Energy costs and the optimal use of groundwater

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Abstract

To meet the growing demand for freshwater, many regions have increased pumping of groundwater in recent years, resulting in declining groundwater levels worldwide. A promising development is technical change regarding groundwater substitutes such as desalination and wastewater recycling. However, because these technologies are energy intensive, optimal implementation also depends on future energy price trends. We provide an operational model for the application to reverse-osmosis seawater desalination. With this foundation, we outline a research agenda for extending the framework to other groundwater substitutes and for adaptation to climate change.

Keywords: Groundwater management, water-energy nexus, dynamic optimization

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1 Introduction

Groundwater is the world's most extracted raw material – current withdrawal rates are estimated at 982 km^3 per year – and provides 25-40 percent of the global population's drinking water (NGWA, 2013). In the United States, groundwater constitutes roughly 20 percent (80 billion gallons per day) of total water withdrawals (USGS, 2009) and supplies nearly all municipal water use in some states, such as Hawaii. Since the beginning of the 20th century, groundwater water tables have fallen in many aquifers across the country. For example, areas in the Gulf Coastal Plain have experienced declines of 70-400 feet, areas in the High Plains and Pacific Northwest have seen declines of more than 100 feet, and the Desert Southwest and Chicago-Milwaukee area have faced declines of 300-500 and 900 feet respectively (Konikow, 2013). A promising development is technical change regarding groundwater substitutes such as desalination and wastewater recycling. Unfortunately these technologies are energy intensive and energy prices are also expected to continue increasing in the long run. This paper aims to extend the renewable resource economics of groundwater to allow for the increasing cost of substitutes and technical change. We provide an operational model for the application to desalination. With this foundation, we suggest a research agenda for extending the framework to other resource substitutes and for adaptation to climate change.

In groundwater economics, the existence of an abundant but costly groundwater-substitute technology, such as desalination, is often assumed. Yet theory and practice, for the most part, have not properly accounted for the energy-intensive nature of water management in determining optimal groundwater extraction profiles. Energy prices will affect optimal water pricing and groundwater extraction rates through two primary mechanisms: pumping costs and production costs of groundwater alternatives.[1] Water scarcity induced by rising per capita incomes and population growth may be compounded in the future by the rising cost of energy-intensive groundwater substitutes. Concurrently, induced innovation will reduce the share of energy costs in technologies like desalination, although the rate of innovation must eventually decline over time. How these competing effects ultimately alter long run optimal groundwater management strategies will depend on the model's underlying assumptions. To that end, we discuss several energy/innovation scenarios and their resulting effects on optimal water management.

2 Energy prices

From 1994 to 2013, energy prices in the United States rose from 6.4 to 6.9 cents/kWh in the industrial sector, 7.8 to 10.3 cents/kWh in the commercial sector, and 8.4 to 12.2 cents/kWh in the residential sector, which translates to an annual average growth rate of 1.5-2 percent across all sectors (US EIA, 2013a). The rate is expected to eventually taper off, however, as fossil fuel and coal generation is increasingly replaced by renewable energy sources. The US EIA (EIA, 2013b) projects energy prices to 2040 under three scenarios: (i) a "reference case" that assumes existing laws and regulations remain unchanged, (ii) a "no sunset case" that assumes tax credits for renewable energy sources in the utility, industrial and building sectors are extended, and (iii) an "extended policies" case that includes additional updates to federal equipment efficiency standards. In the reference scenario, the price of electricity is projected to grow at an average annual rate of 2.0%, 1.9%, and 2.2% in the residential, commercial, and industrial sectors respectively. In the alternative scenarios, the increase in growth rate is more gradual and

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[1] Transmission costs may also be important, especially in areas where a substantial portion of pumped groundwater is sent to higher elevations.

although the price appears to approach its inflection point (Chakravorty and Roumasset, 1990) near the end of the projection period, it never slows substantially. Given the large amount of uncertainty surrounding the conditions that determine future energy prices, we will use the EIA projections as a starting point, and assume that the growth in energy prices are eventually tempered by the increasing substitution of renewable for non-renewable energy and advances in renewable technologies.

3 Groundwater

Inasmuch as our primary objective is to characterize the effects of energy price fluctuations and induced innovation on water management, we employ a simple single-cell aquifer model, augmented to include discharge that varies with the head level (Krulce et al., 1997).[2] A coastal aquifer is naturally recharged (R) by precipitation in its upstream watershed. The volume of water stored in the aquifer in any given period is indexed by the head level (h) – the vertical distance between mean sea level and the water table. While recharge adds freshwater to the aquifer, the head level may be drawn down due to both anthropogenic extraction (q) and natural discharge (d). Since coastal aquifers are lenses of freshwater floating on denser underlying seawater, pressure on the edge of the lens causes groundwater to discharge into the ocean. It follows that the discharge function is head-dependent because lens pressure is size-dependent and head is representative of stored freshwater volume. The evolution of the head level over time is described by the following equation:

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[2] The canonical interior aquifer model, i.e. in which discharge is negligible or not stock-dependent, is a special case of this one.

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

The cost of extracting groundwater is determined primarily by the energy required to lift water from the aquifer to the surface, where lift (L) is equal to the vertical difference between the ground elevation at the well (e) and the water table. Because the well elevations are fixed, we can write the extraction cost function more concisely as a function of the head level and the price of energy: $c_q(h;p^E)$. Unit extraction cost is a decreasing and convex function of head. As the head level is drawn down, the distance that groundwater must be lifted increases, which naturally requires more costly energy. For a given head level, an increase in the price of energy also increases the unit cost of water extraction. Assuming non-positive second derivatives for $c_q(h;p^E)$ allows for both linear and strictly convex costs. The latter characterization might apply, for example, if existing wells are not sufficient to meet pumping demands in the future even after redistribution of the total load across wells. In that case, constructions costs of new wells in the long run could drive up pumping costs non-linearly. Although innovation of pumping technology will reduce extraction costs in the future to some extent, we abstract from that possibility in the discussion that follows.

4 Desalination

Many types of desalination processes currently exist, and new processes are likely to be developed in the future. Of the existing technologies, reverse osmosis (RO) requires the least total equivalent electrical energy (3.5-5 kWh/m^3) and is also the most popular – in 2011 RO was used in approximately 66% of installed desalination capacity (IDA, 2013). For comparison, multi-stage flash distillation (MSF) requires 13.5-25.5 kWh/m^3, multiple-effect distillation

(MED) requires 6.5-11 kWh/m^3 and mechanical vapor compression (MVC) requires 7-12 kWh/m^3 (DESWARE, 2013). For that reason, we focus attention on projected technological developments in the area of RO research. While RO may be applied to seawater, brackish water, or even wastewater with variable recovery efficiencies, all calculations henceforth will be based on seawater treatment. The methodology is generally applicable, however, provided that cost and technology assumptions are adjusted to match the type of feed water desired.

As energy prices continue to rise in at least the short to medium term, energy efficiency of RO may increase due to induced innovation, i.e. the share of RO desalination cost attributed to energy may decline over time. From 1970 to 2008, the power consumption required to produce a cubic meter of desalinated seawater fell from roughly 16 kWh to less than 5 kWh (Elimelech and Phillip, 2011), which corresponds to a 3-4 percent average annual rate of decline. It is important to note, however, that efficiency gains have been steadily declining; from 1970 to 1980, power consumption requirements fell at 10 percent annually, whereas the decline was a modest 3 percent from 2000 to 2008. While it is difficult to project innovation, the historical trend suggests that efficiency gains in terms of energy consumption will continue to slow in the future.

The total cost of RO treatment will also decline with improvements in membrane technology, chemical processes, and machinery, although the rate of decline will eventually decelerate. Since the early 1970s, the cost of producing one cubic meter of desalinated seawater has fallen from $3 to less than $1 (Ghaffour et al., 2013). In some cases (e.g. Ashkelon, Israel and Tampa Bay, USA), desalinated water is being produced for as little as $0.50 per cubic meter (Greenlee et al., 2009). Within the past decade, however, the unit cost of desalination appears to have rebounded and is currently following a slight upward trend. This may be an indication that rising energy costs are already beginning to dominate advances in desalination technology. We characterize the cost of the backstop technology as a function, $c_b(\alpha,\beta,p^E)$, where the time-varying terms α and β represents induced innovation and general technological advancements in RO respectively.

5 The water management problem

The objective is to choose groundwater extraction and desalination (*b*) in every period to maximize the present value of net benefit to society, subject to the aquifer's equation of motion (Eq. 1) and given projections for future energy prices, technological advancements in RO desalination and a positive discount rate (*r*):

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

where *D* is the demand curve for water, and the area under the inverse demand curve measures benefits from water consumption. Eq. 2 can be solved in an optimal control framework. It is straightforward to show that the necessary conditions for the corresponding current value Hamiltonian can be combined to derive the following efficiency price condition for water (Krulce et al., 1997; Pitafi and Roumasset, 2009; Roumasset and Wada, 2012):

$$p_t = c_q(h_t;p_t^E) + \frac{\dot{p}_t - c_q'(h_t;p_t^E)[R-d(h_t)]}{r+d'(h_t)} \tag{3}$$

Eq. 3, which states that the price of water must equal the sum of marginal extraction cost and marginal user cost (MUC), is identical to the standard coastal groundwater case, except that both cost terms are functions of the exogenous price of energy. Although induced innovation and other technological advancements do not enter Eq. 3 directly, an additional necessary condition for the maximization problem (Eq. 1) is

$$p_t \le c_b(\alpha_t, \beta_t, p_t^E) \ \text{ if} < \text{then } b_t = 0 \tag{4}$$

Eq. 4 says that if the efficiency price or marginal benefit of water is less than the backstop cost, using desalination is not optimal. As technological change and the price of energy shift the cost of desalination over time, however, desalination may eventually serve as an optimal supplement to groundwater extraction.

6 Application: Pearl Harbor aquifer

The developed framework will be applied to the most heavily used source of groundwater in the state of Hawaii, the Pearl Harbor aquifer. Pearl Harbor is a suitable case study both because it is a large and well-studied coastal aquifer and because RO seawater desalination is a natural backstop candidate for an island like Oahu. However, the methodology is transferable to other regions, inasmuch as mounting water scarcity and rising fossil fuel prices are phenomena observed worldwide. We begin by incorporating what we feel is the most likely backstop cost scenario – taking into account both projected energy and innovation trends – into a standard coastal groundwater optimization model. We then discuss other possibilities in which either the energy price or technology effect dominates over some period before eventually approaching a constant level in the very long run.

An in depth discussion of the various assumptions, parameter values, and functional forms characterizing the hydrology of the Pearl Harbor aquifer can be found in an earlier paper by Krulce et al. (1997) and will not be repeated in detail here, but key equations and parameters are summarized in Table 1. Evolution of the head level over time, described by Eq. 1, is determined by a combination of recharge, natural recharge to the ocean, and extraction. The objective of the management problem is to choose extraction and desalination in every period to maximize present value, where present value depends on benefits – measured as the area under the inverse demand curve – as well as costs – including those incurred by both groundwater extraction and desalination.

Table 1. Equations and parameters

Description	**Equation/value**	**Units**
Conversion factor (head to volume)	78.149	Billion gallons/foot
Initial head level	15	Feet
Initial backstop cost	3	Dollars/thousand gallons
Recharge	281	Million gallons/day
Discharge	$0.24972h^2+0.022023h$	Million gallons/day
Unit extraction cost	$0.283(15/h)^2$	Dollars/thousand gallons
Demand	$186.2e^{.02t}(p+0.947)^{0.3}$	Dollars/million gallons

We then assume that backstop cost is changing over time. The unit cost of seawater desalination is influenced by three key factors: the price of energy, induced innovation, and advancement in desalination technology. The discussion in section 4 suggests that technological change may be dominating rising energy costs currently but that gains in energy efficiency have slowed considerably in recent years. Although future increases in energy prices are likely to be tempered by more substitution toward renewable energy sources, it appears that the scarcity effect of energy sources will dominate innovation in the foreseeable future. If this is indeed the case, we are either already at or near the bottom of a u-shaped cost curve for desalination, and the price will continue to increase with modest slope in the near term (Chakravorty and Roumasset, 1990).

In the long run, we expect that the unit cost of desalination approximately approaches a constant. Technological progress in the backstop, RO desalination, has already started to slow and is likely to decline asymptotically toward a constant long-run cost (Fischer and Salant, 2012). At the same time, the fraction of petrochemicals used to power the RO process is asymptotically approaching zero as renewable energy alternatives (e.g. photovoltaics) become cost-effective. Consequently, the energy cost component of desalination is increasing, concave, and bounded from above. To illustrate the two opposing forces, we consider an outer bound for the backstop cost of $30 per thousand gallons. (This tenfold increase corresponds to an average annual increase of 2.4% over 100 years.) Since the energy effect appears to already be dominating the innovation effect, we fit an upward sloping curve between the backstop costs at year 0 and year 100: $3.00523 + 0.0837046t + 0.00558572t^2 - 0.0000372381t^3$. The curve starts out convex to illustrate the right side of a u-shaped curve to be consistent with Chakravorty and Roumasset (1990) but become concave after an inflection point as it approaches its long-run level.

The solution method is to first calculate the optimal steady-state head level (h^*) based on the long-run backstop price (c_b^*). The terminal time (T^*) is then solved for, such that the solution to Eqs. 1 and 3 with terminal conditions $p(T)= c_b^*$ and $h(T)=h^*$ results in $h(0)=h_0$. If the optimal price path for water does not reach the backstop price by year 100, then the solution is the same as if the backstop price were constant at the year-100 level. If instead the candidate optimal price path reaches the year-100 backstop price prior to year 100 and then experiences a discreet jump downward, then it must be optimal to switch to the backstop sooner. In that case, move the endpoint toward the present, i.e. use the backstop cost corresponding to an earlier period (e.g.

year 99) and calculate h* again. Use the new terminal values c_b* and h* to calculate the optimal paths. Keep adjusting the guess for the switch-point until the price no longer jumps.

To illustrate the effect that a variable backstop cost has on the optimal solution, we compare our findings with Krulce et al's (1997) original results. When the backstop cost is allowed to rise, desalination is delayed for over 30 years, from year 50 in the constant cost case to year 84. Because the price curve is steeper, the head level is drawn down more slowly and over a prolonged period of time, although the long run head level turns out to be lower than in the constant cost case. Note that even a tenfold increase in the ultimate backstop cost has very little effect on the full marginal cost today, thus requiring only small current adjustments to pricing schedules, provided that efficiency pricing has already been implemented. In one sense, this increases the urgency of switching to efficiency prices now, given the political difficulty of large increases later.[3]

While we believe that an upward sloping, eventually concave, backstop price curve is probable in this particular scenario, one could imagine situations where the starting point is on the left side of a u-shaped backstop price curve or the technology effect always dominates, i.e. the backstop price is always declining. The latter case is especially of interest, inasmuch as the long run implication is that the resource (if renewable) would be allowed to replenish. Once the efficiency price for water reaches the backstop price curve, it must decline at the same rate – otherwise it would only make sense to use the resource with the lower price. And a declining price schedule corresponds to an increasing head trajectory for the aquifer. Depending on the

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[3] The political feasibility of higher marginal charges can also be enhanced by compensating current and near term users with lower prices for inframarginal blocks. The compensatory transfer can be financed via bonds out of the benefits to future consumers from delaying the use of the expensive backstop technology (Pitafi and Roumasset, 2009).

parameters of the particular application, the steady state head level may end up at or above its initial level.

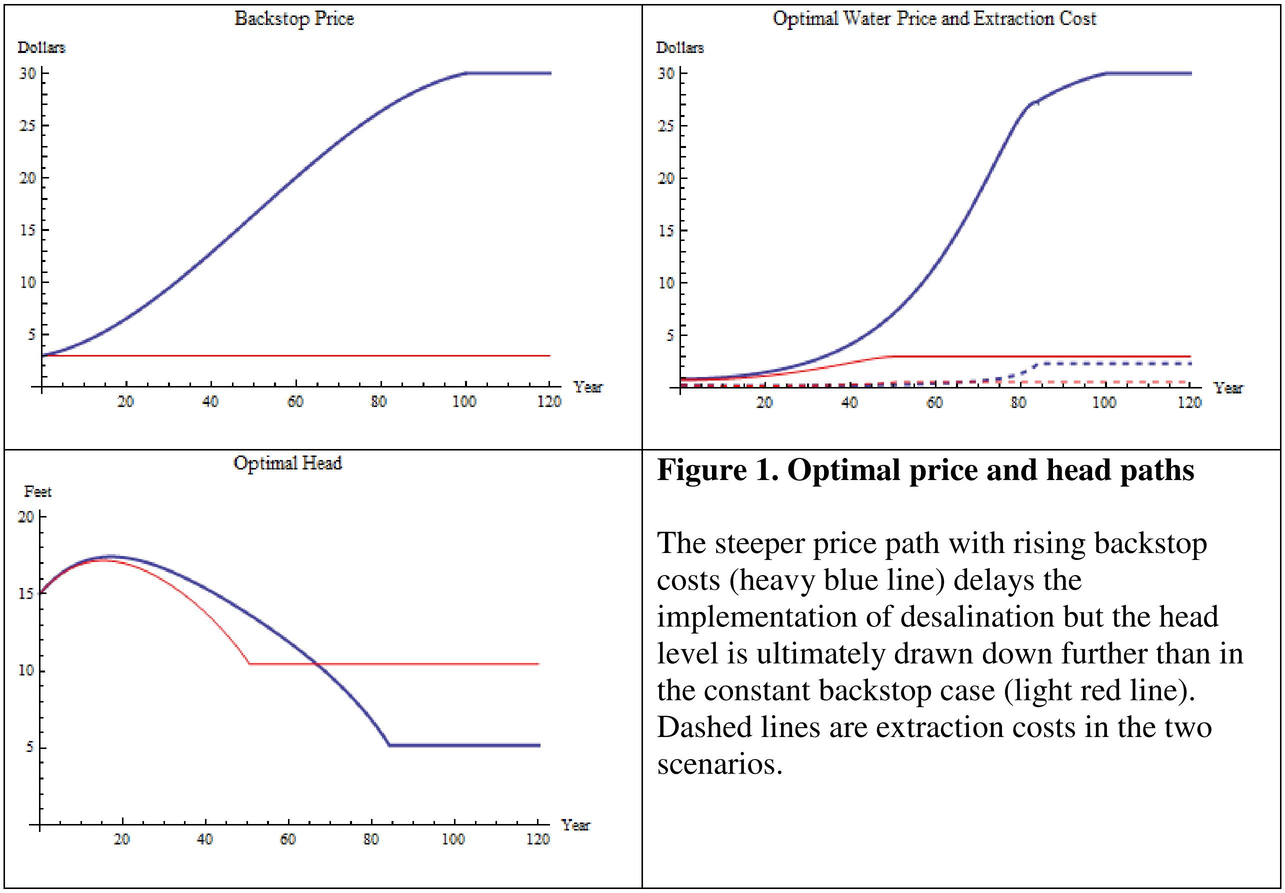

Figure 1. Optimal price and head paths

The steeper price path with rising backstop costs (heavy blue line) delays the implementation of desalination but the head level is ultimately drawn down further than in the constant backstop case (light red line). Dashed lines are extraction costs in the two scenarios.

An important caveat to the results discussed is that we abstracted from energy costs and innovation in groundwater extraction to highlight the effects of a variable backstop cost. The inclusion of energy and technology trends for groundwater pumping increases the complexity of the management problem, but examining the tradeoffs introduced sheds some light on possible outcomes. Rising energy prices have the same qualitative effect on both resources in that it makes them more expensive. However, the quantitative impact depends on how energy intensive pumping is versus desalinating. Similarly, innovation reduces the price for both resources, but the rate of innovation, as well as the location on the projected innovation curve, will determine which resource sees a greater decline in cost due to technological improvements. As an example, suppose that innovation has stagnated for groundwater pumping, but that like desalination, pumping is very energy intensive. As the price of energy goes up, both resources become more expensive, but the effect on desalination is tempered by innovation. Consequently, the price of water rises to the backstop cost sooner and the aquifer drawdown period is shortened.

7 Concluding remarks

Groundwater is a renewable and replaceable resource in the sense that it displays a positive and concave growth function, decreasing unit extraction cost as a function of stock, and can be partially replaced by desalination, an abundant yet costly substitute. For coastal aquifers in particular, the steady state extraction rate is given by the equality of the backstop price and the sum of extraction cost and marginal user cost. The remaining consumption is provided by the backstop resource. The problem with this formulation is that energy costs, an important component of the cost of desalination, are not constant and likely to be rising. Moreover the canonical solution omits technological change, in particular with respect to the backstop cost.

Accordingly, we extend the basic renewable resource model to allow for a changing backstop price, which evolves according to assumptions about energy costs and technological progress regarding the backstop, and illustrate an algorithm for solving for efficiency prices and quantities over time. As an outer bound, we consider the case of a 10-fold increase in desalination cost. This results in a rapid increase in efficiency prices, to the point of plausibly rendering efficiency pricing politically infeasible. We also discuss the general case of a U-shaped backstop price, where operating solely on the right or left sides of the U are special cases, and further numerical exploration of these cases is warranted.

This perspective reveals an important research agenda for managing our increasingly scarce groundwater resources. First, we need better estimates of how the interplay of energy costs and innovation are likely to play out over time. To the extent that these estimates portend substantial increases in efficiency prices, this warrants increased attention to institutional mechanisms for implementing said prices at the margin (e.g. adjusting block-pricing schedules). In the present study we have only considered the effect of a changing backstop price on water management. But clearly other partial substitutes for groundwater are available, most notably watershed conservation and the use of recycled wastewater. To the extent that these partial substitutes are economically viable, they may be capable of dramatically delaying the time at which the steady state solution is reached and accordingly substantially reduce the rate of increase in the full marginal cost. Resource economics needs to be extended to allow for the simultaneous solution for these different instruments of management, including the time path of investment in both infrastructure and natural capital. Implementing these models will require advances in integrated models of economics, engineering, and watershed hydrology.

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