FINAL REPORT

Satisfying Growing Water Demand Through Integrated Groundwater and Watershed Management

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Problem and Research Objectives

Water tables and stream flow in Hawai‘i have been declining over the past century in the face of increasing demand (Bassiouni and Oki, 2012), and demand will continue to increase as per capita incomes rise and the population grows. 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 the ground. If the climate becomes less favorable to groundwater recharge as preliminary projections suggest, the importance of efficient management of both supply and demand options will be paramount.

Sustaining water availability at current prices in the face of growing demand and declining resources is highly unlikely. Therefore, our research aims to develop a management framework with the objective of conserving water resources in a manner that maximizes water users' benefits over time, given projected effects of a continuously changing climate. Specifically, we consider long-term planning for efficient extraction of groundwater and timing for the development of groundwater alternatives such as desalinated water when recharge is declining. Recharge-enhancing watershed conservation would further help to moderate scarcity, resulting from the dual effect of increasing demand and declining recharge, and thus positively affect social welfare. By comparing welfare estimates under different assumptions about recharge, including different rates of decline and maintenance, we are able to indirectly estimate a lower bound for ecosystem benefits associated with hypothetical conservation projects.

Methodology

The methodology consists of three main components or modules: climate, groundwater, and management. Results from currently available analyses of climate, land cover, and watershed hydrology are used to construct three basic recharge scenarios. Although considerable assumptions are necessary to do so, the resulting framework is operational and useful for illustrating the tradeoffs involved in implementing different management tools. The groundwater module is based on a single-cell aquifer model, and the management module ties all of the components together in a socioeconomic dynamic optimization framework.

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), 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 Hawai‘i 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.

Previous studies have provided recharge estimates ranging from 19% to 43% of gross annual rainfall across various sites throughout Hawaiʻi. However, changes in precipitation may be accompanied by changes in other climate variables, which affect water balance in the watershed. Safeeq and Fares (2012) use data from the Mākaha watershed to assess the sensitivity of streamflow and evapotranspiration (ET) to a variety of future climate change models, including two scenarios based on precipitations changes projected by Timm and Diaz (2009). Assuming that ET, streamflow, and recharge comprise 56%, 11% and 33% of rainfall respectively, we construct a conservative scenario, corresponding to a 1.9% decline in precipitation and 3.7% decline in recharge, and a baseline scenario, corresponding to a 5.3% decline in precipitation and 8.5% decline in recharge by the end of the twenty-first century.

Although the estimates are based on 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. We construct a time-dependent groundwater recharge function as follows:

$$R(t) = R_0(1 - \delta t / \tau) \tag{1}$$

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. The result is a linear reduction in annual recharge from R_0 to $R(\tau)$.

Groundwater module

The recharge estimates serve as inputs to a groundwater framework based on Liu's (2006) Robust Analytical Model 2, which characterizes solute-transport within a vertical cross-section of a coastal aquifer. The governing or state equation, which describes the evolution of groundwater stock over time, is

$$\gamma \dot{h}_t = R(t) - l(h_t) - q_t \tag{2}$$

where γ converts head level to stored groundwater volume, h_t is the head level at time t, $R(t)$ is groundwater recharge for period t, q_t is the quantity of groundwater extracted at time t, and l is a leakage function, parameterized for Pearl Harbor by Krulce et al. (1997). Taking into account average well-depth, upconing, and the desirable source-water salinity in Hawaiʻi (2% of seawater salinity), management decisions are constrained to prevent the head level for Pearl Harbor aquifer from falling below 15.125 feet, the minimum allowable head level (h_{min}):

$$h_t \geq h_{\min} \tag{3}$$

Economic module

The benefit of groundwater use is calculated as consumer surplus, or the area under the inverse demand curve. Demand is modeled as a constant elasticity function:

$$D(p_t, t) = \alpha e^{gt} p_t^{\eta} \tag{4}$$

where η is the elasticity of demand, g is the rate of demand growth, and α is a coefficient selected to normalize equation (4) to Honolulu Board of Water Supply (HBWS) data for the average retail price of water and extraction from the year 2009. Non-HBWS pumpage is taken as exogenous and is assumed to grow at rate g.

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

$$c(h_t) = \beta(e - h_t) \tag{5}$$

The coefficient (β) is chosen such that the cost calculated using equation (5) 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. The initial head level of 17.1 feet 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. The unit cost of distribution (c_d) is calculated as the difference between the retail price and the unit extraction cost in 2012 dollars. The inflation-adjusted unit cost of desalinating seawater using reverse osmosis (c_b) includes amortized capital costs.

The optimization problem for a forward-looking planner is to choose extraction and desalination in every period, given a discount rate (r) to maximize the present value of net benefits to society, i.e.

$$\underset{q_t, b_t}{Max} \int_{t=0}^{\infty} e^{-rt} \left\{ \int_{x=0}^{q_t+b_t} D^{-1}(x,t)dx - \left[c(h_t) + c_d\right] q_t - \left[c_b + c_d\right] b_t \right\} dt \tag{6}$$

subject to equations (2), (3), and non-negativity constraints on the control variables. We repeat the optimization procedure for each of the recharge scenarios, including maintenance of the status quo level. Table 1 provides descriptions of the various parameters used to characterize equations associated with each of the three modules.

Table 1. 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

Principal Findings and Significance

In the baseline scenario, desalination is not implemented until year 77. The net present value (NPV) of the resource is \$7.71 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 \$170.5 million. Watershed conservation that maintains recharge at the current level is only warranted if the NPV costs do not exceed \$170.5 million. Thus, even when groundwater is abundant and recharge is projected to decline moderately, the value of watershed conservation can be substantial.

Table 2. 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%

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 because consumers are more responsive to price.

When recharge is expected to decline to 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 2. 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.

Our scenario-based analysis focuses on a single hydrological basin. Future research could be aimed at extending the framework in a variety of directions. Increasing the management boundaries to encompass the entire island of O‘ahu would require a systems approach, including the characterization of natural flow between the various groundwater sectors, distribution or allocation of water between sectors, and the sequencing of all available water sources over space and time. The framework would also be improved by explicitly incorporating stochasticity, with the objective of maximizing the expected present value of the resource, given projected distributions of uncertain climate variables. Lastly, including investment in watershed conservation as a management instrument, i.e., not taking a project-based approach, would improve the utility of the model for decision makers; maintaining recharge at current levels is likely to be costly and less conservation may yield higher net benefits.

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