Integrated Water Management with Multiple Aquifers

Problem and Research Objectives

We provide a general model of groundwater optimization over space and time, allowing for growing demand and a backstop resource. The model is used to compare resource allocation and welfare under efficient groundwater management and status quo management. We present a case study of a groundwater aquifer on the island of Oahu, namely, the Honolulu aquifer. To adequately represent local conditions, we require a general operational model of an exhaustible groundwater aquifer with variable recharge, the possibility of well salinization, desalting as a backstop source of freshwater, and growing water demand. Also, construction of a compensation scheme requires explicit disaggregation of consumers over space and time, as well as analysis of the distributional consequences of efficient management versus the existing inefficient management practice.

After solving for optimal management of the Honolulu aquifer, we will do the same for the Pearl Harbor aquifer. Once individual aquifer models are complete, we plan to integrate them into a single management model, allowing for hydrological interactions.

Methodology

The groundwater aquifers that provide freshwater in coastal areas, such as Honolulu, usually exhibit Ghyben–Herzberg lens geometry, where an underground layer of freshwater floats on saltwater that seeps in from the ocean (J.F. Mink, 1980, State of the Groundwater Resources of Southern Oahu, Board of Water Supply, City and County of Honolulu, Hawaii). If the freshwater is extracted faster than the rate of recharge, the freshwater head falls, the saltwater rises, and the freshwater layer becomes thinner. Since most pumping wells go deeper than the freshwater head, the rising saltwater can ultimately reach the bottom of the current well systems that will then begin to pump out saltwater. The freshwater head, therefore, needs to be constrained from falling below the level at which the well water would begin to turn saline. If more freshwater is required than that allowable under the constraint, it must be obtained through desalination of seawater, which serves as a backstop.

The rate of recharge and discharge of a coastal aquifer depends on the head level. As the head level rises, underground water pressure from a watershed decreases and the rate of recharge decreases. Also, leakage surface area and oceanward water pressure increase, and the rate of leakage increases. Thus net recharge varies inversely with the head level.

In most areas, groundwater users are geographically distributed. Users can be categorized according to their distribution costs. In Honolulu the distribution is over different elevations. In addition, the demand grows over time, depending on factors such as income and population.

Groundwater is typically considered a myopically exploited common property resource (see e.g., P. Koundouri, 2004, Potential for groundwater management: Gisser–Sanchez effect reconsidered, *Water Resources Research* 40:1–13; among many others). This results in a wedge (equal to marginal user cost) between marginal benefits and true marginal cost. Where water extraction is governed by an administered price, the same equilibrium obtains when, as in the Honolulu case, the regulatory authority implicitly sets price at an amount equal to the marginal physical cost of providing water. In Honolulu, status quo management introduces further inefficiencies as the authority sets a uniform price for different elevations—in effect cross-subsidizing high-elevation users.

To accurately model the above features, we require a generic operational model of status quo management and efficient spatial and temporal management of a renewable groundwater aquifer with variable recharge. We also need to allow for increasing demand and a backstop source of freshwater.

Users are distributed over different elevation categories. Consumption in elevation category *i* at time *t* is $q_t^i = D_i\left(p_t^i,\ t\right)$, where D_i is the demand function and p_t^i is the price. The second argument, *t*, of the demand function allows for any exogenous growth in demand.

Water is extracted from a coastal groundwater aquifer that is recharged from a watershed and leaks into the ocean from its ocean boundary, depending on the aquifer head level, *h*. Net recharge, *l*, is a positive, decreasing, concave function of head, i.e., $l(h) \geq 0,\ l'(h) < 0,\ l'' \leq 0$. The aquifer head level changes over time, depending on the net aquifer recharge and the quantity extracted for consumption at all elevations, $\sum_i q_t^i$. The rate of change of head level is given by $\square \cdot h_t = l(h_t) - \sum_i q_t^i$, where $\square$ is the factor of conversion from volume of water in gallons (on the RHS) to head level in feet. However, in the remainder of this section we subsume this factor, i.e., h is considered to be in volume, not feet. Thus, we use $h_t = l(h_t) - \sum_i q_t^i$ as the relevant equation of head motion.

As the freshwater head level falls (depending on the extraction rate), the freshwater–saltwater interface rises. If the head level falls below $h_{\min}$, the interface rises to the level of well bottoms. Therefore, we measure head as the level above $h_{\min}$. Any expansion in demand when the head level falls to $h_{\min}$ would need to be supplied by desalinated seawater. The unit cost of the backstop is represented by c_b, and the quantity of the backstop used in category i is b_t^i.

The unit cost of extraction is a function of the vertical distance water has to be lifted, $f = e - h$, where e is the elevation at the well location. At lower head levels, extraction is more expensive because the water must be lifted over a longer distance against gravity, and the effect of gravity becomes more pronounced as the lift, f, increases. The extraction cost is, therefore, a positive, increasing, convex function of the lift, $c(f) \geq 0$, where $c'(f) > 0,\ c''(f) \geq 0$. Since the well location is fixed, we can redefine the unit extraction cost as a function of the head level: $c_q(h) \geq 0$, where $c_q'(h) < 0, c_q''(h) \geq 0, \lim_{h \to 0} c_q(h) = \infty$. The total cost of extracting water from the aquifer at the rate q given head level h is $c_q(h) \cdot q$. The cost of transporting a unit of extracted water to users in category i is c_d^i.

We model water allocation first under status quo management and then under efficient management. The differences in welfare distribution under the two regimes are then examined and used to derive a mechanism to compensate those who lose welfare when the efficient allocation is implemented with marginal cost pricing and inframarginal blocks that balance the water authority's budget.

Principal Findings and Significance

We find that, compared to the status quo, efficient groundwater management in Honolulu increases welfare by 6.2%. The relatively large welfare gain, in comparison with that of other studies, is due to a combination of factors. Demand is large relative to the initial stock of water, but not so large that stock depletion will occur in the immediate future. In addition, the backstop price is relatively high, thereby contributing to the scarcity value of water.

By decomposing the sources of welfare gains, we find that the relative contributions of spatial optimization and temporal optimization depend on which comes first. In the Honolulu case, if spatial optimization is undertaken without temporal optimization, the gains are relatively small (about \$5 million). On the other hand, if temporal optimization is undertaken first (yielding \$227 million), the additional gains from spatial optimization are about \$180 million.

Temporal efficiency generates welfare gains by delaying aquifer exhaustion and the resulting need for expensive backstop technology. As such, the gains start at the time when status quo management would have resulted in the use of the backstop. Before this time, temporally efficient management causes welfare losses due to the higher efficiency prices. The gains from efficient management in Honolulu are \$441 million and the losses are \$34 million (or 7.7% of the gains) in present value terms.

Even though the gains from efficient management are larger than the losses, those who suffer losses can oppose efficient management. We provide a Pareto-improving mechanism for implementing efficient management. In the Honolulu case, we take 7.7% of the gains from the winners and use it to compensate the losers in each period. This is achieved by providing the losers an inframarginal free quantity of water, the value of which is equal to their welfare loss.

The urban Honolulu water district controls all of the water in the Honolulu aquifer. There are other water districts on Oahu with their own aquifers (e.g., Pearl Harbor aquifer). The aquifers minimally interact with each other through inter-aquifer percolation that is small enough to be ignored in most studies. Sophisticated engineering studies have considered such interactions, and integrating them with economic modeling is the next item on our research agenda. In addition, following the practice of the Honolulu Board of Water Supply, each water district consumes from its own aquifer, and inter-district transfers are not allowed. After repeating the methodology outlined above to solve for optimal management of the Pearl Harbor aquifer, we will solve for optimal joint management of the Honolulu and Pearl Harbor aquifers.