the freshwater lens along the coast.[1] As the lens shrinks and the head level declines, leakage decreases due to the subsequent reduction in surface area and pressure. Thus leakage is a non-negative, increasing, convex function of head, i.e. $l(h_t) \geq 0$,

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[1] Although caprock borders the Pearl Harbor aquifer and is relevant to this study, it is not a general characteristic of coastal aquifers.

$l'(h_t) > 0$, and $l''(h_t) > 0$. Groundwater recharge depends on, among other things, precipitation within the watershed. Inasmuch as annual precipitation is expected to decline to some extent over the next century, recharge is specified as a positive but non-increasing function of time, i.e. $R(t) > 0$ and $R'(t) \leq 0$. The equation of motion for the aquifer can then be constructed as follows:

$$\gamma \dot{h}_t = R(t) - l(h_t) - q_t \tag{1}$$

where γ is a head-to-volume conversion factor, q is the quantity of groundwater extracted, and $\dot{h}_t$ is the derivative of h with respect to time. The coastal aquifer system is depicted in Figure 1.

Since coastal aquifer users have essentially unlimited access to seawater, desalination, although currently expensive, serves as a natural alternative to groundwater. Desalinated seawater (b) can be produced at unit cost c_b, inclusive of amortized capital costs. We assume that seawater would be treated to potable quality standards, thus ensuring compatibility with existing distribution infrastructure. If desalination is centralized at a treatment facility near the coast and connected to an existing water main, the average unit distribution cost of sending water to users at higher elevations (c_d) will be the same for desalinated seawater and pumped groundwater.

The optimization problem for a forward-looking resource manager is to choose the quantities of groundwater to extract and seawater to desalinate in every period, given a positive discount rate (r), to maximize the present value of net benefits to society, i.e.

$$\underset{q_t, b_t}{Max} \int_{t=0}^{\infty} e^{-rt} \left\{ \int_{x=0}^{q_t + b_t} D^{-1}(x,t)dx - \left[c(h_t) + c_d\right]q_t - \left[c_b + c_d\right]b_t \right\} dt \tag{2}$$

subject to equation (1), non-negativity constraints on the control variables, and $h_t \geq h_{\min}$. Each period, benefits are calculated as the area under the inverse demand curve (D^{-1}) up to the total quantity of water consumed. Costs include those resulting from groundwater extraction, seawater desalination, and water distribution. The minimum allowable head level (h_{min}) constraint ensures maintenance of acceptable water quality.[2] The dynamic optimization problem (2) can be posed in an optimal control framework, and the current value Hamiltonian is

$$H = \int_{x=0}^{q_t+b_t} D^{-1}(x,t)dx - \left[c(h_t) + c_d\right]q_t - \left[c_b + c_d\right]b_t + \lambda_t \gamma^{-1}\left[R(t) - L(h_t) - q_t\right] + \mu_t\left[h_t - h_{\min}\right] \tag{3}$$

where λ_t and μ_t are the costate variables corresponding to the aquifer's equation of motion and the head constraint respectively. The Maximum Principle requires that

$$\frac{\partial H}{\partial q_t} = D^{-1}(q_t + b_t, t) - c(h_t) - c_d - \gamma^{-1}\lambda_t \le 0, \qquad \text{if} < \text{then } q_t = 0 \tag{4}$$

$$\frac{\partial H}{\partial b_t} = D^{-1}(q_t + b_t, t) - c_b - c_d \le 0, \qquad \text{if} < \text{then } b_t = 0 \tag{5}$$

$$\dot{\lambda}_t - r\lambda_t = -\frac{\partial H}{\partial h_t} = q_t c'(h_t) + \gamma^{-1}\lambda_t l'(h_t) - \mu_t \tag{6}$$

$$\frac{\partial H}{\partial \mu_t} = h_t - h_{\min} \ge 0, \qquad \text{if} > \text{then } \mu_t = 0 \tag{7}$$

$$\frac{\partial H}{\partial \lambda_t} = \gamma \dot{h}_t = R(t) - l(h_t) - q_t \tag{8}$$

The unit price of water (p_t) corresponding to the optimal level of extraction is indicated by the inverse demand curve. To simplify notation in the discussion that follows, we replace all instances of $D^{-1}(\bullet)$ with p_t. Condition (4) can then be rewritten as

$$\gamma^{-1}\lambda_t = p_t - c(h_t) - c_d \tag{9}$$

i.e. the *in situ* shadow price of water is equal to the efficiency price less the marginal costs of extraction and distribution.

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[2] The United States Environmental Protection Agency's standard for potable water is 2% of seawater salinity.

The efficiency price can be rewritten as a function of the head level and time by first taking the time derivative of equation (9) and combining the result with equation (8) to get an expression for $\dot{\lambda}_t$, then substituting the $\dot{\lambda}_t$ expression and equation (9) into necessary condition (6) as follows:

$$p_t = c(h_t) + c_d + \frac{\dot{p}_t - \gamma^{-1} c'(h_t)[R(t) - l(h_t)] + \gamma^{-1}\mu_t}{r + \gamma^{-1} l'(h_t)} \tag{10}$$

The third term on the right hand side of the efficiency price equation (10) is the *marginal user cost* (MUC), or the loss in present value that would result from an incremental reduction of the resource stock. The MUC includes the effects of current pumping on both future marginal extraction costs and future leakage.

The optimization problem allows for a variable terminal state, subject to the constraint that $h_t \geq h_{\min}$ as $t \to \infty$, which means that the transversality condition can be summarized as (Chiang, 2000)

$$\lim_{t\to\infty} \lambda_t \geq 0 \quad \text{and} \quad \lim_{t\to\infty} \lambda_t (h_t - h_{\min}) = 0 \tag{11}$$

In general, it is not known *ex ante* whether or not a minimum constraint on the state variable is binding. However, under the realistic assumption that demand for water is growing as the population expands and per capita income rises, we can narrow down candidate steady state solutions to those for which $\dot{p}_t = 0$ and $p_T = c_b + c_d$; in the long-run, groundwater extraction needs to be supplemented with desalination to meet growing demand. From the efficiency price equation (10), the optimal steady state head can then be written as a function of time. Inasmuch as the state variable (head) must remain constant in the steady state, however, the equality can only be maintained as $R(t)$ changes if μ_t is positive for $t \geq T$, which implies that $h_T = h_{\min}$. The steady state also requires that $\dot{h}_t = 0$, and from equation (8), $q_t = R(t) - l(h_{\min})$ for $t \geq T$.

Given terminal conditions for the price ($p_T = c_b + c_d$) and head level ($h_T = h_{\min}$) and an initial measurement of the head level ($h_0 = h_{initial}$), the system of differential equations (8) and (10) can be solved. The endogenously determined T represents the time at which desalination should be optimally implemented to supplement groundwater pumping. For $t \geq T$, the head level is maintained at the minimum allowable level, but extraction is declining in step with recharge. At the same time, the total quantity and share of desalinated water is increasing to meet growing demand. If the decline in recharge eventually levels off, extraction also converges to a constant level, while desalination continues to increase over time.

3 Application

The model is applied to the Pearl Harbor aquifer on the island of O‘ahu, Hawai‘i. As mentioned previously, groundwater supplies nearly all of municipal water use in Hawai‘i, and the Pearl Harbor aquifer is of particular importance because it is the most heavily used aquifer in the State, having produced between 100 and 200 million gallons of fresh water per day over the past several decades (Oki, 2005).

3.1 Climate module

Although historical trends of air temperature and precipitation in Hawai‘i have been extensively documented (Chu and Chen, 2005; Chu et al., 2010; Giambelluca et al., 2008), very few studies have attempted to simulate future climate change in Hawai‘i at a regional scale. Timm and Diaz (2009) apply statistical downscaling to rainfall of the Hawaiian Islands under the assumption that GCMs reasonably simulate large-scale atmospheric circulation patterns. Based on a six-model ensemble selected from the models presented in the Intergovernmental Panel for Climate Change Fourth Assessment Report (Christensen et al., 2007), their results suggest that the most likely scenario for Hawaiʻi is a 5-10% reduction in precipitation during the wet-season (November-April) and a 5% increase during the dry season (May-October) by the end of the twenty-first century. Given that approximately 70% of normal precipitation falls during the wet season (Safeeq and Fares, 2012), the net effect is a decline in annual precipitation and hence groundwater recharge.

All else equal, a reduction in precipitation can be viewed as roughly proportional to a reduction in groundwater recharge. Previous studies have provided recharge estimates ranging from 19% to 43% of gross annual rainfall across various sites throughout Hawaiʻi (Table 5 in Safeeq and Fares, 2012). However, changes in precipitation may be accompanied by changes in atmospheric CO_2 and temperature, which affect other important water balance components such as evapotranspiration (ET). Using streamflow and rainfall data from the Mākaha watershed on the Island of Oʻahu, Hawaiʻi to calibrate the Distributed Hydrology Soil Vegetation Model (DHSVM), Safeeq and Fares (2012) assess the sensitivity of streamflow and ET to future climate change scenarios. Although they run dozens of simulations for various assumptions about emissions, temperature, and precipitation change, we focus on the two scenarios based on precipitation changes projected by Timm and Diaz (2010).

If annual precipitation declines by 1.9% (conservative), the model projects a decline in recharge of 3.7% (Table 1). For a precipitation decline of 5.3% (baseline), the corresponding reduction in recharge is 8.5%. Although the model is calibrated specifically to the Mākaha watershed, we extend the results to the neighboring Koʻolau watershed, which recharges the large and heavily used Pearl Harbor aquifer. The responsiveness of each watershed to climate change is not realistically identical. Nevertheless, we aim to illustrate how the present value of a groundwater resource can vary even for a seemingly small change in precipitation over the next century, and how that result can be used to value watershed conservation programs that aim to slow or halt the expected decline in groundwater recharge over the next century. Based on the total percentage change in precipitation, we construct the time-dependent groundwater recharge function as follows:

$$R(t) = \begin{cases} R_0(1-\delta t/\tau) \text{ for } t \le \tau \\ R(\tau) \text{ for } t \ge \tau \end{cases} \tag{12}$$

where R_0 is the current value of recharge, δ is the projected percentage reduction in precipitation relative to R_0 for year 2100, and τ is the total number of periods of expected recharge reduction, in this case, 87 years.[3] The result is a linear reduction in annual recharge from R_0 to $R(\tau)$, followed by maintenance of recharge at the constant level $R(\tau)$.

3.2 Hydrology module

Under unexploited conditions, the freshwater in a basal aquifer is separated from underlying seawater by a relatively sharp interface located below mean sea level at a depth of approximately 40 times the head level. When groundwater is pumped from the aquifer, however, the sharp interface rises and expands into a brackish transition zone wherein salinity increases with depth. To address the expansion of the transition zone, Liu (2006) developed a robust analytical groundwater flow and salinity transport model (RAM2). Taking into account average well-depth, upconing, and the desirable source-water salinity in Hawai‘i (2% of seawater salinity), he estimated that the minimum allowable head level required to avoid seawater intrusion for the Pearl Harbor aquifer (h_{min}) is 15.125 feet.

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[3] Due to the lack of rainfall projections beyond year 2100, we use a slightly modified version of the infinite horizon framework laid out in section 2. The planning horizon is restricted to 87 years but the objective is to still maximize PV subject to the head and price constraints.

Although the surfaces of the lens are technically parabolic, we follow Krulce et al. (1997) in assuming that the relationship between groundwater storage and head is approximately linear and that 78.149 billion gallons of freshwater are stored per foot of head in the Pearl Harbor aquifer. To construct the equation of motion for the head level, we use the leakage function econometrically estimated by Krulce et al. (1997):

$$l(h_t) = 0.24972h_t^2 + 0.022023h_t \tag{13}$$

measured in millions of gallons per day (mgd). The recharge function (12) is parameterized using *Liu's* (2006) estimate that approximately 220 million gallons of freshwater naturally recharge the aquifer daily (R_0).

3.3 Economic module

The benefit to water consumers in a given period is calculated as the area under the inverse demand curve up to the total quantity of water consumed. The demand is modeled as a constant elasticity function:

$$D(p_t, t) = \alpha e^{gt} p_t^{\eta} \tag{14}$$

Although demand elasticities vary considerably across studies, we follow Pitafi and Roumasset (2009) in assuming that $\eta = -0.25$ in the baseline scenario. Also, given their estimate that demand for water is growing by 1% on O‘ahu (0.2% due to population growth and 0.8% due to income growth), we assume that $g = 0.01$. The value of the demand coefficient $\alpha = 107.4$ is selected to normalize equation **(**14) to data for the average retail price of water ($2.97 per thousand gallons)[4] and the 107.38 mgd pumped from the Pearl Harbor aquifer in 2009 (Barry Usagawa, Honolulu Board of Water Supply, personal communication, January 25, 2013). In addition to extraction by the Board of Water Supply (BWS), groundwater from the aquifer is also used by the military, industry, and for various types of irrigation. Pumpage by non-BWS users totaled 22.17 mgd in 2009. Given that changes in BWS water prices will not incentivize non-BWS users to change their behavior, we take non-BWS pumpage as exogenous and assume that the quantity grows at rate g.

The marginal extraction cost is specified as a linear function of the distance water must be lifted from the aquifer to the surface:

$$c(h_t) = \beta(e - h_t) \tag{15}$$

The coefficient (β) is chosen such that the cost calculated using equation **(**15) together with data for average well elevation (e) and the initial head level (h_0) matches the volume-weighted average of unit extraction costs for all primary wells in the initial period. For $h_0 = 17.1$ feet, $e = 272$ feet, and $c(h_0) = \$0.35$ per thousand gallons (tg), the cost coefficient (β) is equal to 0.00137, where the initial value of c is calculated by adjusting Roumasset and Wada's (2012) estimate for inflation. The initial head level is estimated by taking the average of water levels measured at six monitoring wells (Moanalua, Halawa, Kalauao, Pearl City, Waipahu, and Hoaeae-Kunia) over the period 2009-2012 (Barry Usagawa, Honolulu Board of Water Supply, personal communication, January 25, 2013). The unit cost of distribution is calculated as the difference between the retail price and the unit extraction cost in 2012 dollars, i.e.

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[4] The average retail price is calculated assuming the average household uses 30,000 gallons of water per day. In 2009, the rate schedule increased in blocks such that the first 13,000 gallons were priced at \$2.66/tg and the remaining 17,000 gallons were priced at \$3.20/tg.

$c_d = \$3.74 - \$0.35 = \$3.39/\text{tg}$. The inflation-adjusted unit cost of desalinating seawater using reverse osmosis is \$8.46/tg. A detailed description of the amortization procedure and underlying assumptions can be found in Roumasset and Wada (2012).

3.4 Numerical simulation: baseline scenario

We calculate the net present value (NPV) of the aquifer resulting from optimal management in the face of climate change, using the parameter values discussed in sections 3.1-3.3 and summarized in Table 2. The NPV is the net benefit of water use aggregated over time and discounted to the present at rate *r* (equation 2). Rather than optimize over an infinite time horizon, however, we restrict attention to the years leading up until the end of the 21st century, i.e. groundwater withdrawals are optimized over a finite, 87-year time horizon. In the baseline scenario, desalination is not implemented until year 77. The NPV of the resource is \$7.72 billion, and the benefit of maintaining recharge at the current level, calculated as the difference in NPV when recharge is maintained and when it is declining, is \$163.9 million. Watershed conservation that maintains recharge at the current level is only warranted if the NPV costs do not exceed \$163.9 million. Thus, even when groundwater is abundant and recharge is projected to decline moderately, the value of watershed conservation can be substantial.

3.5 Sensitivity analysis

To explore the model's sensitivity to assumed parameter values, we run simulations with different values of *g*, *η*, *β*, and *r*, for high and low recharge scenarios. When recharge decline is projected to be relatively small and groundwater is fairly abundant, changes to some parameters do not substantially affect the optimal management strategy. For example, lowering the discount rate to 1% or doubling the extraction cost parameter does not have much effect on the timing of desalination. Increasing *g* to 3% brings desalination much closer to the present (year 34), however, inasmuch as groundwater must be drawn down faster to meet growing demand. Doubling the elasticity of demand has the opposite effect, as expected. When consumers are more responsive to price, consumption is expected to be lower all else equal, meaning desalination can be avoided altogether until the end of the planning horizon. Results are summarized in Table 3 and Figures 2-4. For comparison, Figures 8-10 depict optimal trajectories assuming that recharge is held constant.

When recharge is expected to decline by 8.5% of its current level by the end of the century, the qualitative effects (i.e. the direction of the changes) on PV benefits of perturbations to various parameter values remain intact. Furthermore, the value of maintaining recharge is higher if recharge is expected to decline by a larger amount absent watershed management, as evidenced by the last two columns in Table 3. For each scenario, the PV benefit of maintaining recharge is at least twice as large for a recharge decline of 8.5% as it is for a decline of 3.7%. The difference in benefit in percentage terms is especially large for the high demand growth scenario; when water is already scarce owing to increased demand, maintaining recharge is especially valuable. Trajectories for the 8.5% recharge reduction scenario are depicted in Figures 5-7.

4 Conclusion and directions for further research

To address the challenge of managing groundwater in the face of climate change, we modify a standard groundwater economics model to allow for declining recharge. The model is applied to the Pearl Harbor aquifer on the island of O‘ahu for two plausible climate change scenarios, and PV gains ranged from $31.1 million to $1.5 billion. The results highlight the potentially large value of investing in recharge-augmenting watershed conservation in conjunction with optimal groundwater management. While an important first step, the utility of our results depends strongly on the availability of information regarding the benefits – measured in terms of the net effect on recharge – and costs of various types of conservation instruments. As more of the requisite information is revealed through scientific investigations, the economic model can be revised to explicitly include investment in watershed conservation as a management instrument, given that maintaining recharge at the current level is likely to be very costly and hence not PV-maximizing.

The results from the numerical application would likely be different in the case of a multiple demand/aquifer system. For constant groundwater recharge, Roumasset and Wada (2012) show that groundwater from Pearl Harbor would optimally supply residents of neighboring Honolulu for a period of time before the Honolulu aquifer comes online. When recharge is declining, one might expect the same general pattern of extraction but a higher price path overall to reflect increased water scarcity, and Honolulu aquifer would be expected to come online sooner to supplement extraction from Pearl Harbor aquifer. In a two aquifer/watershed system, watershed management decisions would also become more complex, requiring designation of not only the type of conservation instrument but also the location. Patterns of optimal investment in watershed conservation would depend on a combination of factors, including aquifer-specific leakage and extraction cost functions, as well as how cost effective each instrument is within each watershed.

Another possible research extension would be to allow for exogenous improvements in groundwater extraction technology. If extraction costs were allowed to decline over time, we expect that the overall effect would be a reduction in the present value of watershed conservation. All else equal, when the scarcity value of water is lower due to a reduction of the extraction cost effect in the marginal user cost, an additional unit of recharge provided via watershed conservation has less value. At the same time, however, the cost of energy may be rising as coal and oil becomes scarcer. If the energy cost effect dominates the innovation effect and the extraction cost instead increases over the planning horizon, watershed conservation may generate more value. One could even imagine a situation in which technological innovation is complemented by falling energy prices if substitution toward renewable energy sources eventually reduces the price of electricity for groundwater pumping.

References

Bassiouni, M., and D.S. Oki (2012), Trends and shifts in streamflow in Hawai‘i, 1913-2008, Hydrological Processes, doi: 10.1002/hyp.9298.

Brown, G., and R. Deacon, (1972), Economic optimization of a signle cell aquifer, Water Resources Research, 8, 552-564.

Chiang, A.C. (2000), Elements of Dynamic Optimization, Waveland Press, Inc., Illinois.

Chu, P.S., and H. Chen (2005), Interannual and interdecadal rainfall variations in the Hawaiian Islands in a warming climate, Journal of Climate, 18, 4796-4813.

Chu, P.S., Y.R. Chen, and T. Schroeder (2010), Changes in precipitation extremes in the Hawaiian Islands in a warming climate, Journal of Climate, 23, 4881-4900.

Christensen, J.H., B. Hewitson, A. Busuioc, A. Chen, X. Gao, I. Held, R. Jones, R.K. Kolli, W.-T. Kwon, R. Laprise, V. Magaña Rueda, L. Mearns, C.G. Menéndez, J. Räisänen, A. Rinke, A. Sarr, and P. Whetton (2007), Regional Climate Projections, in Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth

Assessment Report of the Intergovernmental Panel on Climate Change, edited by S. Solomon et al., Cambridge University Press, Cambridge, United Kingdom and New York.

Feinerman, E., and K.C. Knapp (1983), Benefits from groundwater management: magnitude, sensitivity, and distribution, American Journal of Agricultural Economics, 65, 703-710.

Giambelluca, T.W., H.F. Diaz, and M.S.A. Luke (2008), Secular temperature changes in Hawai‘i, Geophysical Research Letters, 35, L12702.

Gingerich, S.B., and D.S. Oki (2000), Ground Water in Hawaii, U.S. Geological Survey Fact Sheet 126-00, 6 pp.

Gisser, M., and D.A. Sanchez (1980), Competition versus optimal control in groundwater pumping, Water Resources Research, 31, 638-642.

Kaiser, B (2012), Watershed Conservation in the Long Run, Manuscript.

Kaiser, B., N. Krause, and J. Roumasset (1999), Environmental Valuation and the Hawaiian Economy, University of Hawaii Economic Research Organization Working Paper.

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, 1218-1228.

Liu, C.C.K. (2006), Analytical Groundwater Flow and Transport Modeling for the Estimation of the Sustainable Yield of Pearl Harbor Aquifer, Project Report PR-2006-06, Water Resources Research Center, Hawaii.

Mink, J.F. (1980), State of the Groundwater Resources of Southern Oahu, Honolulu Board of Water Supply, Hawaii.

Oki, D.S. (2005), Numerical Simulation of the Effects of Low-Permeability Valley-Fill Barriers and the Redistribution of Ground-Water Withdrawals in the Pearl Harbor Area, Oahu, Hawaii, U.S. Geological Survey Scientific Investigations Report 2005-5253, 111 pp.

Pitafi, B.A., and J.A. Roumasset (2009), Pareto-Improving Water Management over Space and Time: The Honolulu Case, American Journal of Agricultural Economics, 91(1), 138-153.

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

Safeeq, M., and A. Fares (2012), Hydrologic response of a Hawaiian watershed to future climate change scenarios, Hydrological Processes, 26, 2745-2764.

Sumiye, J. (2002), Koʻolau Mountains Watershed Partnership Management Plan.

Timm O, Diaz, HF (2009) Synoptic-Statistical Approach to Regional Downscaling of IPCC Twenty-First-Century Climate Projections: Seasonal Rainfall over the Hawaiian Islands. J Climate 22:4261-4280.

Table 1. Percentage changes in ET, streamflow, and groundwater recharge.

Precipitation (% change)	**ET (% change)**	**Streamflow (% change)**	**Recharge (% change)[a]**
-1.9 (conservative)	+0.1	-6.7	-3.7
-5.3 (baseline)	-1.1	-17.2	-8.5

[a] The percentage change in recharge is calculated assuming that the reference proportions of rainfall for ET, streamflow, and recharge are 56%, 11%, and 33% respectively.

Table 2. Parameter descriptions, units, and values.

Parameter	**Description [units]**	**Value**
R_0	Initial recharge [mgd]	220
δ	Projected change in recharge by 2100 [-]	-0.037
τ	Length of climate projection [years]	87
h_0	Initial head level [feet]	17.1
h_{min}	Minimum head level [feet]	15.125
α	Demand coefficient [mgd/$]	107.4
g	Rate of demand growth [-]	0.01
η	Elasticity of demand for water [-]	-0.25
β	Extraction cost coefficient [$/foot/tg]	0.00137
e	Average well elevation [feet]	272
c_d	Unit distribution cost [$/tg]	3.39
c_b	Unit cost of desalination [$/tg]	8.46
r	Discount rate [-]	0.03

Table 3. Sensitivity analysis

Scenario	δ [recharge decline]	T [years until desalination]	h(T) [feet]	NPV [millions]	Benefits of conservation [millions]	PV gain relative to no conservation [percent]
Baseline	0%	81	hmin	$7,885.7	-	-
	3.7%	77	hmin	$7,721.8	$163.9	2.12%
	8.5%	73	hmin	$7,538.0	$347.7	4.61%
High demand growth (*g*=0.03)	0%	34	hmin	$6,481.9	-	-
	3.7%	34	hmin	$6,450.8	$31.1	0.48%
	8.5%	33	hmin	$6,288.8	$193.1	3.07%
Elastic demand (*η*=-0.5)	0%	87	hmin	$6,529.5	-	-
	3.7%	87	hmin	$6,511.2	$18.3	0.28%
	8.5%	87	hmin	$6,476.3	$53.2	0.82%
Low discount rate (*r*=0.01)	0%	83	hmin	$15,804.7	-	-
	3.7%	79	hmin	$15,053.9	$750.8	4.99%
	8.5%	75	hmin	$14,272.7	$1,532.0	10.73%
High extraction cost (*β*=0.00274)	0%	82	hmin	$7,530.9	-	-
	3.7%	78	hmin	$7,377.9	$153.0	2.07%
	8.5%	74	hmin	$7,206.0	$324.9	4.51%

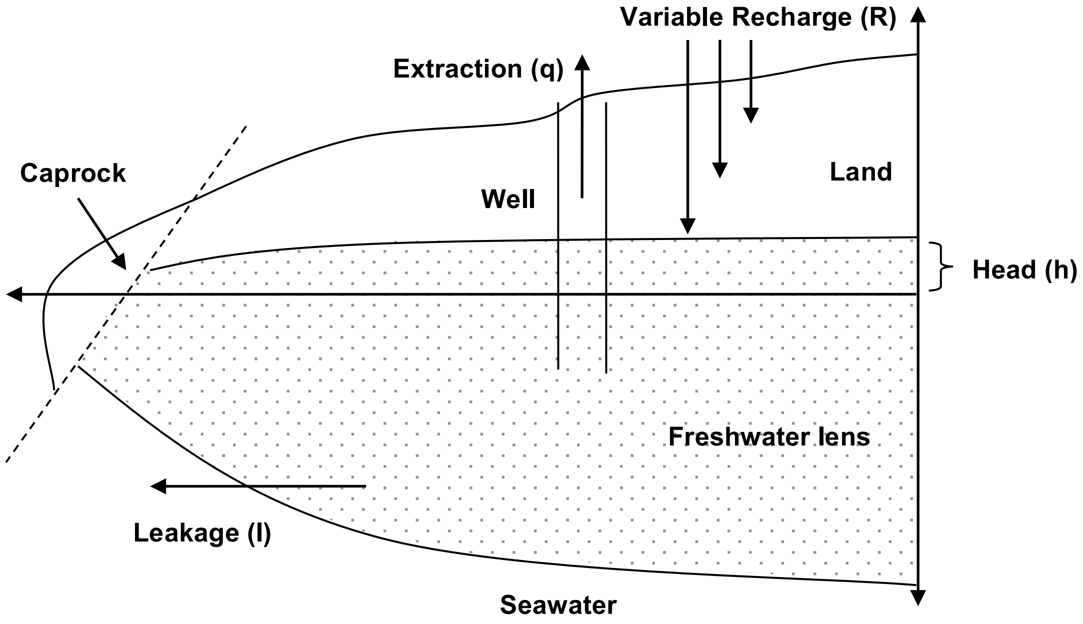

Figure 1. Coastal aquifer cross-section, adopted from Roumasset and Wada (2012)

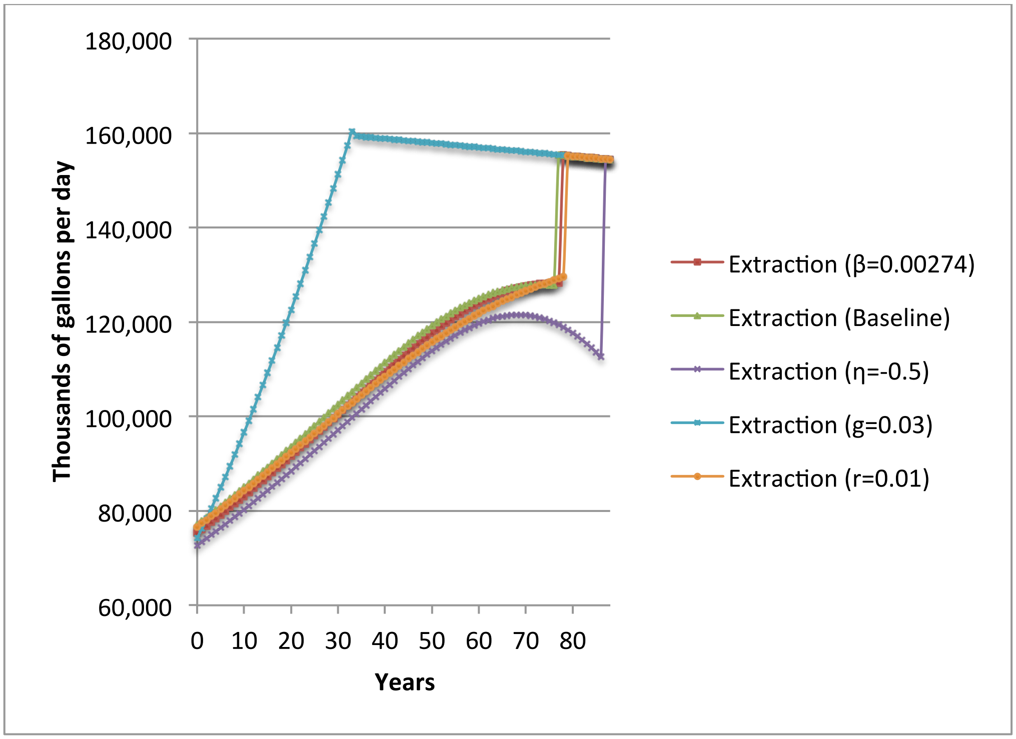

Figure 2. Extraction (BWS only) trajectories for a 3.7% decline in recharge by 2100

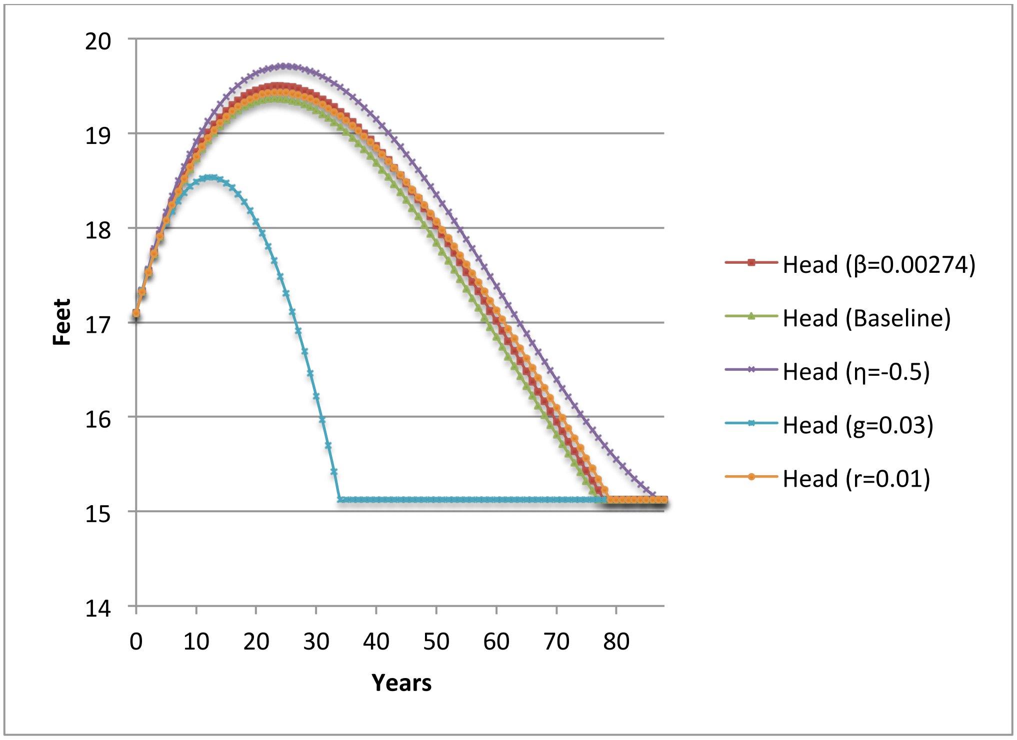

Figure 3. Aquifer head level trajectories for a 3.7% decline in recharge by 2100

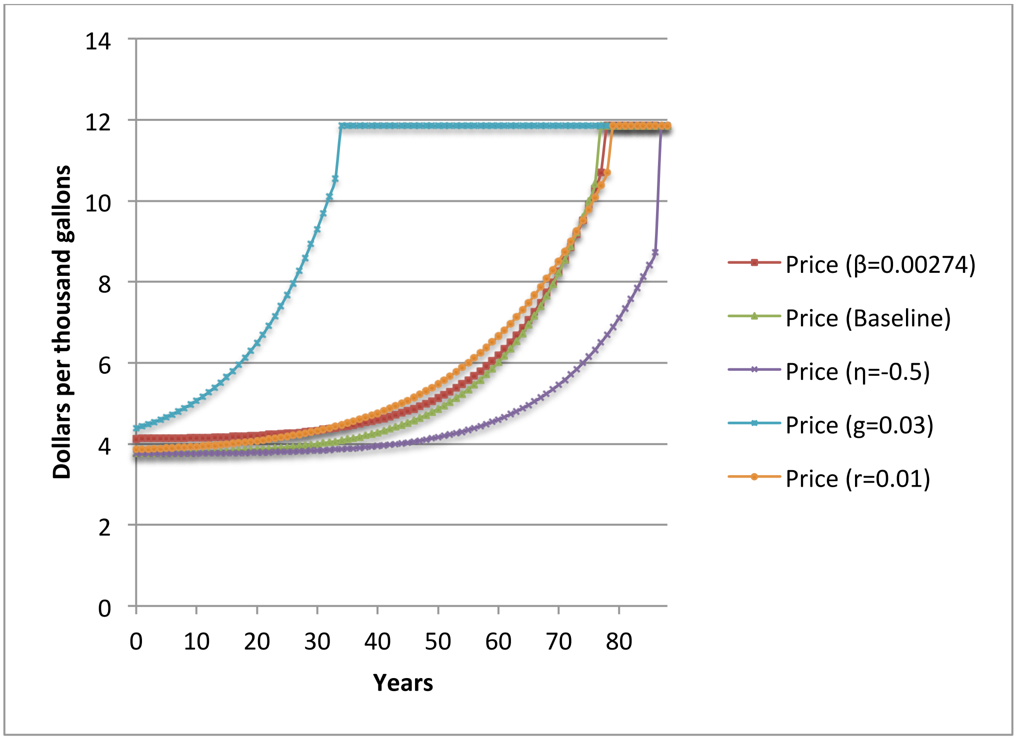

Figure 4. Efficiency price trajectories for a 3.7% decline in recharge by 2100

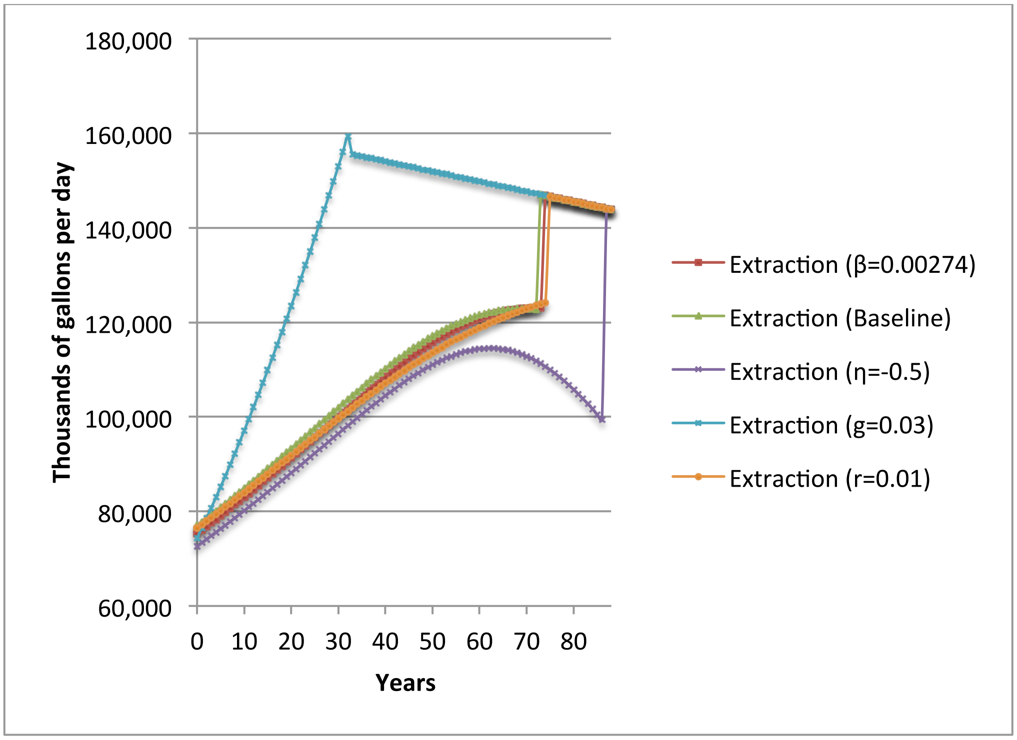

Figure 5. Extraction (BWS only) trajectories for an 8.5% decline in recharge by 2100

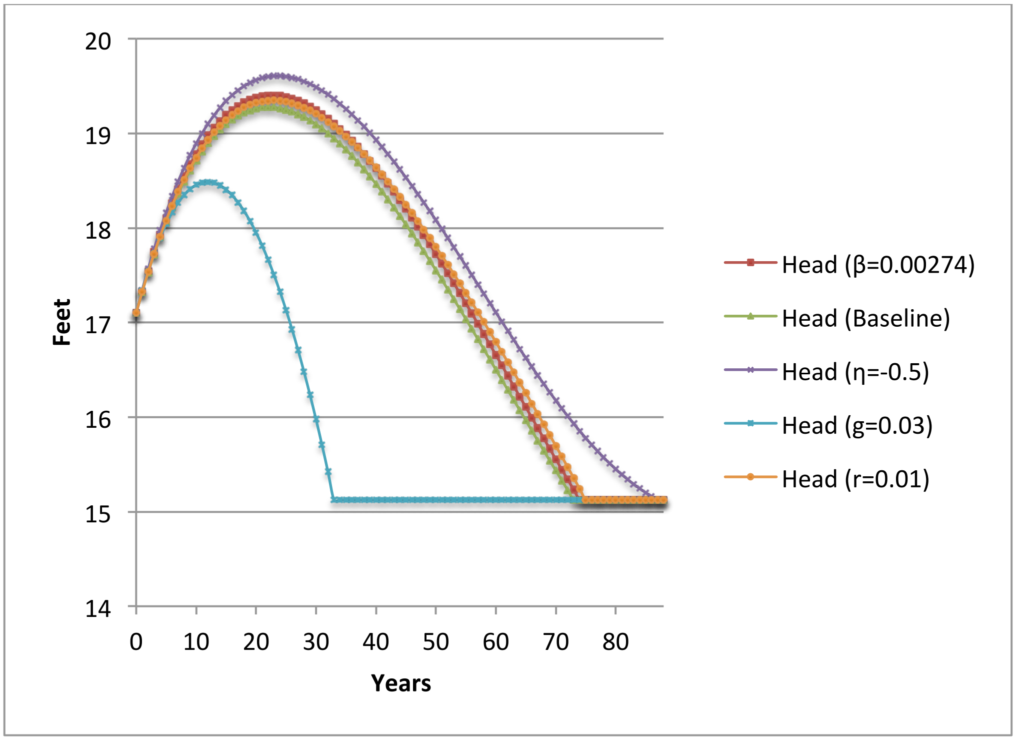

Figure 6. Aquifer head level trajectories for an 8.5% decline in recharge by 2100

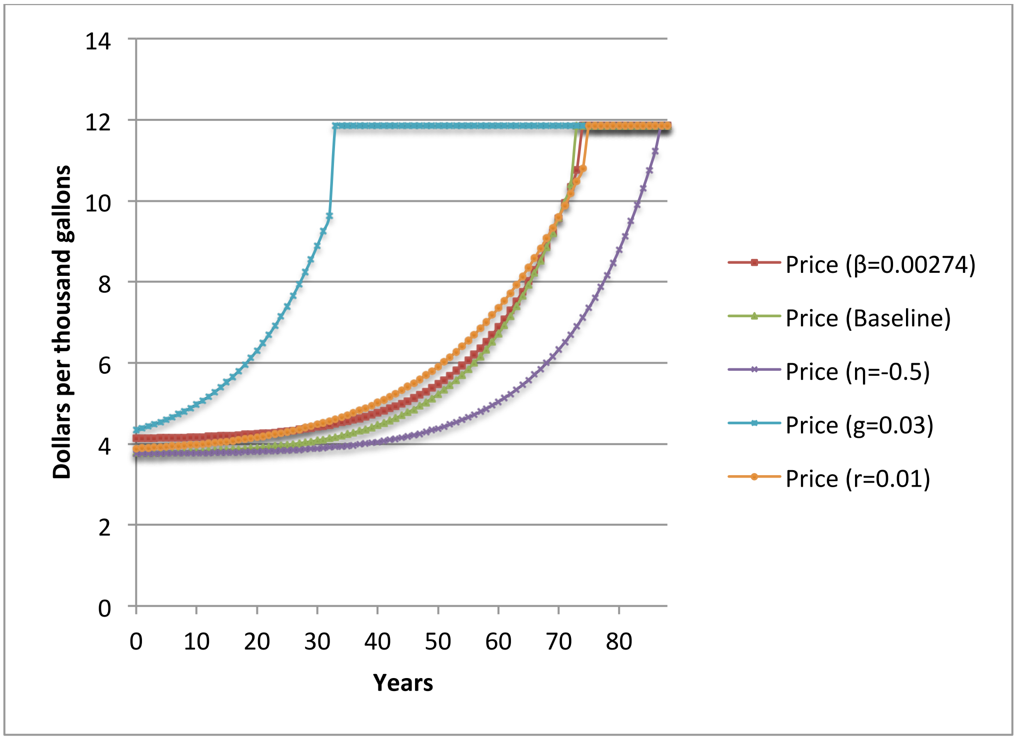

Figure 7. Efficiency price trajectories for an 8.5% decline in recharge by 2100

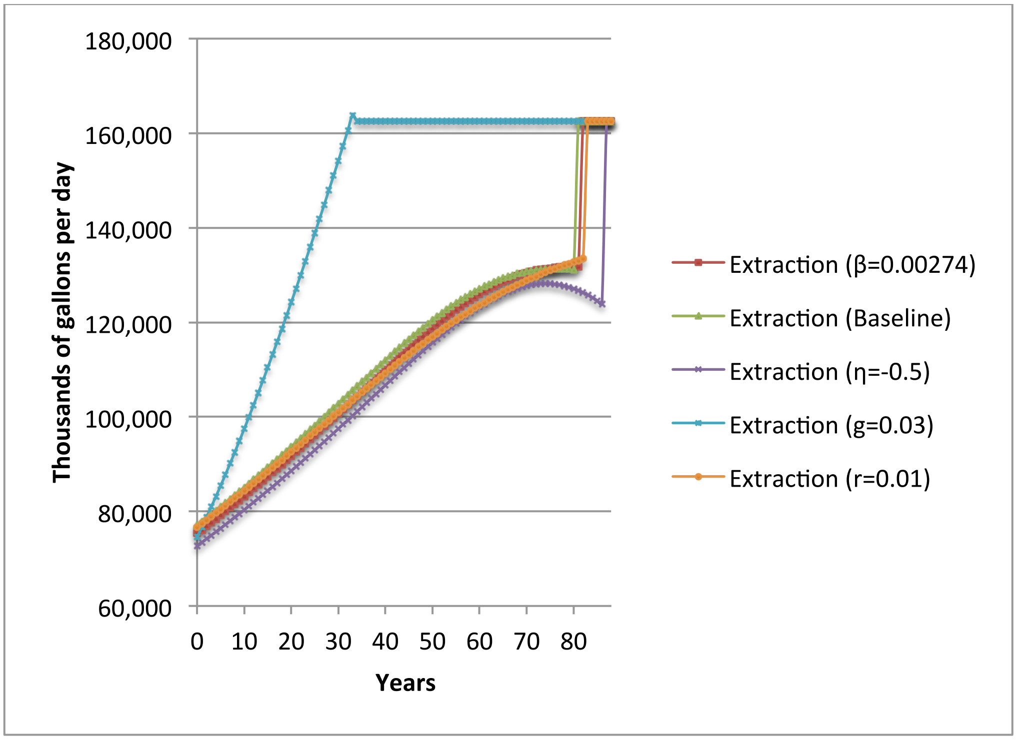

Figure 8. Extraction (BWS only) trajectories when recharge is held constant until 2100

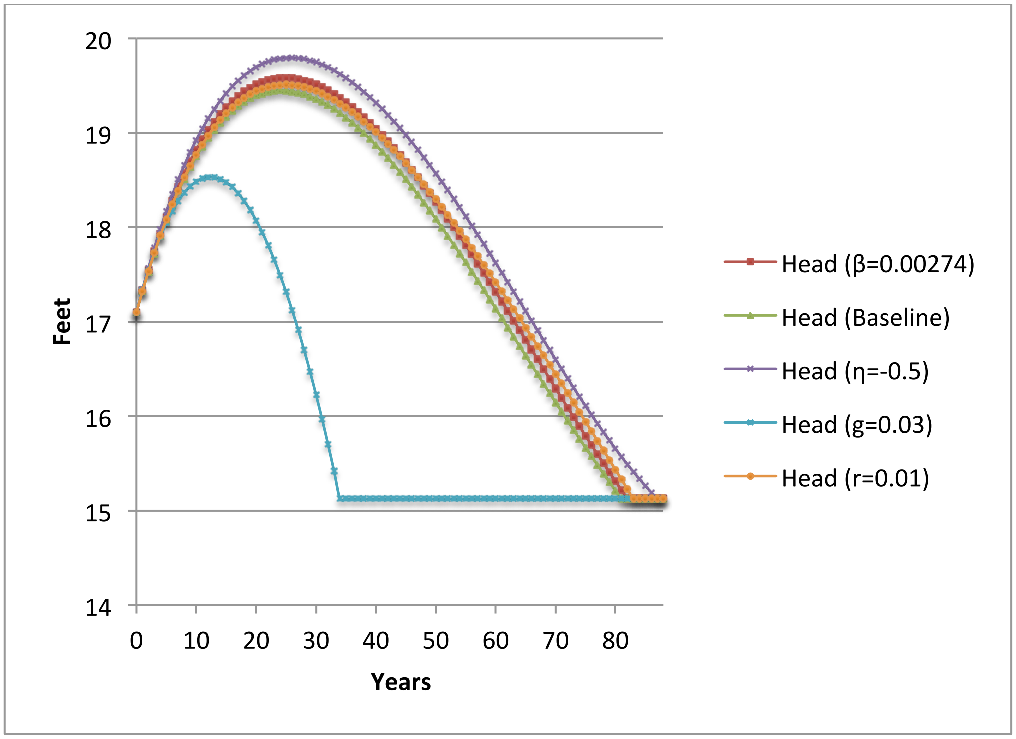

Figure 9. Aquifer head level trajectories when recharge is held constant until 2100

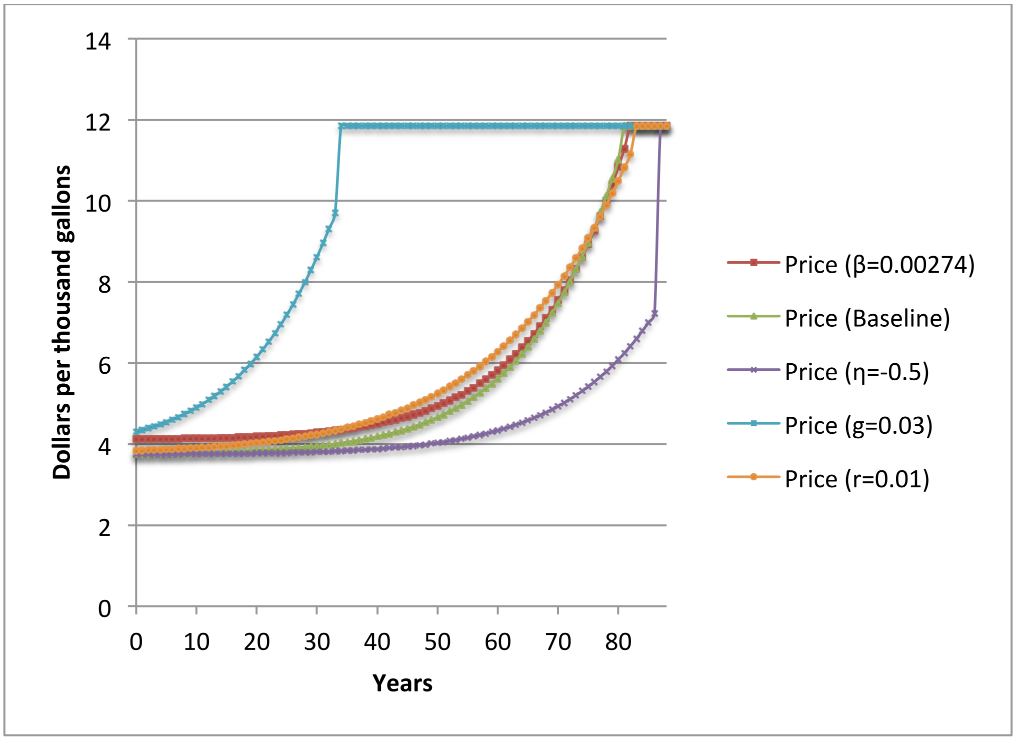

Figure 10. Efficiency price trajectories when recharge is held constant until 2100