RESEARCH PAPERS

Dynamically Efficient Urban Water Policy

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ABSTRACT: Many urban communities are considering infrastructure investments to augment their water supply in response to actual or expected shortages due to weather variability and, in some cases, due to climate change. To address short-term imbalances between supply and demand, water utilities frequently use mandatory water restrictions to curb demand. By contrast, adjustments to the volumetric price of water are rarely used as a demand-management tool in response to variability in catchment inflows. To evaluate the welfare losses from the typical water restrictions approach to demand management and supply augmentation, we compare ‘business as usual’ to the use of dynamically efficient water pricing to determine: (1) the volumetric price and (2) the optimal time to invest in additional supply given variability in water availability. To calculate welfare losses a practical method is used that simultaneously calculates the optimal dynamic volumetric price, the optimal time to invest in new supplies, and the optimal use of water restrictions while accounting for climate variability, the costs of supply augmentation, and the demand for water by households. Using actual data from a large metropolitan center, model results show that the present value of the expected costs from using supply-inflexible volumetric water pricing generates large welfare losses in excess of the annual average household water bill. These losses are attributable to: (1) on-going water restrictions and (2) premature supply augmentation, but could be avoided if dynamically efficient volumetric pricing were to be adopted by price regulators or water utilities in response to variability in water availability. The results are both important and of general interest because global expenditures on water infrastructure are estimated to be some \$75 billion/year and there is no jurisdiction, as far as we are aware, that employs dynamically efficient water pricing.

KEYWORDS: water scarcity, water pricing, infrastructure investment, desalination, water supply, water restrictions

November 12, 2010

Revision 2

INTRODUCTION

Many of the world's urban centers are close to, or have reached, their existing capacity to deliver water to their residents (Mays, 2009). In some locations, such as US South West, Spain, and Southern Australia, the problems of meeting existing demands have been compounded by extended periods of low inflows into catchments and water storages. Meeting these challenges of balancing supply and demand requires a mix of water conservation and supply augmentation that, in turn, necessitates an understanding of the demand for water, the costs of new water supplies and the dynamics of climate variability.

The policy response to urban water stress has largely been two-fold. The first is widespread investments in supply augmentation. For desalination alone, one recent market report predicts almost \$90 billion in investment over the period 2010-2016 (Pike Research, 2010). In many cases, such infrastructure investments arise from short-run pressures associated with reduced water availability. For example, Santa Barbara, California, built a desalination plant during a 1991 drought; the drought ended before the plant was on-line, and the plant has been mothballed since construction (Welsh, 2008). The second major response has been rationing at times of water shortfalls, typically through restrictions on outdoor water use. For example, in the recent past 32 departments in France, the five largest cities in Australia, and cities in at least 20 U.S. states have imposed residential water restrictions.

Adaptive or flexible pricing whereby volumetric prices rise in response to reduced water availability is rarely used to manage urban water demand. In many cases, water suppliers are obliged to conform to a 'zero profit' constraint to avoid monopoly pricing that prevents utilities from raising their prices in periods of drought if their costs have not increased (Howe, 2005). While several cities in California, as well as Denver and San Antonio, have imposed "drought surcharges", we are not aware of any urban center that systematically (e.g. annually) manages water demand by adjusting water prices to reflect both available storages and supply augmentation possibilities. Such price inflexibility is in sharp contrast to the price volatility of many goods provided in a competitive market, such as gasoline, for which prices rapidly reflect both current and anticipated supply availability.

Current practices to balance water supply and demand in urban centers are typ-

ically not economically efficient. Inflexible pricing results in current demand that is too large when water storages are low. This, in turn, encourages premature and/or over-investment in supply augmentation. By contrast, if the volumetric price of water accounts for its scarcity value then it should be set to balance short-run supply and demand by raising the price above the short-run marginal cost of supply so as to reduce water demand. As a result, such pricing can beneficially postpone investment in supply augmentation. Flexible pricing can also reduce or eliminate the need for quantitative water restrictions. Such restrictions impose significant welfare costs, relative to price-based demand management, as they prevent the equalization of the marginal benefits of restricted and unrestricted uses within households, and the equalization of marginal benefits from water consumption across households (Hirshleifer et al., 1960, pp. 36–41).

In this paper, we address the problem of balancing supply and demand for water in cities by presenting an approach that derives a dynamically efficient volumetric price schedule for water that varies with available water storages. These optimal volumetric prices account for climate variability, the costs of supply augmentation and the demand for water by households. We apply stochastic dynamic programming to solve a series of connected problems before and after investment supply augmentation and use actual data from a large metropolitan center. Our approach to calculate dynamically efficient volumetric prices, and also the optimal trigger point of when to invest in supply augmentation, can be applied to any city where there is reliable data on water consumption and pricing, past and current water supplies, and estimated costs of supply augmentation.

Our findings indicate that dynamically efficient pricing has the potential to substantially increase consumer welfare and could generate savings globally of multiples of billions of dollars. Such savings accrue from the optimal postponement of supply augmentation such as desalination plants, as well as from avoiding water restrictions. The large welfare gains we find from dynamic pricing under supply uncertainty contrast sharply with a literature which examines the gains from water price reform. For example, Garcia and Reynaud (2004), Renzetti (1992), Swallow and Marin (1988), and Crew and Kleindorfer (1987) all find small welfare gains from water pricing reform in situations without supply uncertainty. Similarly, for the case of groundwater Gisser and Sanchez (1980) find that the benefits of optimal

dynamic management are “is so small that it can be ignored for practical purposes,” although in contrast Timmins (2002) finds significant losses from dynamically inefficient groundwater extraction. In our study, supply uncertainty increases the welfare importance of intertemporal effects and, thus, the importance of dynamic pricing because conserving water storages serves as a form of insurance against adverse supply shocks.

In the following section, we review the theory and practice of efficient water pricing and explain why it is important to account for uncertainty in water supplies when setting the dynamically efficient price. In section three, we describe the problems with the regulatory pricing system employed in Sydney, Australia and its implications for the decision to invest in supply augmentation in the form of a desalination plant. In section four, we use stochastic dynamic programming to determine the optimal trigger point to invest in Sydney’s desalination plant and also dynamically efficient volumetric water prices. We calculate consumer welfare under two scenarios: (1) optimal investment in desalination with dynamically efficient volumetric prices and (2) actual investment in desalination with the actual price and mandatory water restrictions in place when the decision was taken to invest in desalination. Our modeling also allows us to separate the expected welfare costs of ‘business as usual’ into losses from sub-optimal investment in desalination and from the use of inefficient pricing. In section five we discuss the general implications of our approach for optimal urban water supply augmentation and provide conclusions.

EFFICIENT WATER PRICING

Economic Principles

The standard economic prescription for water pricing is to set the volumetric price of water equal to marginal cost of supply (Hirshleifer et al., 1960) in the absence of external costs associated with water supply or consumption. This ensures the marginal benefit of all water uses, and across all users, is the same provided that all consumers face the same volumetric price.

Implementing marginal cost pricing for residential water consumers poses a

number of challenges. Foremost among these difficulties is how to define marginal cost. This is because efficient water pricing not only depends on the cost of supply augmentation beyond the current capacity constraint, but also also requires consideration of the possibility of either delaying or permanently avoiding supply augmentation through higher current prices (Riordan, 1971a,b; Gysi and Loucks, 1971). Typically, marginal cost that is based on current capacity is called short-run marginal cost, while marginal cost that is based on augmentation to existing capacity is called long-run marginal cost. Long-run marginal cost is properly a forward-looking concept (Turvey and Christie, 1971, p. 74). However, the common long-run practice of charging a volumetric price based on the annualized cost of providing the most recent realized supply augmentation is backward-looking and, this, is not forward-looking marginal cost pricing.

Typically price regulators and utilities treat marginal cost as exogenous and deterministic and that depends solely on the capital and operational costs of supply augmentation. Under these circumstances, Turvey (1976) has developed method to calculate the marginal costs associated with incremental increases to capacity. While this approach is valid in the case of certain demand and supply, it presupposes there is no random variability in water availability. If, however, marginal cost is calculated on the basis of augmented capacity then when this increased capacity is triggered, which depends on uncertain future inflows to water catchments and storages, determines the actual cost. Thus, long-run marginal cost is state-contingent; in an uncertain world there is no unique long-run marginal cost.

A related issue in terms of marginal cost is that using additional water today creates an opportunity cost of not having that water tomorrow, provided there is limited storage capacity. The value of having additional water tomorrow is not fixed; indeed it depends on both supply uncertainty, investment rules, and the pricing policy itself. Consequently, long-run marginal cost is endogenous, and is better viewed as an outcome of the optimal pricing problem rather than as an input to the decision process. In other words, long-run marginal cost pricing is a useful description of the optimal pricing policy, but by itself does not provide a useful method to solve the optimal water pricing problem. Many commonly-used forward-looking schemes, such as setting prices equal to the annualized supply cost associated with the next cheapest source of supply that augments current capacity, do not represent

dynamic or forward-looking marginal cost pricing. The proper forward-looking analytical framework for evaluating the marginal cost of water, which accounts for the issue of supply variability and for infrastructure investment options, is the method of stochastic dynamic programming (Hughes et al., 2009). Unfortunately, this approach is, typically, not used in actual regulatory price-setting where the principal concern is to avoid monopolistic pricing and to provide price certainty to consumers. We contend, however, that it is possible to both prevent monopolistic pricing and ensure dynamically efficient water prices.

A practical difficulty with pure marginal cost pricing is that many urban water suppliers are natural monopolies such that the average cost is decreasing in the amount supplied. Consequently, marginal cost pricing will usually not provide the water supplier with sufficient revenues to cover costs, unless there is also a fixed cost component to the water tariff, or some subsidy paid to the water supplier. This problem is well recognized and, for this reason, almost all urban water utilities that impose volumetric water prices on consumers have a two-part tariff that includes a fixed charge component. Setting the volumetric charge equal to the marginal cost of supply and establishing the access fee at a level that allows the water supplier to break even is called the Coase Result (Coase, 1946). It is a first-best pricing scheme provided that the demand for water supply access is independent of the access fee over the relevant range, which is a reasonable approximation in most developed countries. Our analysis makes use of this result in that we do not explicitly evaluate revenue from the pricing policy; instead we assume that the regulator fixes the access fee to control utility profits. If, however, the demand for water supply access depends on the access fee, the two-parts of the tariff should be calculated jointly.

Frequently, regulators impose a block-rate tariff structure, where the water price changes with the amount consumed. An increasing block-rate pricing structure, as applied in many US cities, is often advocated for equity reasons. However, empirical studies show that the number of people in a household increases water consumption (Hanke and de Maré, 1984; Lyman, 1992). Thus, an increasing block tariff price structure has the unfortunate consequence that large and poor households, who may have little discretionary use about water they can use, may pay a higher price for water than small and high-income households (Bithas, 2008; Momi and Udi, 2007). An increasing block tariff also fails to satisfy a fairness test that the total

water bill of each household is proportional to their share of water consumption (Loehman, 2008). Moreover, it is economically inefficient if consumers differ in their preferences because it results in households with different marginal benefits of water consuming the same volumes of water while facing the same marginal price (Train, 1991, pp. 223–224). For this reason, our analysis focuses on a uniform rate scheme, where the price of water is independent of household water consumption.

Dynamic Programming

To calculate dynamically efficient prices, we use the method of stochastic dynamic programming (Bellman, 1957; Rust, 1996). In this approach, the regulator faces a complicated decision problem. At the beginning of each year t , a price p must be selected. This price implies consumption through the demand function $q(p)$, which may be weather-dependent. The regulator does know the level of water storages s at any point in time that cannot exceed storage capacity, but does not know the weather or the amount of random inflows r that will occur over the year. Storages at the start of next year are linked to current consumption through the balance equation $s_{t+1} = s_t + r_t - q(p_t)$.

We first consider the pricing decision in a simplified framework, before complicating the calculations with supply augmentation or water restrictions. The regulator's problem is to select a pricing policy that maximizes the expected net present utility of water consumption. Changes in consumer utility are assumed to be well-approximated by changes in the area under the ordinary inverse demand curve.¹ The net utility of consumption q in a given period is then $\int_0^q (P(q) - c) dq$, where $P(q)$ is the ordinary inverse demand curve, and c is the marginal variable cost of water supply. This expression for current net utility can be written equivalently in terms of the ordinary demand as defined by Equation (1):

$$U(p) = Q(p)(p - c) + \int_p^\infty Q(s) ds, \quad (1)$$

for p such that $q = Q(p)$. The regulator is concerned not just with the current period

¹Provided that the income elasticity is zero, or if the somewhat weaker Willig (1978) condition holds, this approximation will be exact.

net utility, but also with the discounted net present utility of all future periods. We write this *value function* as

$$V(s_{t+1}) = V(s_t + r_t - q(p_t)). \quad (2)$$

This is a function of future water storages, which is random because of its dependence on weather-dependent inflow r and, potentially, also through weather-dependent demand q .

A risk-neutral regulator would make decisions based on the expectation of $V(s)$, denoted by $\mathbb{E} V(s)$, where the expectation is taken over the random components of future stock s . The *Bellman equation* is defined by Equation (3):

$$V(s_t) = \max_p U(p) + \delta \mathbb{E} V(s_t + r_t - q(p)), \quad (3)$$

where δ is a positive discount factor strictly less than one. Given the form of V , and the available storage s_t the regulator's choice of optimal p is defined below:

$$p = \delta \mathbb{E} V'(s_t + r_t - q(p)) + c. \quad (4)$$

Equation (4) has the following interpretation: the regulator should set price equal to marginal cost, where marginal cost reflects both direct operating expenses (c) and the discounted expected marginal cost of having lower storages at the beginning of the next period, ($\delta \mathbb{E} V'$). The practical difficulty in implementing this pricing scheme is that marginal cost depends on the value function, and on p itself, neither of which are known *a priori*. Given that marginal cost will not be known until the dynamic programming problem is solved, the marginal cost pricing rule given by Equation(4), by itself, cannot be used to determined the dynamically efficient volumetric price.

There are a variety of techniques to solve for the unknown value function, but perhaps the simplest is the method of *value function iteration*, also known as successive approximations. The method proceeds as follows: First, make an arbitrary initial approximation, labeled V_0 , for the value function and, second make succes-

sive approximations V_i by applying the iteration given by Equation (5):

$$V_{i+1}(s_t) = \max_p U(p) + \delta \mathbb{E} V_i(s_t + r_t - q(p)), \quad (5)$$

Convergence to the true value function V is guaranteed because the iteration is a contraction mapping. However, it is not computationally possible to independently specify V at each of the infinite possible storage states. Instead, we approximate V by a cubic spline with 1000 knots evenly spaced between 0 and 100 percent of storage capacity.

The supply augmentation problem can be solved through backwards recursion. First, we solve for the optimal pricing policy, and associated value function $V^*(s)$, assuming supply augmentation has occurred. This solution proceeds by the iteration procedure illustrated in Equation (5) while accounting for inflows r that may change with supply augmentation and subtract extra production costs due to supply augmentation. Second, we solve for the optimal pricing and investment policy or supply augmentation, assuming the supply augmentation has not yet occurred. The value function definition for the first stage is given by Equation (6):

$$V(s_t) = \max \begin{cases} \max_p U(p) + \delta \mathbb{E} V(s_t + r_t - q(p)) \\ \max_p U(p) + \delta \mathbb{E} V^*(s_t + r_t - q(p)) - K \end{cases} \quad (6)$$

The essential difference between Equation (3) and Equation (6) is that in the latter equation in each period the regulator must choose whether to invest in the new supply at some net present capital cost of K . If investment in supply augmentation occurs, the relevant continuation value function becomes $V^*(s)$, that is a known function because of the backwards recursion; otherwise the relevant continuation value function is $V(s)$ that can again be calculated through the method of successive approximations. This general backwards-induction procedure can be extended to handle an arbitrary number of supply augmentation possibilities, so long as the investment opportunities are implemented in a known sequence. It is also straightforward to account for time-to-build lags between the investment decision and the availability of new supply.

REGULATORY WATER PRICING: SYDNEY, AUSTRALIA

Figure 1: Sydney Water Storages and Monthly Catchment Inflows

Sydney is Australia's largest city with over four million residents. Its water supply is sourced primarily from water storages in the form of 11 dams that have been built in catchments west of the city to both capture and store rainfall. Water is delivered to households via a single distribution network provided by a single supplier, the Sydney Water Corporation (SWC). The SWC is a state-owned corporation and provides dividends to the Government of New South Wales. As a protection to consumers and to avoid monopoly pricing, the maximum price the SWC can charge its water consumers is set by the Independent Pricing and Regulatory Tribunal (IPART) of New South Wales. Its role in terms of water is to determine the maximum prices that can be charged for metropolitan water supply, wastewater and storm-water services supplied by declared public water authorities.

IPART's most recent determination of the maximum residential water prices in

Sydney is for the period 1 July 2008 to 30 June 2012. Maximum prices are set for both the access fee and the volumetric prices. It determination provides for a more than a 30 percent increase in real terms in the average water bill of Sydney households over the 2008–2012 period. Almost half of this cost increase compensates SWC and its partners for the operating costs and annualized capital costs associated with a desalination plant that became operational in February 2010. This desalination plant has a capacity to produce about 90 billion liters of potable water per year, an amount equivalent to about 15 percent of Sydney’s annual water consumption and cost US\$2.0 billion to construct (IPART, 2008).²

IPART’s price setting rule is to establish the maximum volumetric price equal to what it considers to be the long-run marginal cost of supply (IPART, 2008, p. 93). To calculate this price it uses an Average Incremental Cost Method for what it considers to be the next best available supply augmentation. What IPART calls long-run marginal cost includes an allowance for both the cost of the capital to construct the plant and also its operating costs. A stylized representation of how it calculates the volumetric price charged to water consumers is given by Equation (7):

$$\text{Average Incremental Cost} = \frac{\text{Least cost investment (\$)}}{\text{Incremental output from capacity expansion (kL)}} \quad (7)$$

IPART’s regulatory pricing is typical of the procedures employed in other parts of Australia, and also in other countries (Howe, 2005). It claims to base its pricing on long-run marginal cost. However, there is no unique long-run marginal cost as it depends on the highly variable inflows of water into Sydney’s catchments and dams (Grafton and Kompas, 2007). Thus, the long-run marginal cost it uses to set water prices is one of many measures of cost that could be used.

If IPART’s pricing policy were economically efficient then the price charged to consumers prior to the decision to build the desalination plant should have accounted for the added cost of supply augmentation associated with desalination. Unfortunately, IPART’s did not calculate a forward-looking scarcity price to opti-

²All international currencies are first converted by the local CPI into local 2010 values, then translated in US dollars at the prevailing exchange rates of November 2010.

mally postpone investments in supply augmentation and its ‘fixed price’ approach, whereby prices vary only with the costs associated with existing or just augmented capacity, interest rates or inflation, ignores the affect of weather of current supplies. As a result the volumetric prices it established in its immediate past determination were not set in an economically efficient manner so as to maximize consumer surplus.

Sub-optimal volumetric pricing that is not dynamically efficient generates other welfare costs beyond the supply augmentation decision. This is because to help balance current demand and supply with volumetric prices that are too low, and prior to any supply augmentation, water rationing in some form has to be imposed. In the case of Sydney, mandatory outdoor water restrictions were imposed on residential households in terms of how water could be used outdoors, at what times, and for what purposes. Rationing water with mandatory water restrictions is economically inefficient and resulted in aggregate welfare losses equal to about \$275 million (2010 dollars) in 2004–2005 relative to a volumetric price that would have ensured the same level of demand and remitted revenues, in excess of supply costs, back to consumers in the form of lower access fees (Grafton and Ward, 2008).

WELFARE COSTS OF ‘BUSINESS AS USUAL’: SYDNEY

In this section, we calculate the optimal combination of volumetric price, water restrictions, and supply augmentation using actual data for Sydney. This provides the first-best, dynamically efficient policy. We then compare the welfare outcome of that optimal policy to the welfare outcome of the actual water prices charged to household, the actual water restrictions, and the actual decision to invest in desalination. To gain further insight into the welfare costs on not adopting dynamically efficient water pricing, we provide two further comparisons. First, to highlight the importance of efficient pricing separate to the timing of investment or supply augmentation, we examine a counter-factual scenario where the desalination investment is made optimally, but given the constraint that prices and rationing follow the actual observed pattern. Second, to highlight the importance of optimal investment decisions separate to efficient pricing, we examine a counter-factual scenario where volumetric pricing is optimal, but given the constraint that the desalination

Table 1: Per-capita Sydney water demand regression results

Covariate	Coef.	Std. Err.	95% Confidence	
Price	−0.328	0.016	−0.36	−0.30
Restrictions (2003–05)	−0.182	0.008	−0.20	−0.17
Restrictions (1994–96)	−0.089	0.008	−0.11	−0.07
Rain (meters)	−1.134	0.117	−1.36	−0.90
Rain (lagged)	−1.242	0.118	−1.47	−1.01
Temperature (100 °C)	1.035	0.039	0.96	1.11
Temperature (lagged)	0.271	0.039	0.19	0.35
Constant	−7.688	0.024	−7.73	−7.64

investment follows the actual observed pattern.

Model specification

Demand Water demand is estimated from daily aggregate water consumption in kL over the period January 1994 through October 2010 during which a single uniform price was used. During October 2005 through June 2009 a two-tier price system was used, and data from this period are therefore excluded from the demand estimation. The demand specification is given in Equation (8),

$$\ln q_t = \alpha_0 + \alpha_1 p_t + \beta X \quad (8)$$

where q_t is daily per-capita consumption and p_t is volumetric price. The term X is a vector of exogenous variables that includes rainfall (current and lagged one day), maximum temperature (current and lagged one day), a dummy variable for water restrictions 1994–1996, a dummy variable for water restrictions imposed from October 2003 through October 2010, and seasonality / day-of-week corrections. The semi-log specification in Equation (8) allows the price elasticity of demand to increase with price while ensuring an infinite marginal penalty for zero consumption. Key results of the demand regression, estimated in Stata with a Prais-Winsten correction for serial correlation, are presented in Table 1. A first-order Fourier series seasonality correction, and also a first-order Fourier series correction for day of week, are significant but are not reported.

Water restrictions The main advantage of water restrictions is that they can be imposed quickly in the face of an unexpected water shortfall. By contrast, due to lags in the billing cycle, price changes may take several months to be fully implemented. The regression results in Table 1 indicate that the most recent water restrictions, scheduled to be imposed whenever water storages fall below 50 percent of capacity, reduced demand by about 18 percent. However, achieving a given reduction in water consumption through water restrictions will generally have a higher welfare cost than achieving the same reduction through price increases. The welfare cost of water restrictions is approximated by the diminished Marshallian surplus, represented by the reduction in the area under the demand curve under water restrictions compared to the demand curve without water restrictions (Roibás et al., 2007; Grafton and Ward, 2008). The welfare cost of management by restrictions is automatically reflected in our analysis, because the regulator's objective function includes the Marshallian surplus.

Short-run backstop technology To implement the dynamic programming approach to establish dynamically efficient pricing, we must make explicit that consumption cannot exceed the sum of storages plus inflows. However, it is possible that demand at a given price will exceed available supply, even with water restrictions. Some communities have dealt with this situation by introducing a backstop supply of water transported from elsewhere (Morgan, 2008; Burnett, 2008). Such emergency backstop measures are expensive compared to the typical price of water. Thus, water utilities have a strong incentive to minimize this possibility.

On occasion, and despite attempts to avoid this outcome, water supplies may become exhausted. For example, in 2008 the city of Barcelona, Spain imported 1.7 million kL of water per month by ship, at an average cost of \$18/kL (Burnett, 2008). In our model, we conservatively assume that the regulator incurs a \$50/kL charge for consumption in excess of the available supply without the backstop. This high cost reflects the expenses of sudden short-run adjustment in the mechanics of water supply. The marginal cost of treating and pumping water from dams is estimated at \$0.20/kL, based on regulatory submissions (Sydney Water Corporation, 2007).

Desalination plant The Sydney desalination plant required a \$2.0 billion capital expenditure including costs of connecting to existing water infrastructure, and two

years of construction. The city formally signed a construction contract for the plant on July 18, 2007 when dam storages were at 57 percent of total capacity. The plant has an operating capacity of 250,000 kL per day, which is around 15 percent of typical usage in Sydney. The marginal cost of water production at the plant is redacted from planning documents that are not publicly available. However, Zhou and Tol (2005) indicate that an operating marginal cost of \$0.60/kL is feasible given recent technology; we add \$0.20/kL for pumping and transport for a final marginal cost of \$0.80/kL. In 2007 it was announced After two years of unconditional operation, the plant is scheduled to operate whenever water supplies fall below 75 percent of storage capacity. The weighted average cost of capital determined by the regulator is 7.5 percent, so we use this as the discount rate in the dynamic optimization problem.

Weather and reservoir inflow To account for the uncertainty in water supply in Sydney dams we assume that the realizations of inflows and weather over the 30 years prior to the desalination investment decision (1977–2007) provide a reasonable empirical approximation to the true variability. The null hypothesis that the historical inflow data is not serially correlated on an annual basis cannot be rejected for this period. This simplifies the dynamic programming problem; however if it were to be present, correlation in inflow variations over years can be handled with an additional state variable in the model. In the sensitivity analysis we also present results based on only the most recent 15 years of weather and inflows (1992–2007), which is a somewhat drier period on average, as shown in Figure 1.

Timing The time-step in the model is one year, for all decisions. For example, we assume the regulator can adjust prices once a year, on a specified date. Lags in meter-reading and the billing cycle make extremely frequent price updates impractical. Between price-setting dates, new information about catchment inflows for the year become available. We allow the decision of whether to impose restrictions to occur after this information is known. This reflects the practicality that restrictions can be announced and enforced more rapidly than changes in the volumetric price and that the decision about whether to operate the desalination plant for the coming year is conditioned on knowledge of the realized inflows for the year.

RESULTS

Figure 2: Dynamically Efficient Price by Storage Level

Our model generates results for three different management scenarios. The first scenario is the first-best dynamically efficient policy combination of water pricing, water restrictions, and investment timing. This scenario serves as the benchmark against which we compare the welfare outcome of other scenarios. Figure 2 displays this efficient pricing policy as a function of storage levels. An important feature of our results is that it is not optimal to invest in desalination, regardless of the initial storage levels. The reason for this outcome is that it takes two years to construct the plant, and it is likely that there will be sufficient inflow before the plant becomes operational. For example, in the case of Sydney, heavy rains increased storages from 37 percent to 57 percent from the beginning of June until the middle of July 2007, when the contract was signed to build the desalination plant. Using other parameter values for the backstop cost of water and discount rate, it is possible for it to be

Figure 3: Dynamically Efficient Price and Actual Price over Time

optimal to build the desalination plant at very low storages, but at no reasonable parameter values is the investment decision to build the desalination plant taken at 57 percent of storage levels, as actually occurred. Figure 3 compares the actual and optimal prices over the last ten years. The most notable feature is that prices were substantially too low over the period prior to the desalination investment decision in 2007.

The second scenario is the ‘business as usual’ model. In this case, we take the actual management decisions in 2007 as given. These are as follows: (1) a price of \$1.18/kL prior to investment; (2) water restrictions when storages fall below 50 percent; (3) a commitment to invest in the \$2.0 billion desalination plant made when water storages were at 57 percent of capacity (4) and a price of \$2.01/kL after the investment was decided, with the price increase set to pay for the capital cost. The top line in Figure 4 displays the welfare cost of this policy, as a function of initial storage levels, relative to the baseline dynamically efficient policy. A

Figure 4: Expected Welfare Cost of Inefficient Demand and Supply Policies

break in expected welfare costs occurs at 57 percent of capacity. This represents the sub-optimal timing of the actual investment, but conditional on this investment, it allows for a relaxation of mandatory water restrictions should supply remain at 57 percent of capacity. The overall expected welfare cost is the difference in expected net present value with dynamically efficient water pricing and 'business as usual', accounting for uncertain future weather and catchment inflows.

It is not clear from the full welfare-cost figure what the relative impacts of inefficient demand-side and supply-side policies are. While these are not independent policies, we present a scenario where the supply-side desalination investment occurs when storages hit 57 percent of capacity. However, the demand-side pricing and rationing policies are made optimally, subject to this investment strategy. The bottom line in Figure 4 presents the welfare impacts of this, which is the cost of premature investment in desalination.

Finally, Table 2 presents the results of a sensitivity analysis for our key param-

Table 2: Sensitivity Analysis

Weather (years)	Discount (%)	Backstop (\$kL)	Inv. Trigger (% storage)	Inv. Cost (\$ million)	Full Cost (\$ million)
1992–2007	7.5	18	0	560	2768
1992–2007	7.5	36	15	557	2722
1992–2007	5	18	36	64	2817
1992–2007	5	36	37	57	2769
1977–2007	7.5	18	0	811	2997
1977–2007	7.5	36	0	806	2956
1977–2007	5	18	19	161	2934
1977–2007	5	36	21	154	2887

eters. The first three columns are modeling and parameter choices. Columns 4-6 are the results of interest. Column 4 gives the optimal investment trigger point. For most combinations, this is zero, which indicates that investment in desalination is never optimal. However, with a drier climate (1992-2007), lower discount rate (5 per cent), and higher backstop cost (\$36) the optimal trigger point increases. In no case, however, does it exceed 37 percent of the current supply capacity. Column 5 provides the expected welfare cost of premature investment in desalination at 57 percent of storage capacity. For most parameter combinations this cost is some hundreds of millions, but it is never less than \$50 million. Column 6 gives the present value of the expected welfare cost of the full ‘business as usual’ combination of inflexible price, rationing, and desalination investment. The losses are large and, in all cases, exceed 2.7 billion dollars, or on a per household basis over four times greater than the average annual household water bill of Sydney households.³

Discussion

The actual determination of water prices in Sydney, or in any city as far as we are aware, does not include a scarcity price. As a result, in the case of Sydney the regulated water price was too low before the desalination plant was constructed and too high after the supply augmentation. The volumetric price was set at too low a

³The number of Sydney households was 1.623 million while the average residential water bill of Sydney households in 2008-09 was about \$400.

level before the decision to build the desalination plant was taken because a failure to include a scarcity price resulted in a higher demand and brought forward prematurely the need to invest in supply augmentation. The volumetric price was set at too high a level after the desalination plant was built because as soon as the decision was made to invest in supply augmentation, the incremental costs associated with the desalination plant became incorporated in IPART's price determination that is set independently of the stock of water in Sydney's dams. The key difficulty with water pricing independent of supply variability is that it fails to account for supply uncertainty associated with variable inflows. In the case of Sydney, inflow data indicates that the catchment has periods where inflows are below average for extended periods of time, and periods when the volume of water in storage can increase substantially following a major rainfall event.

In general, if historical inflows indicate that there is high likelihood that a major rainfall event will occur in the following 12 months, it is likely to be economically efficient to raise the volumetric price and reduce demand to balance it with current supply rather than prematurely invest in expensive supply augmentation. This is a supply-variable approach to volumetric pricing that is analogous to peak-load pricing (Renzetti, 1992), but is different because it is supply variability that determines the price rather than demand variability. By contrast, the setting of water prices years in advance and independent of the actual realizations ignores supply variability and the uncertainty associated with inflows. Thus, inflexible volumetric water as occurs in Sydney and many other urban centers, that fails to respond to changes in water availability results in sub-optimal prices charged to consumers, and also sub-optimal timing as to when to invest in supply augmentation.

IMPLICATIONS AND CONCLUSIONS

Our work provides an evaluation of how water should be priced volumetrically, and how it is actually priced or regulated for residential households. We show that with supply uncertainty associated with weather events there cannot be a unique long-run marginal cost — the marginal cost of supply associated with the least expensive future source of supply. This is because when the supply augmentation occurs is dependent on current, past and future weather events as well as the past

and current volumetric price that, in turn, determine water demand. Thus, long-run marginal cost is endogenously determined by the volumetric price and exogenously by the weather.

Typically, regulators suppose there is a deterministic long-run marginal cost when establishing regulated water prices while water utilities take the volumetric price as given when they decide to invest in supply augmentation. Consequently, decisions about when to augment the water supply, and by how much, made independently of current and future volumetric prices that are inflexible to variations in inflows and weather-related events, will be sub-optimal. To overcome this sub-optimal pricing, we show how to calculate dynamically efficient volumetric prices so as to optimally determine the time to invest in supply augmentation while also accounting for existing non-price approaches to regulate demand.

Using data from a major metropolitan city subject to water supply variability we find that because the regulated volumetric price was set independent of current water supply, the decision to supply augment in the form of a desalination plant in July 2007 was taken prematurely. If the volumetric price had been set to account for the effect of price on demand and the expected future weather, the present value of expected welfare losses could have been as much as three billion dollars or approximately \$1,800 per household. We also show that if the water utility were constrained to the regulated volumetric price and obliged to employ the actual mandatory water restrictions, the decision to supply augment with desalination was still taken prematurely.

As a result of the decision to prematurely build the desalination plant, the regulated volumetric price has increased in nominal terms by about 50 percent between 2007 and 2010 to cover the high capital costs and operating costs of the desalination plant. By contrast, if prices had been allowed to rise as water storages fell, and if prices could fall as water storages increased, the current price would currently be some 15 percent lower than the current regulated volumetric price.

Our results are of general interest because, as far as we are aware, there are no water utilities or water regulators that have systematically implemented dynamically efficient volumetric water pricing. Thus, current supply augmentation in terms of urban water globally, is sub-optimal. Given that total expenditures in water infrastructure are estimated to be some \$75 billion per year (World Water Vision, 2000, p.

51) this suggests that there are likely to be a very large welfare losses world-wide from inefficient and supply-inflexible water pricing in the presence of variability in terms of the water supply. These welfare losses include both the current costs of water rationing instead of efficient pricing to manage water demand, and the long-run costs associated with premature investment in supply augmentation.

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