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Urban water management:
optimal price and investment policy under uncertainty

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Australian urban water utilities face a significant challenge in designing appropriate demand management and supply augmentation policies in the presence of increasing water scarcity and uncertainty over future dam inflows. This paper considers the design of optimal demand management and supply augmentation policies for urban water. In particular, scarcity pricing is considered as a potential alternative to the predominant demand management policy of water restrictions.

A stochastic dynamic programming model of an urban water market is developed based on data from the Australian Capital Territory. The model involves an explicit consideration of uncertainty via a probability distribution over dam inflows. Given a specification of the demand and supply for urban water, state dependent optimal price and investment policies are estimated. The results illustrate how the optimal urban water price varies inversely with the prevailing storage level and how the optimal timing of investment differs significantly between rain dependent and rain independent augmentation options.

Introduction

Recent drought conditions across Australia have significantly depleted urban water storages and have resulted in severe water restrictions being implemented in most capital cities. While the recent drought has been abnormally severe, current urban water shortages are indicative of a broader long term trend of increasing urban water scarcity in Australia. This trend has been driven by a gradual long term decline in mean inflows into storages, increasing demand driven by population growth and minimal additions to supply capacity.

Given the increasing scarcity of urban water and the potential for climate change to further reduce water availability and increase variability, there is increased pressure on urban water utilities to implement efficient demand management policies and to make optimal supply augmentation decisions. Currently urban water demand management predominantly involves the imposition of water restrictions to ration water during times of scarcity. In this paper, scarcity pricing is proposed as an alternative to the use of water restrictions. Scarcity pricing of urban water was considered in a recent conference paper by Grafton and Kompas (2006).

One of the main difficulties in designing urban water policy, particularly in Australia, is the extreme uncertainty surrounding future rainfall and dam inflows. This paper considers the design of optimal demand management and supply augmentation policies under uncertainty, by constructing and applying a stochastic dynamic programming model of an urban water market. This model is used to demonstrate how a scarcity pricing system would operate in theory and to evaluate the basic factors governing the optimal timing of supply augmentation investment.

Urban water policy

Urban water is typically provided by a monopoly supplier, while the demand for urban water is relatively inelastic. Under these conditions an unregulated profit maximising firm may increase prices to achieve monopoly rents, resulting in an inefficient allocation of water. To prevent such monopolistic behaviour urban water is, in Australia, typically supplied by a government owned and/or operated organisation and is subject to substantial government regulation, including price control. In this paper, the role of the water utility is characterised as that of a social planner who seeks to maximise social welfare, given water availability constraints. Implicitly, it is assumed that the water utility is government operated and/or effectively regulated to ensure that it acts in the public interest. Issues of privatisation and competition in urban water provision are not considered in this paper.

In its role as a social planner, the water utility has two main policy tools — demand management and supply augmentation. Demand management is a term used to encompass a range of polices designed to restrict or reduce water use in times of scarcity. Given the regulatory control over urban water prices, water utilities must rely on a range of alternative policies to ration demand. These policies can include water restrictions, awareness campaigns and incentives for improvements in water use efficiency.

It is useful to draw a distinction between essential and nonessential water consumption. Essential water consumption refers to the minium amount of water required to meet basic sanitation, drinking, bathing and food preparation needs. For the purposes of this paper, essential water is defined as that component of water consumption that is unresponsive to changes in price. A minimum level of essential water must be supplied at all times. However, it may be optimal policy to ration nonessential water consumption in times of scarcity.

Supply augmentation policy is concerned with the nature and timing of additions to water supply infrastructure. In this paper, the focus is specifically on infrastructure that generates additional water inflows and storage capacity such as new dams or desalination plants.

Demand management

It is useful to consider demand management policy over short and long run time frames. In the short run, when supply infrastructure is fixed, inflow and demand variability can combine to produce substantial reductions in storage levels, which necessitate a rationing of demand. Demand management polices (such as water restrictions or pricing) can be used to allocate the available supply of water during such periods. In the long run, supply infrastructure can be altered and demand management policy and supply augmentation policy are simultaneously determined.

This involves a tradeoff between the consumer surplus associated with nonessential water consumption and the costs of supply augmentation. In Australia, urban water utilities accept that 'gold plating' supply infrastructure (so that all nonessential demand for urban water can be met at all times) would be unnecessarily costly. The optimal long run

demand management policy (long run mean frequency of restrictions or mean price level) will maintain the ideal balance between the benefits of nonessential water consumption and the costs of supply augmentation.

Water restrictions

Water restrictions are currently the main mode of short run demand management employed by Australian water utilities. Water restrictions involve complex rules that regulate the outdoor use of urban water. Water restrictions do not impose pure quantity based limits on water consumption, rather they involve a combination of complete bans on certain water uses and limitations on others.

The less severe stages of water restrictions rely largely on the imposition of inconvenience costs to discourage consumption. For example, restrictions may involve limits on the hours of the day or days of the month in which watering can occur and/or bans on the use of sprinkler systems. Some households may be willing to work around these restrictions, while for others the inconvenience of having to hand water at irregular hours will present a major barrier to outside water use. In economic terms, these types of restrictions can be represented as a transaction cost imposed on consumers. From a social welfare perspective, a tax on water consumption yielding the same reduction in consumption would be preferable, since it would involve a transfer of rent to the utility/government rather than imposing irrecoverable time and inconvenience costs. A tax or scarcity price would, however, result in some distributional changes — for example, it would tend to benefit consumers with higher time opportunity costs.

Water restrictions in their more severe forms involve complete bans on outdoor water uses. Where there are heterogeneous preferences for water, prescriptive bans will result in an inefficient allocation of resources where water is not necessarily directed to its most valued uses. The allocative inefficiency of water restrictions has been noted by many economists, including Edwards (2006). Water restrictions further distort market outcomes by targeting different water uses to varying degrees, while providing implicit and explicit exemptions for other uses. This effectively imposes arbitrary judgments on the social desirability of certain water uses that override private valuations (Edwards 2006). For example, water restrictions are limited to outdoor residential water use (for reasons of enforcement) and do not directly limit inside residential water use and industrial water use.

In addition to the transaction costs and the allocative efficiency costs, water restrictions involve substantial implementation costs, such as the costs of advertising and enforcement. Quantifying the various costs associated with water restrictions is a complex task and one that is not attempted in this paper. A number of economists, including Hensher et al. (2006), Brennan et al. (2007) and Grafton and Ward (2007), have attempted to estimate the costs of restrictions, using a variety of techniques.

Water restrictions have historically been used as a short term demand management tool. However, in recent times, restrictions have increasingly been used to achieve long term reductions in demand, with some jurisdictions going as far as imposing permanent restrictions.

Other demand management measures

Water utilities also employ a range of other nonprice based polices aimed at reducing the long term consumption of urban water, including marketing campaigns and subsidies for water saving equipment. Marketing or awareness campaigns typically involve advertising across various mediums promoting a water conservation message and providing advice on how to improve water use efficiency. These campaigns aim to reduce consumption by encouraging water consumers to behave in an altruistic fashion. Marketing campaigns can be costly, while their actual impact on water consumption is difficult to measure.

One of the problems with government subsidies for water saving devices is that they may induce overinvestment in products that are of little benefit in some cases. For example, most states in Australia offer broad subsidies for rainwater tanks; however, the relative effectiveness of rainwater tanks varies significantly across regions and across households within regions. Where practicable, an efficient price signal is preferred to subsidy measures, which tend to be less efficient.

Current pricing regime

In Australia, urban water pricing is regulated by state government based regulatory agencies. These agencies make price determinations specifying water charges over time frames of three to five years. In the absence of scarcity or capacity constraints, an efficient allocation of water can be achieved with a price set to the short run marginal cost (SRMC) of supply. The SRMC comprises the marginal pumping and treatment costs associated with transferring water from storages to households for consumption. Australian water utility price regulators generally advocate some form of long run marginal cost (LRMC) pricing. There exists some controversy over the use of LRMC pricing in urban water (Sibley 2006).

Definitions and methods of estimating LRMC differ. The Victorian Essential Services Commission (2005) defines LRMC as equal to SRMC plus marginal capital costs. Marginal capital costs are a measure of the marginal increase in expected future supply augmentation costs associated with an incremental increase in demand. A fixed LRMC price does not explicitly consider uncertainty over dam inflows and the potential for short run fluctuations in storage levels. As a result, a fixed LRMC price will typically be too low during a drought (necessitating the implementation of restrictions) and too high when storage levels are full.

Given the significant capital and fixed operating costs of water utilities, marginal cost pricing alone (SRMC or LRMC) would result in substantial underrecovery of costs. Australian water utilities impose a two part tariff, combining a consumption based price component and a residual fixed access charge designed to recover total costs. Issues of revenue and cost recovery are not considered in detail in this paper.

Inclining block pricing schemes are implemented in most Australian capital cities. Such schemes are economically inefficient relative to a single uniform price (Edwards 2006; Brennan 2006). In the ACT a three block pricing system applies — in 2007-08 the pricing structure involves a price of $0.75 a kilolitre for the first 100 kilolitres, $1.67 for 100–300 kilolitres and $2.57 for consumption over 300 kilolitres.

Scarcity pricing

In this paper the scarcity price is defined as the price that maximises the expected net present value of social welfare over an appropriate time horizon, given uncertain inflows and optimal supply augmentation policy. This scarcity price represents the full opportunity cost of urban water — the SRMC plus the marginal cost of forgone storage. Where the marginal cost of storage forgone represents a reduction in the reliability of future supply and a bringing forward of the expected time of future supply augmentation. This price will be state dependent, meaning that it will vary depending on the prevailing conditions. For example, a scarcity price would vary inversely with storage levels. Scarcity pricing presents a potentially more efficient way of allocating urban water resources relative to using restrictions.

A scarcity price is likely to represent an increase in price relative to a LRMC price in times of scarcity. Increases in the price of urban water are often opposed on the grounds of equity. However, ABS (2006) statistics show that water and sewerage charges represent a relatively small proportion of average weekly household expenditure — around 0.7 per cent. The OECD (1999) demonstrated that Australia has relatively affordable water charges in comparison with other OECD nations.

For equity reasons, the provision of essential water at a low cost to all households is a desirable outcome. One way to achieve this objective would be to use a two block price scheme, where a low constant price would apply to the first block of consumption and a variable scarcity price would apply to consumption above this level. A two block price scheme would involve some loss of efficiency; however, it would represent a substantial improvement over a three block system. Ideally the threshold between the two pricing blocks would ensure that all nonessential water demand would be exposed to the scarcity price. In practice setting the threshold point would involve a tradeoff between equity and efficiency objectives. Efficiency costs could be minimised further if the threshold took into account differences across households, such as the number of occupants per dwelling.

With scarcity pricing, it would become necessary to accurately measure household water consumption occurring within each billing period, which is currently quarterly. Actew has noted that it is currently not possible to read all meters on the same day, consequently meter reading cannot occur on the last day of the billing cycle for each household. One way to overcome this problem would be to invest in new smart metering technology. The ACT Government has recently endorsed a pilot smart metering program (Actew, personal communication, 2007).

Another issue remains how to set these scarcity prices in practice. One way to implement a scarcity pricing system could be to adopt a stage framework similar to that used for water restrictions, where there are a limited number of scarcity stages with corresponding price levels and storage trigger points. This approach is discussed in more detail in the results section.

Supply augmentation

Traditionally, growth in Australian water demand has been met by the periodic construction of new dams. However, a lack of suitable sites, concern over adverse environmental impacts and the potential for climate change to reduce future rainfall have all reduced the attractiveness of investment in new dams. Two of the main alternatives to new dam construction are water recycling and desalination. Both of these alternatives have the capacity to provide a stable source of water insulated from rainfall variability (at least partially[1]). However, both options involve substantially higher capital and operating costs. This paper focuses specifically on the timing of supply augmentation investment under uncertainty and not on making comparisons between specific supply projects. Decisions between alternative supply augmentation projects should be guided by comprehensive cost benefit analyses which take into account financial, social and environmental considerations.

Investment in urban water supply infrastructure is often described as 'lumpy', in that it involves large, infrequent additions to capacity rather than incremental growth. The optimal timing of supply augmentation projects, involves a comparison of the expected net benefits of investing now to the expected net benefits of delaying investment. Such decisions are complicated by the substantial uncertainty surrounding future demand and more importantly future rainfall and inflows.

Demand management policy and supply augmentation policy are interdependent: a supply augmentation project generating additional inflows will improve the reliability of supply (reduce the frequency of drought) allowing urban water utilities to reduce the long run mean frequency of restrictions (or the mean water price). Supply augmentation will also result in a reduction in the probability of a shortfall of essential water. Understandably urban water utilities typically maintain supply infrastructure so as to ensure that the probability of such a system failure would be near zero.

The timing of supply augmentation involves trading off the benefits of supply reliability with the costs of augmentation: investing earlier will improve reliability but increase augmentation costs in present value terms. Industry practice has historically involved the targeting of an 'acceptable level' of reliability, measured as the expected time that households are subject to restrictions. In the past, water utilities have made relatively arbitrary judgments on this acceptable level of restrictions and have placed little emphasis on consumer preferences (Hensher, Shore and Train 2006)[2]. One of the reasons for this is that the benefits of increased water supply reliability depend on the community's willingness to pay. Estimating this willingness to pay is difficult without a price mechanism that reflects scarcity.

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[1] Water recycling may have some limited exposure to rainfall variability since waste water is supplemented by stormwater inflows and infiltration. Any exposure would depend on the size of the plant relative to the regions waste water base flow volume.

[2] In recent years, ACTEW has incorporated estimates of willingness to pay derived from stated choice experiments (Hensher et al. 2006).

While not the focus of this paper, another option for sourcing urban water is to acquire it through trade with rural water holders. This is dependent on the existence of a physical connection between rural and urban water systems, which in some cities would require significant investment in pipeline and pumping infrastructure. CSIRO and CoPS (2006) demonstrated the potential economic gains of urban–rural water trade in Australia using general equilibrium modelling. The potential for urban–rural water trade using options contracts has been examined by Page and Hafi (2007).

Environmental flows

An additional aspect of urban water policy not considered in detail in this paper is that of environmental flows. Environmental flows are releases from storages back into streams, with the aim of maintaining the ecology of the local river system. The ACT Government (2006) maintains guidelines that outline specific minimum environmental flow requirements from each ACT water storage. Provisions are made that permit the reduction of environmental flows during droughts when urban water supplies are threatened.

There exists a clear tradeoff between releasing water to meet environmental objectives and maintaining storage levels to secure urban water supply. In times of drought, water has a substantial scarcity value that may exceed the benefits of environmental flows. Environmental flows in rural water systems have been the subject of previous ABARE research (Beare et al 2006; Heaney and Hafi 2005).

An urban water model

This section provides a brief discussion of an economic model of urban water supply and demand. The model is a single sector, single region model of the water market in an urban centre. The model is formulated as a stochastic dynamic optimisation problem that estimates socially optimal price and investment policy functions.

Dynamic programming techniques are commonly applied in the economics literature to consider the optimal extraction paths of scarce natural resources, such as oil, fish or forests. Dynamic programming techniques have been applied to a range of water related problems, including estimating optimal extractions from groundwater aquifers (Hafi 2002) and estimating optimal release rules from irrigation storages (Brennan 2007). Previous dynamic programming models of urban water pricing and investment include the work of Hirshleifer et al. (1960) and Riordan (1971a,b), although these earlier models focused on capacity constraints rather than water scarcity as the driver of supply augmentation. Stochastic dynamic programming techniques are often used in engineering literature to estimate the optimal release rules for reservoirs given uncertain inflows. The engineering literature typically has a stronger focus on supply side issues than on issues of demand and pricing — see, for example, Perera and Codner (1996).

The model is based on the ACT region and incorporates data on the demand and supply of urban water in the region, provided by the Actew Corporation. While an attempt has been made to incorporate a degree of realism, the model remains a significant simplification of reality. In particular, a number of simplifying assumptions are made on the supply side of the model, in order to keep the level of hydrological and engineering

detail to a minimum. The UWM is not a forecasting model and does not attempt to predict or estimate the likely impact of a change in urban water policy in the ACT. For example, the model is not designed to compare social welfare under a system of restrictions with that under a system of scarcity pricing. Rather, the model has been constructed to demonstrate a number of general economic concepts related to urban water pricing and investment decisions in the presence of uncertainty.

The model comprises two main components, one specifying the evolution of water demand and the other specifying water supply.

Demand for urban water

The demand side of the model makes use of urban water consumption data for the ACT (Figure 1).

Figure 1: ACT water consumption (ML) per season 1960 to 2006, quarterly
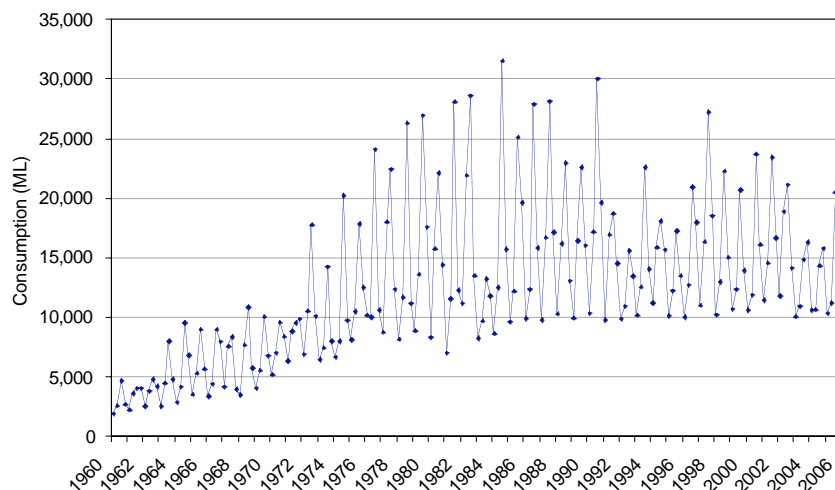
Econometric studies have used a range of variables to explain observed variation in urban water demand over time and across households. Common explanatory variables include population, income levels, water use efficiency, housing characteristics, water prices and weather conditions, such as temperature and evaporation (Dalhuisen et al. 2003; Hoffman, Worthington and Higgs 2006). For the purposes of this model, a simple aggregate demand function is constructed, which accounts for long term growth in urban water consumption, seasonal variation, response to weather variability (equation 1) and response to price changes (equation 2).

The seasonal variation of demand and the response to weather variability are estimated econometrically. A simple explanatory equation for urban water consumption was estimated based on quarterly ACT data over period 1960–2000, with explanatory variables including seasonal indicators, a time trend, total inflows and two intervention terms. The intervention terms account for two structural breaks in the data: lower levels of consumption in the ACT before 1973 and after 1992. Inflows were used as a proxy for

prevailing weather conditions (such as rainfall and temperature) since this allows the model to have a single source of uncertainty.

Table 1: Demand regression results

Dependent variable:	Log of total water consumption (ML)	
Explanatory variables	**Estimate**	**Standard error**
Constant	7.716	0.086
Summer	0.397	0.037
Autumn	–0.0332	0.037
Winter	–0.371	0.035
Inflow (ML)	–2.156E-06	2.85E-07
Time trend	0.332	0.025
1973 intervention term	0.464	0.047
1992 intervention term	–0.184	0.037
Standard Error	0.0248	
Adjusted R Squared	0.91	

In the model, demand is projected over an arbitrary 25 year time horizon, notionally the period 2000–25. The long term growth in demand over time adheres to a logistic functional form. The long run growth projection should be considered to be an illustrative scenario rather than a forecast. The modelled growth rate is, however, broadly in line with the 'high growth' scenarios developed in Actew (2004). Equation 1 specifies the evolution of demand for water over time given a fixed short run marginal cost price.

(1)
$$Q_t^{MC} = \exp\left(b^{con} + b_s^{seas} + b^{in}\{IN_t\}\right)\left[\frac{g_1}{1 + (g_1 - 1)e^{-g_2 t}}\right]$$

Where:

Q_t^{MC}	= quantity demanded (ML) when price is equal to marginal cost
IN_t	= level of inflows at time t (ML)
b^{con}	= estimated demand equation constant
b_s^{seas}	= estimated seasonality parameters
b^{in}	= estimated inflow coefficient
g_1, g_2	= long term growth parameters
t	= time periods (quarters)
s	= seasons (*summer, autumn, winter, spring*).

The price elasticity of urban water demand has been the focus of a major volume of economic literature. Dalhuisen et al. (2003) present a comprehensive meta analysis of 64 US econometric studies, estimating a mean price elasticity of –0.41. Hoffman et. al. (2006) conducted a panel data study of urban water demand in Brisbane, estimating a contemporaneous price elasticity of between –0.67 and –0.55. A panel data study by Xayavong et. al. (2008) in Perth estimated an indoor elasticity of between –0.70 and –0.94, and an outdoor elasticity of between –1.30 and –1.45. A study by Graham and Scot (1997) estimated the price elasticity of residential water demand in the ACT region to be in the range of –0.15 to –0.39.

A constant elasticity relationship is assumed to exist between urban water demand and price, set to a value of –0.45 based on a search of the literature. For each consumer, it is

assumed there exists a certain proportion of urban water consumption that is essential and hence unresponsive to price. The level of essential water demand is assumed to be nonseasonal and is calculated in the model as a fixed proportion of winter equivalent aggregate water demand.

Equation 2 specifies the inverse demand function that defines the relationship between price and aggregate water consumption.

(2) $\quad P_t = \left(Q_t^{MC} mc^{1/a} \right)^a Q_t^{-a}$

Where:

$\quad\quad Q_t \quad$ = final quantity of water demanded (ML)
$\quad\quad mc \quad$ = short run marginal cost ($/ML)
$\quad\quad 1/ \quad$ = assumed demand elasticity.

Supply of urban water

For the supply side of the model it is assumed that there is a single initial storage, with stochastic inflows. No attempt has been made to incorporate multiple connected storages, distribution networks or water treatment services. The ACT at present maintains three major water storages. A single storage model can be interpreted as an aggregation of a multiple reservoir system. Perera and Codner (1988) demonstrate the use of an aggregation approach as a way of limiting complexity and avoiding the curse of dimensionality problem inherent in stochastic dynamic programming models.

Seasonal inflow probability distributions were estimated using historical inflow data for the ACT. When estimating inflow distributions, the sample was limited to the period 1980–2006 in an attempt to represent the lower mean inflows occurring in recent decades. Log normal distributions were fitted using maximum likelihood estimators and the estimated parameters are shown in Table 2.

Table 2: Log normal inflow distribution parameters

	E(*IN*)		
Summer	27 138	9.81	0.89
Autumn	24 158	9.51	1.08
Winter	47 543	10.48	0.77
Spring	45 752	10.61	0.49

The supply side of the model also accounts for evaporation from storages and environmental flows. In the interests of simplicity it is assumed that evaporation from storages adheres to a simple seasonal average and that environmental flows are a fixed proportion of total inflows, both based on historical data. The water storage level evolves over time according to equation 3.

(3) $\qquad S_t = S_{t-1} + TotIN_t - E_t - Q_t$

$\qquad S_t \geq S^{\min}, \quad S_t \pounds K_t$

Where:

$\qquad S_t \qquad$ = storage level
$\qquad TotIn_t \qquad$ = total inflows (dependent on supply augmentation)
$\qquad E_t \qquad$ = total storage losses (dependent on supply augmentation)
$\qquad K_t \qquad$ = total storage capacity (dependent on supply augmentation)
$\qquad S_{MIN} \qquad$ = storage minimum feasible level.

The model allows for two forms of supply augmentation investment — rain dependent and rain independent. Rain independent augmentation is assumed to generate a fixed increase in inflows and no increase in storage capacity. Rain independent augmentation is meant to broadly represent either desalination or water recycling. Rain dependent augmentation represents construction of dams and is assumed to generate additional storage capacity and additional stochastic inflows. For simplicity it is assumed that new dam inflows are perfectly correlated with existing inflows. Equations 4 and 5 specify the relationship between inflows, storage capacity and supply augmentation investment.

(4) $\qquad TotIN_{t,s} = (1 - ef)\left[IN_s + \sum_{i=1}^{I} I_{t-LT_i,i}\left(f_i IN_s\right)\right] + \sum_{i=1}^{I} I_{t-LT_i,i} nrin_i$

(5) $\qquad K_t = k_0 + \sum_{i=1}^{I}\left(I_{t-LT_i,i} ik_i\right)$

Where:

$\qquad I_{t,i} \qquad$ = 1 for all $t > T$ where T is the time of execution for investment i
$\qquad ef \qquad$ = the proportion of inflows released to the environment
$\qquad nrin_i \qquad$ = fixed non rain dependent inflows of investment i (ML)
$\qquad {}_i \qquad$ = proportional increase in rain dependent inflow for investment i
$\qquad ik_i \qquad$ = additional storage capacity of investment i (ML)
$\qquad LT_i \qquad$ = lead time (construction period) of investment i (quarters).

Each option also has a capital expenditure cost, an annual running cost and a lead time or construction period. The capital cost is spread equally over the construction period, while the ongoing running costs are incurred every season following the construction period. It is assumed that each augmentation option is operated permanently at full capacity such that inflows are always generated and costs always incurred. It is assumed that the SRMC of water supply is constant over time and is independent of the level of water consumption and the level of supply augmentation. A value of $1 per kilolitre (kL) is assumed for the SRMC.

Solving the model

The objective function of the model is the expected discounted sum of market surplus less the cost of any new investment and less a penalty imposed for an inability to meet essential water demand, see equations 6 and 7.

$$(6) \quad E\left[\sum_{t=1}^{T} b^t \left(MS_t\left(Q_t, Q_t^{\min}\right) - TC_t - PENALTY_t\right)\right]$$

$$(7) \quad MS_t\left(Q_t, Q_t^{\min}\right) = \int_{Q_t^{\min}}^{Q_t} \left(Q_t^{MC} mc^{1/a}\right)^a Q_t^{-a} dQ_t - \left(Q_t - Q_t^{\min}\right)mc$$

Where:

MS_t = market surplus (consumer and producer)
$Q_t^{\min}$ = level of essential water demand at time t
TC_t = total cost (capital and/or ongoing costs) of augmentation investment at time t
$PENALTY_t$ = penalty imposed in the event essential water is unable to be met
= discount factor.

The costs associated with a failure to supply essential water are difficult to estimate in practice and may include costs imposed on consumers as well as the costs of implementing contingency water supply options. The approach taken in this study is to set a penalty term in the objective function to a sufficiently high level to ensure the probability of a shortage of essential water is near zero. This would be consistent with the behaviour of water utilities that appear unwilling to accept any significant probability of such an event.

The model is formulated as a discrete time, finite time horizon, stochastic dynamic programming problem. The problem has two state variables, the storage level and the level of supply infrastructure (owing to previous supply augmentation), and two policy or control variables, price and supply augmentation investment. The problem is specified in the standard Bellman (1957) equation form with the continuos variables evaluated over a discrete grid. Given the discrete state and policy space and the finite time horizon the model can be solved using backwards induction. The model is evaluated over a length of time greater than the 25 year simulation period to estimate a terminal value — the value function at the end of the last time period.

Results

Two scenarios are constructed — a rain dependent augmentation scenario and a rain independent scenario. This approach was necessary because of the so-called 'curse of dimensionality', which meant that the inclusion of multiple investment projects would make the problem unfeasibly large. These scenarios are intended to be illustrative and not meant to represent accurate forecasts of specific ACT circumstances.

It is worth noting that scenarios involving a single augmentation option will tend to overstate the extent of water scarcity relative to the case of multiple investment projects, since an additional investment project provides an option value benefit that is realised even if the project is not executed within the relevant time frame. For example, a water utility may adopt a more relaxed pricing policy if, following construction of a dam, it maintains an option to construct a desalination plant in the event it is required.

Rain dependent scenario

This scenario assumes an augmentation project representative of a new dam as defined by the following parameters.

Table 3: Rain dependent augmentation option parameters

Capital cost, c	$100 million
Ongoing cost, a	$1.5 million a year
Increase in mean inflow,	0.20
Additional storage capacity, ik	70 000 ML
Lead time, LT	2 years

The model estimates the price and investment policy functions that specify the optimal policy action as a function of the prevailing conditions For example, the price policy function specifies the optimal price given the time period, the prevailing storage level and the state of supply augmentation (that is, no augmentation, in progress, or online). Figure 2 and 3 show the estimated price policy function. As expected, the price policy function demonstrates a clear inverse relationship between price and storage level.

Figure 2: Rain dependent scenario, price policy function, pre-augmentation, 2015.
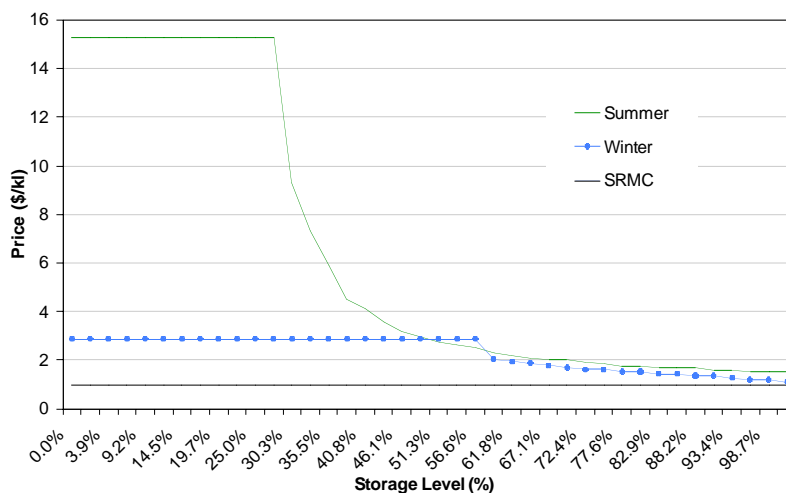
As the storage level approaches 100 per cent, price approaches, but does not necessarily reach, the SRMC. The optimal price is seasonal, being higher in summer and lower in winter. At low storage levels, price increases sharply to the maximum price level. The maximum price is that where nonessential demand is reduced to zero — this maximum price is dependent on the season, being highest in summer and lowest in winter. In reality it may not be practical to use scarcity pricing in emergency situations where it is necessary to reduce consumption to essential levels. As such these maximum prices should be interpreted more as shadow prices, representative of high level water restrictions. The estimated optimal price is, for a given storage level and augmentation status, increasing in time as a result of demand growth. The optimal price is, for a given time and storage level, lower after the completion of an augmentation project (see figure 5). Before augmentation, the price policy function is defined over the initial storage state space 10 000 – 200 000 megalitres, while after augmentation the price policy function is defined over the new storage state space (10 000 – 270 000 megalitres).

Figure 3: Rain dependent scenario, price policy function, spring 2015.
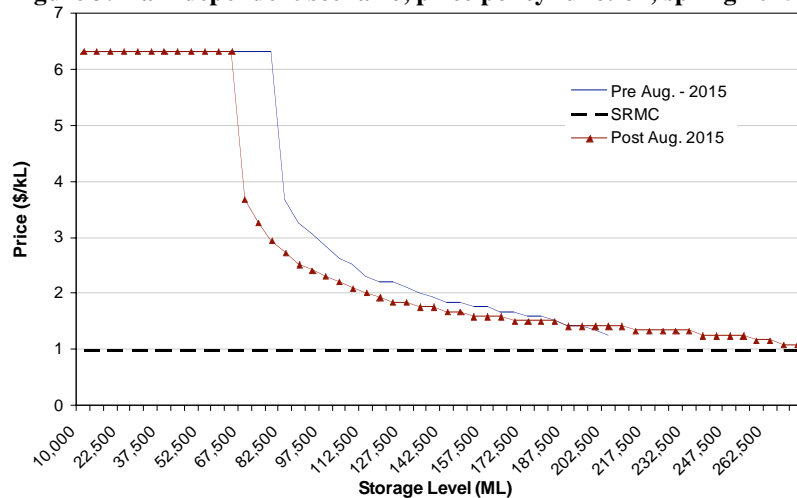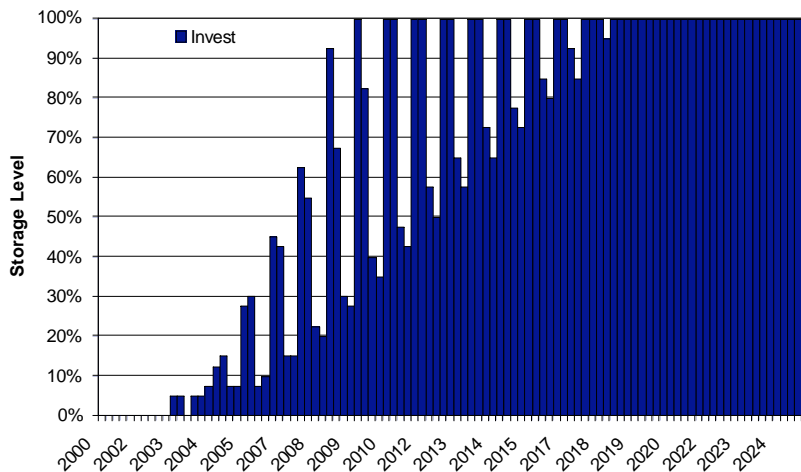

Figure 4 shows the estimated investment policy rule as a function of time and the prevailing storage level.

Figure 4: Rain dependent scenario, investment policy function

For each point in time the investment rule defines a storage trigger poin — for storage levels below this point, the investment is executed. Over time the storage trigger point increases due to demand growth. The investment rule also displays strong seasonality. The storage trigger point peaks in winter where the project (new dam) comes online in time for the winter high rainfall season in two years time. This result is dependent on the assumption of a fixed (two year) lead time, known with certainty. The investment storage trigger point reaches 100 per cent by winter 2009, rendering the remainder of the investment policy rule trivial.

Given the estimated policy functions model simulations can be generated by drawing a series of inflow observations from the defined probability distributions. A Monte Carlo analysis can be performed by generating a large number of such simulations and combining the results. Figure 5 displays a single example simulation and the increase in storage capacity represents the supply augmentation project (new dam) coming online.

Figure 5: Rain dependent scenario, example simulation, price and storage level
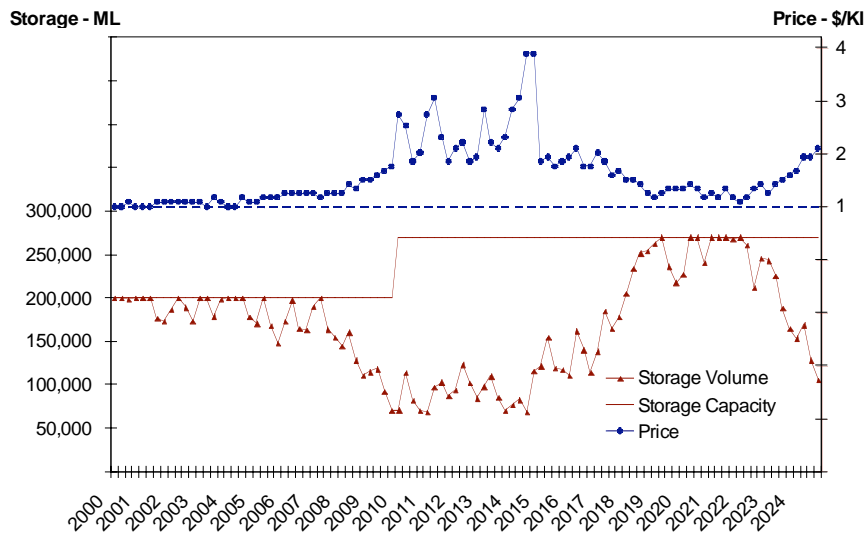
The simulated timing of investment varies depending on the realised conditions (the stochastically generated inflows), with a mean execution time of 8.1 years. The variability of investment timing for rain dependent augmentation is relatively low compared with that of rain independent augmentation (Figure 9). Figure 6 displays the mean price level and 90 per cent confidence interval estimated by Monte Carlo analysis. The mean price level increases over time due to demand growth. The growth in the mean price level slows around the time of supply augmentation, before continual demand growth eventually drives it up. Figure 6 also displays how the variability in price increases with the mean level of scarcity (mean price level).

Figure 6: Rain dependent scenario, mean price level with 90% confidence interval
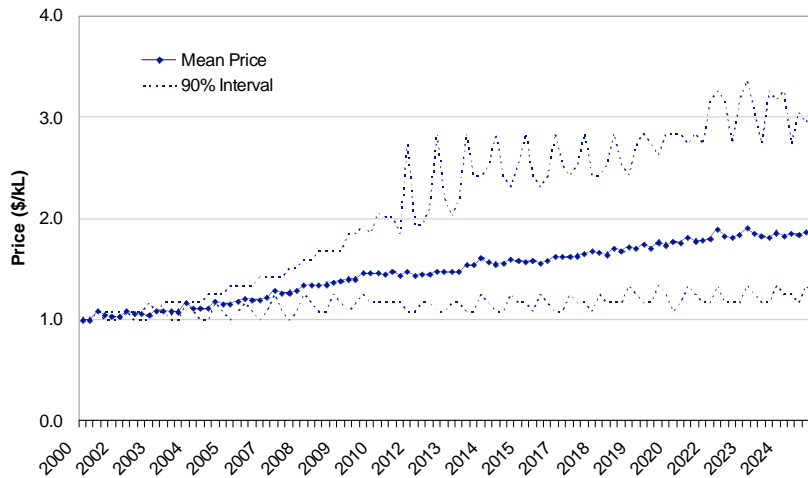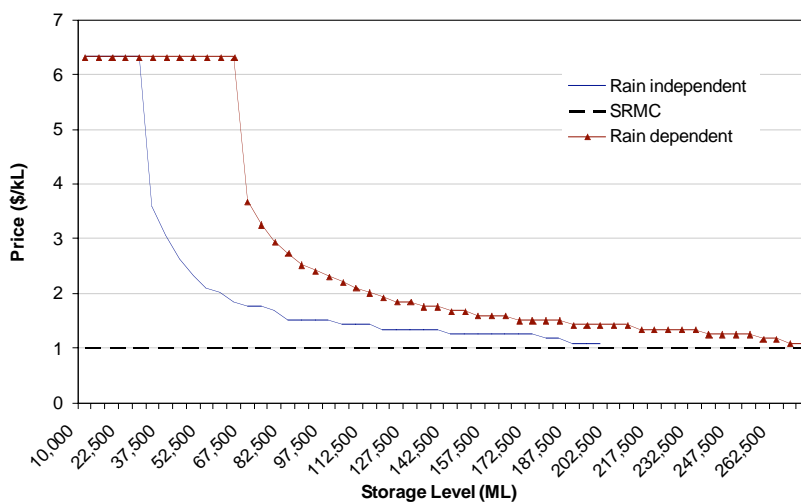

Rain independent scenario

The rain independent scenario assumes a rain independent augmentation project as defined by the following parameters.

Table 4: Rain independent augmentation option

Capital cost, c	$200 million
Ongoing cost, a	$10 million a year
Additional inflow, $nrin$	6 000 ML a season
Additional storage Capacity, ik	0
Lead time, LT	2 years

In the ACT, water recycling is the most practical form of rain independent supply given the distance to the coast. However, it is intended that this scenario be representative of rain independent augmentation generally, whether that be recycling or desalination. Within the model, desalination and recycling can be considered equivalents in that they both involve high capital and operating costs and provide a fixed supply of water.

Figure 7: Rain independent scenario, price policy function, spring 2015.

The estimated price policy functions for the rain independent scenario, given the initial supply capacity (for example, prior to augmentation) are essentially identical to those estimated for the rain dependent scenario. However, after augmentation the estimated optimal prices are significantly lower in the rain independent scenario (Figure 7).

The estimated investment policy function is shown in Figure 8. The storage trigger points remain lower, peaking at around 60 per cent at the end of the simulation period (2025). With rain independent augmentation, the investment policy essentially involves delaying investment where possible until storage levels decline substantially. There are two reasons for this. First, rain independent augmentation is more expensive and therefore there is more to be gained by delaying its introduction. Second, rain independent augmentation provides additional inflows with certainty. This certainty allows the water utility to delay investment until storage levels are low, in the knowledge the augmentation project will provide inflows sufficient to improve storage levels and ensure that the essential water supply is maintained. With rain dependent augmentation, additional storage capacity is provided with certainty, but inflows remain highly uncertain.

Figure 8: Rain independent scenario, investment policy function
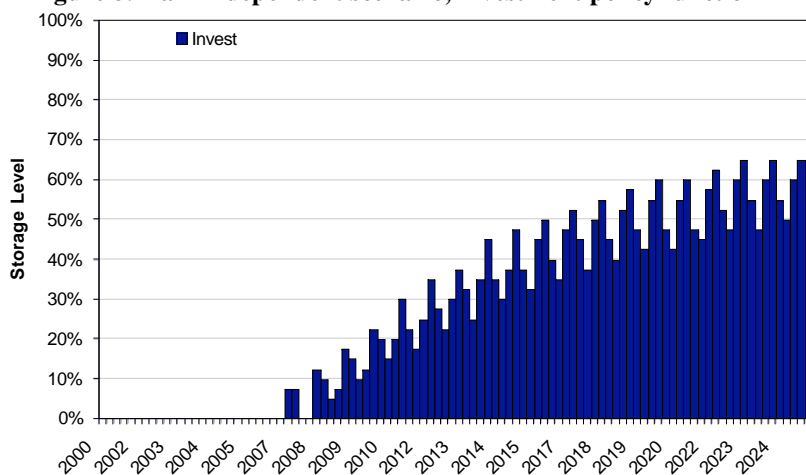
The rain independent augmentation investment rule also displays a degree of seasonality. With rain independent augmentation the storage trigger point peaks in summer, where the project will come on line in time for the critical summer period in exactly two years time.

Figure 9 displays the cumulative probability distribution over investment timing for rain dependent and rain independent augmentation, generated via Monte Carlo analysis. Rain dependent augmentation occurs earlier on average (8.1 years compared with 16.7 years) and is less variable. The timing of rain independent augmentation is highly variable, being strongly dependent on realised inflow levels. For example, there remains a positive probability (0.05) that a series of inflows is realised that allows the rain independent augmentation project to be delayed beyond the simulation period.

Figure 9: Cumulative probability distribution of investment timing
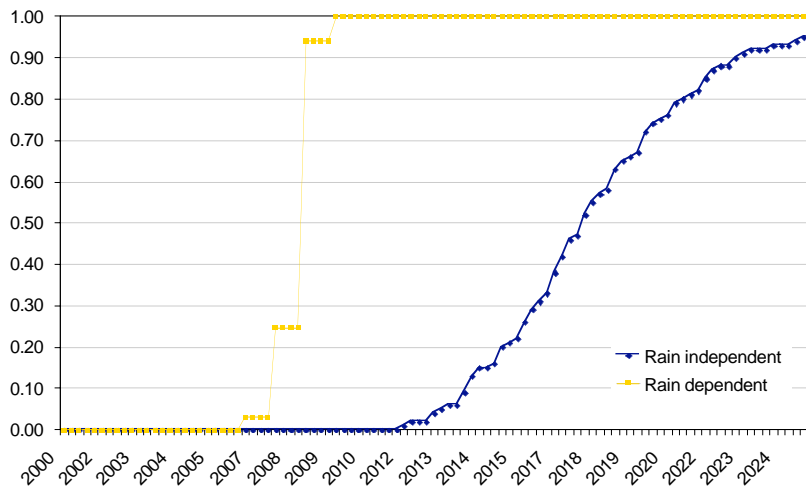
The results of this analysis are, in a number of respects, consistent with the recent policy responses of urban water utilities in Australia. The severity of the recent drought has led most major water utilities to pursue the introduction of rain independent supply. However, the introduction of rain independent supply has, in most cases, been delayed wherever possible, with water utilities first making use of a range of demand management polices. The results also demonstrate the importance of maintaining a flexible approach to supply augmentation policy in order to manage risk. Water utilities can, for example, invest in lead time reduction, adopt smaller upgradeable investment projects (where the risk savings outweigh the economies of scale) and develop temporary supply options such as water trade with rural water holders. Such options improve the ability of water utilities to respond to reductions in storage levels and facilitate the delaying of investment in costly rain independent supply augmentation.

Figure 10: Rain independent scenario, mean price level with 90% confidence interval
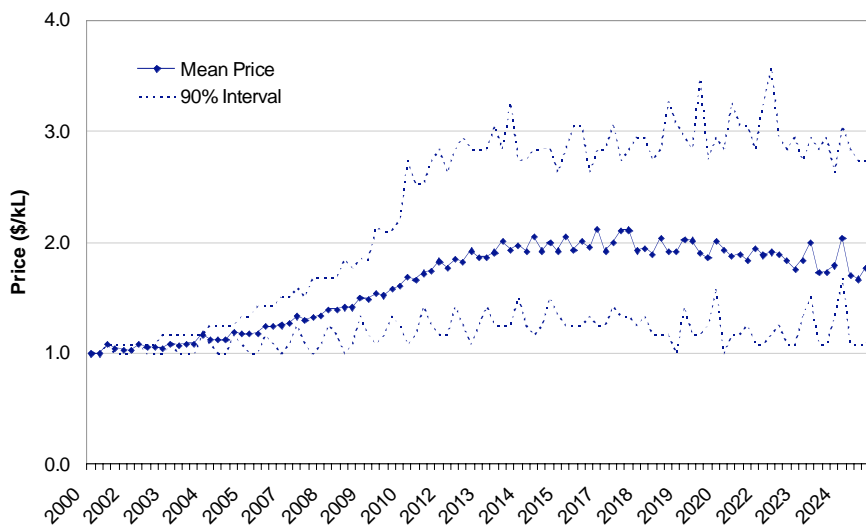
Figure 10 displays the mean price for the rain independent scenario. In this scenario mean price rises quickly at first given that augmentation occurs on average later than in the rain dependent scenario. The mean price falls gradually after year 17, given that augmentation is more likely to have occurred.

'Staged' scarcity pricing

Scarcity pricing could potentially be implemented using a system of stages similar to that used for water restrictions. A number of price stages could be defined, each of which corresponds to a different level of scarcity. As with restrictions, each stage would aim to achieve a specific reduction in water consumption and have an associated trigger point. In theory the water utility could simply replace each stage of restrictions with an equivalent scarcity price, which they estimate will achieve an equivalent reduction in consumption.

A staged scarcity pricing system can be represented in the model by limiting the number of points within the discrete price policy grid. The model results above are based on a 50 point price grid. To estimate the impact of a staged price system the model was run separately for price grids containing 12 and 6 points the results of these simulations are displayed below. The reader might be tempted to interpret these limited price point simulations as an implicit representation of water restrictions; however, such an interpretation has not been intended and would be an oversimplification of current water restriction systems. A reduction in the number of price points yields a reduction in welfare. However, the results demonstrate that this loss of welfare is relatively small.

Table 5: Limited price grid summary results

		Price grid size		
		50	12	6
Objective value	$ million	1 335	1 333	1 328
Change	%		–0.2%	–0.5%

Figure 11: Limited price grid, price policy function (rain dependent, spring 2015, pre aug.)
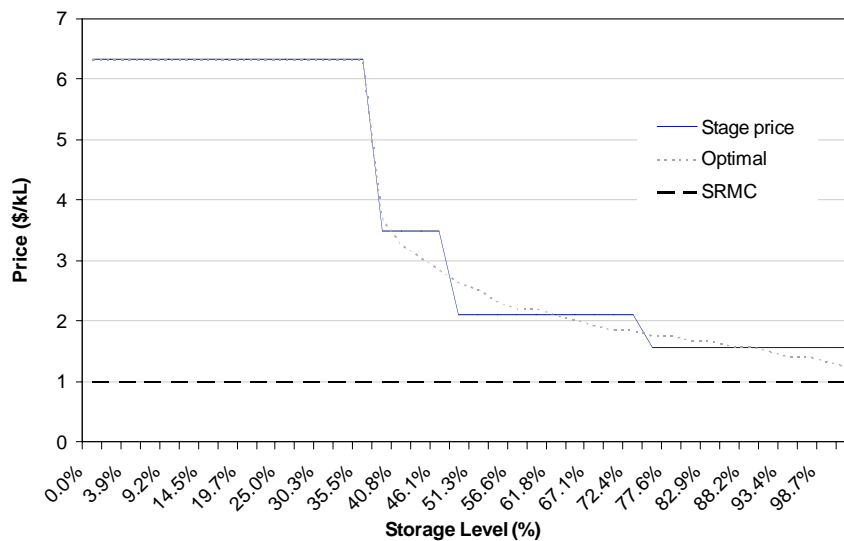
In the model the water utility is assumed to have full information. In reality, the water utility will not have full information on the exact distribution of future inflows, the long run growth rate of demand and the elasticity of the demand curve for water. This information problem means that, in practice, setting optimal prices would be a nontrivial task. It is important to realise, however, that this information problem is not necessarily more burdensome than that faced under a system of water restrictions. Water utilities in theory require the same information to optimally set water restriction quantity targets and storage trigger levels. Further the use of scarcity pricing may over time reveal more information, particularly on consumers' willingness to pay.

One way to approach the problem of setting prices is to recast it in terms of optimal quantities. Water utilities are quite experienced in determining the optimal quantity of water consumption given available information on demand and supply. Determining a price that achieves this quantity is not necessarily a more difficult problem than developing a list of restrictions that achieves the same result. One of the additional advantages of scarcity pricing is that there exists more flexibility over the number of scarcity stages chosen. With water restrictions, defining distinct stages of varying severity is difficult given that each stage involves numerous rules referring to different water use activities.

A scarcity pricing system implemented in the fashion described need not result in highly volatile water prices since price changes would occur no more frequently than do changes in restriction stages at present. The adoption of such a pricing system would not increase the aggregate uncertainty faced by urban water consumers, it would merely replace existing restriction uncertainty with price uncertainty.

Conclusion

In this paper the role of the urban water utilities is characterised as that of a social planner, setting demand management and supply augmentation policies to maximise social welfare. In Australia the predominant approach to demand management is the imposition of water restrictions. Water restrictions are a relatively limited and inefficient method of rationing demand, imposing inconvenience costs, allocative efficiency costs as well as involving significant enforcement costs. In this paper, scarcity pricing is proposed as a potentially more efficient demand management tool.

Scarcity pricing would involve the water utility adopting a variable price that responded to changes in the level of water scarcity, where for example price would vary inversely with the storage level. Scarcity pricing could be implemented under a two block price scheme such that essential water consumption remained affordable at all times.

A stochastic dynamic optimisation model of an urban water market was constructed using data on urban water supply and demand in the ACT. The model estimates the optimal price and investment policy functions under conditions of uncertainty, given a theoretical probability distribution over future dam inflows. The model results demonstrated how a scarcity pricing system would operate, with the optimal price inversely related to storage levels, increasing in time with demand growth and decreasing with the introduction of supply augmentation. The model was also used to demonstrate how a scarcity pricing

system could be implemented under a system of price stages similar to the current system of water restrictions.

The nature of optimal investment policy, involving the execution of investments once storage levels decline below specific storage trigger points, was also demonstrated by the model. Substantial differences were observed between the optimal investment rules of rain dependent and rain independent augmentation options. The higher costs and the certain inflows associated with rain independent augmentation mean that water utilities are more likely to adopt an opportunistic approach: where investment is delayed until substantial decline in storage levels occurs.

Continual demand growth, increasing supply augmentation costs and potential climate change impacts are driving a long term trend toward increased urban water scarcity in Australia. Urban water utilities will have to rely on more stringent demand management, such as more frequent imposition of restrictions or higher prices, and/or substantial investment in costly rain independent supply options. Given this reality, policy makers should be considering ways of improving the efficiency of demand management and supply augmentation policies. Scarcity pricing is one approach that warrants further consideration.

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