The Australian Journal of
Agricultural and
Resource Economics

Journal of the Australian Agricultural and Resource Economics Society

The Australian Journal of Agricultural and Resource Economics, 53, pp. 175–192

Urban water management: optimal price and investment policy under climate variability*

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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 significant water scarcity and climate variability. This article 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 ACT region. 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.

Key words: demand management, scarcity pricing, stochastic dynamic programming, supply augmentation, urban water.

1. Introduction

Recent drought conditions across Australia have significantly depleted urban water storages and have resulted in stringent 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 decline in mean inflows into storages, increasing demand because of 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

* The authors acknowledge Actew Corporation, for providing data and advice on the URBAN WATER INDUSTRY and comments on the draft of this article. The views expressed in this article are however, those of the authors and do not represent the official view of Actew Corporation. Assistance with initial modelling efforts was provided by Nathan Brownlowe. Comments on the draft of this article were provided by Mike Hinchy and Sharon Page. The authors also thank Stephen Beare for providing the initial inspiration for this project.

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doi: 10.1111/j.1467-8489.2007.00446.x

to make optimal supply augmentation decisions. Current urban water demand management predominantly involves the imposition of water restrictions to ration water during times of scarcity. In this article scarcity pricing is proposed as an alternative to the use of water restrictions. Scarcity pricing of urban water was recently considered by Grafton and Kompas (2007).

One of the main difficulties in designing urban water policy, particularly in Australia, is the extreme variability of rainfall and dam inflows. This article considers the design of optimal demand management and supply augmentation policies under climate variability, by constructing and applying a stochastic dynamic programming model of an urban water market. This model is used to estimate the socially optimal price (demand management) and investment (supply augmentation) policy functions of the urban water utility.

2. Urban water policy

In this article we characterise the role of the urban water utility as that of a social planner who seeks to maximise social welfare, subject to water availability constraints. Concerns of potential monopoly behaviour by Australian urban water utilities have been raised by a number of economists see for example Dwyer (2006). However in this article it is implicitly assumed that the monopoly water utility is government owned and/or operated and effectively regulated to ensure that it acts in the public interest. In its role as social planner, the water utility has two main policy tools: demand management and supply augmentation.

2.1 Demand management

Demand management is a term used to encompass a range of polices designed to reduce water use in times of scarcity. These policies can include water restrictions, pricing as well as advertising campaigns and incentives for improvements in water use efficiency.

In the short run, when supply infrastructure is fixed, inflow and demand variability can result in substantial reductions in storage levels, which necessitate a rationing of demand. In the long run, supply infrastructure can be altered and demand management policy and supply augmentation policy are simultaneously determined. The optimal long run demand management policy (long run mean frequency of restrictions or mean price level) will maintain the optimal balance between the benefits of water consumption and the costs of supply augmentation.

In this article a distinction is drawn between non-essential and essential water, where essential water provides for basic sanitation, drinking, bathing and food preparation needs. It is assumed that non-essential water can be rationed but a minimum level of essential water must be supplied at all times.

2.1.1 Water restrictions

Water restrictions are currently the main mode of demand management employed by Australian water utilities. Urban water restrictions are a relatively inefficient method of rationing demand, a fact noted by a number of economists including Edwards (2006) and Grafton and Ward (2007). The costs of water restrictions can be disaggregated into at least three main components: inter-household allocative inefficiency, intra-household allocative inefficiency and inconvenience costs.

Water restrictions involve complex rules which regulate the outdoor use of urban water. These rules 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 time and 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. In economic terms these types of inconvenience costs can be considered as a transaction cost imposed on consumers.

Water restrictions in their more severe forms involve complete bans on outdoor water uses. Where there are heterogenous preferences for water, prescriptive rationing will result in an inefficient allocation of water resources, (inter-household allocative inefficiency). Water restrictions generate further inefficiencies by targeting different water uses to varying degrees while providing implicit and explicit exemptions for other uses, (intra-household allocative inefficiency). For example water restrictions are, partly for reasons of enforcement, limited to outdoor residential water use.

In addition to the inconvenience 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 which is not attempted in this article. A number of economists have attempted to estimate the costs of restrictions using varying techniques including Hensher *et al.* (2006), Brennan *et al.* (2007) and Grafton and Ward (2007).

2.1.2 Current pricing regime

In Australia urban water prices are set by state government regulatory agencies, which make price determinations over three to five years time frames. In the absence of scarcity or capacity constraints an efficient allocation of water can be achieved with a price set to short run marginal cost (SRMC). In the presence of demand growth, scarcity and capacity constraints become inevitable in the long run. Urban water price regulators generally advocate some form of long run marginal cost (LRMC) pricing.

The Victorian Essential Services Commission (2005) defines LRMC as SRMC plus 'marginal capital costs', where marginal capital costs measure the marginal increase in expected future supply augmentation costs associated with an incremental increase in demand. A fixed LRMC price does not account for variable dam inflows and the potential for short run fluctuations in storage levels. 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.

Australian water utilities generally impose a two part tariff involving a marginal (consumption based) price and a residual fixed access charge designed to achieve cost recovery. In this article we focus the marginal price of water rather than the average price. The impact of different price and investment polices on revenue and cost recovery is not considered in detail in this article.

Finally in most Australian capital cities inclining block pricing schemes have been adopted, such schemes are economically inefficient relative to a single uniform price (Brennan 2006; Edwards 2006).

2.1.3 Scarcity pricing

In this article the scarcity price is defined as the price which maximises the expected net present value of social welfare, given uncertain inflows and optimal supply augmentation policy. The scarcity price represents the full opportunity cost of urban water: the SRMC plus the opportunity cost of forgone storage. Water in storage has an opportunity cost since a reduction in storage levels can result in a reduction in the expected reliability of future supply and a bringing forward of expected future supply augmentation. This price is state dependent. For example, a scarcity price would vary inversely with storage levels.

An alternative to scarcity pricing would be a system of tradable water entitlements. Such a system would be subject to substantial administration costs and transaction costs and is not considered in detail here. Scarcity pricing of urban water is sometime apposed on the grounds of equity. However equity concerns can be addressed by a range of targeted policy measures, see for example Grafton and Kompas (2007) and Quiggin (2007). A move from water restrictions to scarcity pricing may also result in some incidental distributional changes, for example it may benefit consumers with higher time opportunity costs.

There are a number of important practical considerations that would need to be evaluated before a scarcity based pricing system could be implemented. Firstly a scarcity pricing system would require a relaxation of current water price control. There would be a need however, to maintain some form of regulatory effort to prevent abuse of monopoly power, how this could be achieved is not discussed in detail here. With a scarcity pricing system it may also be necessary to improve the accuracy of water metering, this may require an investment in ‘smart’ metering technology.

Another issue is how the urban water utility sets the optimal scarcity price. The urban water utility faces an information problem since it has incomplete information on important variables such as the probability distribution over future inflows and the price elasticity of demand. However water utilities face much the same information problem in setting water restriction targets and storage trigger levels. Further the use of scarcity pricing may over time reveal more information on consumers’ willingness to pay. 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.

Scarcity pricing may not be practical in an extreme water scarcity situation, where it may be necessary to reduce water consumption to near essential levels. It may therefore be advisable to retain water restrictions in some form as a backup option, to be used only in worst case situations.

2.2 Supply augmentation

Supply augmentation policy is concerned with the nature and timing of additions to water supply infrastructure, such as new dams, desalination plants or water recycling. Both desalination and recycling offer a stable source of water insulated (at least partially) from rainfall variability, however, both involve substantially higher capital and operating costs. Another option for sourcing urban water is to acquire it through trade with rural water holders, rural urban water trade is not considered further here, for more see Quiggin (2006), CSIRO and the CoPS (2006) and Page and Hafi (2007).

This article focuses specifically on the timing of 'lumpy' supply augmentation under climate variability and not on making comparisons between specific supply projects. The optimal timing of supply augmentation projects, involves the repeated comparison of the expected net benefits of investing now to the expected net benefits of delaying investment.

In the long run demand management policy and supply augmentation policy are interdependent: a supply augmentation project generating additional inflows will improve the reliability of supply allowing urban water utilities to reduce the long run mean frequency of restrictions (or the mean water price). Supply augmentation is also motivated by the need to maintain the supply of essential water. Urban water utilities typically maintain supply infrastructure so as to ensure the probability of a shortfall in essential water is near zero.

The timing of supply augmentation involves trading off the benefits of supply reliability with the costs of augmentation. Industry practice has historically involved the targeting of an 'acceptable level' of reliability, measured as the expected time households are subject to restrictions. In the past water utilities have made relatively arbitrary judgements on this acceptable level of restrictions and have placed little emphasis on consumer's preferences (Hensher *et al.* 2006). One of the reasons for this is that the benefits of increased water supply reliability depend on the communities' willingness to pay which is difficult to estimate without a price mechanism that reflects scarcity.

3. An urban water model

This section provides a brief discussion of an economic model of urban water supply and demand. The model incorporates data on the demand and supply of urban water in the ACT region; however, the model is intended to be general rather than ACT centric. The aim of the model is to demonstrate the nature of optimal price (demand management) and investment (supply augmentation) polices rather than to forecast the economic impacts of a change in urban water policy in the ACT. The model is formulated as a stochastic dynamic programming problem.

3.1 The model in context

Dynamic programming techniques have been applied to a range of water related problems including estimating optimal extractions from ground water 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. Riordan (1971a) developed a model of optimal water pricing and investment by a regulated monopoly whereby price is set equal to short run cost plus a capacity charge which keeps demand within existing capacity constraints. The model makes use of deterministic dynamic programming techniques to derive the optimal timing of capacity expansion.

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. For example Perera and Codner (1996) use stochastic dynamic programming estimate the optimal distribution of stored water across individual dams so as to maximise supply reliability and minimise dam spills in a multiple reservoir system.

3.2 The model in detail

The model uses stochastic dynamic programming techniques to estimate the price and investment policy functions which maximise the expected discounted value of social welfare. In this instance social welfare refers to the expected discounted sum of market surplus (from non-essential water), less the costs of supply augmentation and less penalties imposed for any inability to meet essential demand. The estimated policy functions are state dependent. For example, the price policy function specifies the optimal price given the time period, the prevailing storage level and the state of supply augmentation. The model comprises two main components, one specifying the evolution of water demand and the other specifying water supply.

3.2.1 The demand for urban water

Econometric studies have used a range of variables to explain observed variation in urban water demand over time and across households, such as population, income levels, water use efficiency, housing characteristics, water prices and weather conditions (Dalhuisen *et al.* 2003; Hoffman *et al.* 2006). For this model a simple aggregate demand function is constructed, accounting for long-term growth, seasonal variation, response to weather variability and response to price changes.

The seasonality of demand and the response to weather variability are estimated econometrically using quarterly ACT data over period 1960–2000, for more detail see Hughes *et al.* (2008). Inflows were used as a proxy for weather conditions (such as rainfall and temperature) since this allows the model to have a single source of risk. In the model demand is projected over an arbitrary 25 years time horizon, notionally the period 2000–2025. The long-term growth of demand over time adheres to a logistic functional form. The long run growth projection should be considered an illustrative scenario rather than a forecast. Equation (1) specifies the evolution of demand for water over time given a fixed SRMC price.

$$Q_t^{\mathrm{MC}} = \exp(b^{\mathrm{con}} + b_s^{\mathrm{seas}} + b^{\mathrm{in}}\{\mathrm{IN}_t\})\left(\frac{g_1}{1 + (g_1 - 1)e^{-g_2 t}}\right) \tag{1}$$

Where:

t = time periods (quarters/seasons)
s = seasons (*Summer, Autumn, Winter, Spring*)
Q_t^{MC} = quantity demanded (ML) when price equals SRMC
IN_t = inflows (ML)
b^{con} = demand equation constant (= 9.7)
b_s^{seas} = seasonal parameters (*Summer* = 0.397, *Autumn* = –0.033, *Winter* = –0.371)
b^{in} = inflow parameter (= -2.2×10^{-6})
g_1, g_2 = long-term growth parameters ($g_1 = 2.4$, $g_2 = 0.037$)

The price elasticity of urban water demand has been the focus of a substantive volume of 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 and estimated a 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 recent study by Grafton and Kompas (2007) estimated an aggregate demand equation for urban water in Sydney, with a price elasticity of –0.35.

A constant elasticity relationship is assumed to exist between urban water demand and price, an elasticity of –0.45 is assumed based on a search of the literature. Equation (2) specifies the inverse demand function.

$$P_t = (Q_t^{\mathrm{MC}} \mathrm{mc}^{1/\alpha})^{\alpha} Q_t^{-\alpha} \tag{2}$$

Where:

Q_t = quantity of water demanded (ML)
mc = short run marginal cost (\$/ML) (= 1)
$1/\alpha$ = demand price elasticity (= 0.45)

It is assumed that essential water consumption is unresponsive to price. The level of essential water demand is assumed to be non-seasonal and is calculated in the model as a fixed proportion of winter equivalent aggregate water demand.

3.2.2 The supply of urban water

On the supply side of the model it is assumed that there is a single storage with stochastic inflows. A single storage model can be can be interpreted as an approximation of a multiple reservoir system, see Perera and Codner (1988). Seasonal inflow probability distributions were estimated using historical inflow data for the ACT. 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 the estimated parameters are shown in Table 1.

The supply side of the model also accounts for evaporation from storages and environmental flows. For simplicity it is assumed that evaporation 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).

$$\begin{aligned} S_t &= S_{t-1} + \text{Tot IN}_t - E_t - Q_t \\ S_t &\geq S^{\min}, S_t \leq K_t \end{aligned} \tag{3}$$

Where:

S_t = storage level (ML)
Tot IN_t = total inflows (dependent on supply augmentation) (ML)
E_t = total storage losses (dependent on supply augmentation) (ML)
K_t = total storage capacity (dependent on supply augmentation) (ML)
$S^{\min}$ = storage minimum feasible level (ML) (= 10 000)

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 intended to broadly represent desalination and water recycling. Rain dependent augmentation represents construction of new dams and is assumed to generate additional storage capacity and additional stochastic inflows. For simplicity it is assumed that new dam inflows are perfectly

Table 1 Log normal inflow distribution parameters

	Mean inflows (ML)	μ	σ
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

correlated with existing inflows. Equations (4) and (5) specify the relationship between inflows, storage capacity and supply augmentation investment.

$$TotIN_t = (1 - ef)\left(IN_t + \sum_{i=1}^{I} I_{t-LT_t,i}(\phi_i IN_t)\right) + \sum_{i-1}^{I} I_{t-LT_i,i}\, nrin_i \tag{4}$$

$$K_t = k_0 + \sum_{i=1}^{I}(I_{t-\mathrm{LT}_i,i}\, ik_i) \tag{5}$$

Where
$I_{t,i} = 1$ for all $t > T$ where T is the execution time for investment
ef = proportion of inflows released to the environment (= 0.25)
$n\mathrm{rin}_i$ = rain independent inflows of investment i (ML)
ϕ_i = proportional increase in rain dependent inflow for investment i
ik_i = additional storage capacity of investment i (ML)
LT_i = lead time of investment i (quarters)
k_0 = initial storage capacity (ML) (= 200 000)

Each option also has a capital cost, a fixed annual operating cost and a lead time or construction period. For simplicity it is assumed that rain independent augmentation options are operated permanently at full capacity such that inflows and operating costs are fixed. In practice it is likely that production levels at desalination or recycling plants will vary, for example plants could potentially be shutdown when the value of water generated is lower than plant operating costs. Furthermore it is assumed that the SRMC of water supply is constant over time and across supply augmentation options. An arbitrary value of \$1 per kilolitre (kL) is assumed for the SRMC.

3.2.3 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).

$$E\left(\sum_{t=1}^{T} \beta^t (\mathrm{MS}_t(Q_t, Q_t^{\min}) - \mathrm{TC}_t - \mathrm{PENALTY}_t\right) \tag{6}$$

$$MS_t(Q_t, Q_t^{\min}) = \int_{Q_t^{\min}}^{Q_t} (Q_t^{\mathrm{MC}}\mathrm{mc}^{1/\alpha})^{\alpha} Q_t^{-\alpha}\,\mathrm{d}Q_t - (Q_t - Q_t^{\min})\mathrm{mc} \tag{7}$$

Where:
MS_t = market surplus (the sum of consumer surplus and scarcity rent)
$Q_t^{\min}$ = level of essential water demand at time t
TC_t = total cost (capital and operating) of augmentation at time t

$PENALTY_t$ = penalty imposed if essential water is not met ($= 1 \times 10^{10}$)
β = quarterly discount factor (= 0.015)

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 so as to ensure the probability of a shortage of essential water is near zero. 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 and two policy or control variables, price and supply augmentation investment. Given a discrete state and policy space the model is solved using backward induction.

4. Results and discussion

Two scenarios are constructed: a rain dependent augmentation scenario and a rain independent scenario. This approach was necessary because with multiple investment projects the problem became unfeasibly large, due to the 'curse of dimensionality' problem. Scenarios involving a single augmentation option will tend to overstate water scarcity (over estimate price) relative to multiple investment projects scenarios, since an additional investment project provides an option value benefit that is realised even if the project is not executed. 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.

4.1 Rain dependent scenario

This scenario assumes an augmentation project representative of a new dam as defined by the following parameters (Table 2).

Figures 1 and 2 show the estimated price policy function. As expected the price policy function demonstrates a clear inverse relationship between price and the storage level.

As the storage level approaches 100 per cent price approaches 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 occurs where non-essential demand is reduced to zero, this

Table 2 Rain dependent augmentation option parameters

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

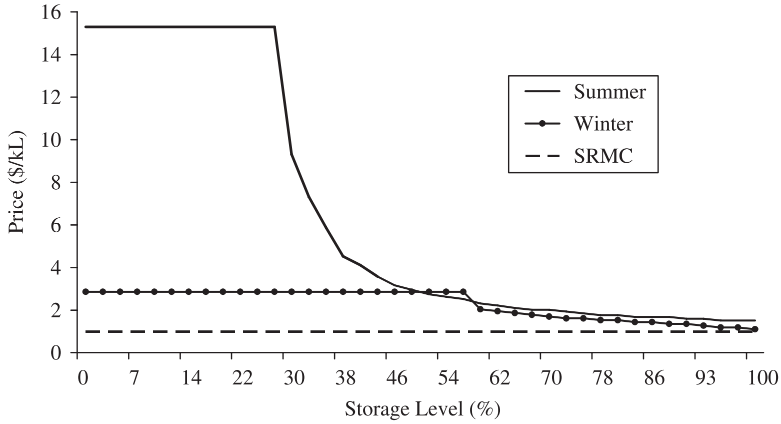

Figure 1 Rain dependent scenario, price policy function, pre augmentation, 2015.

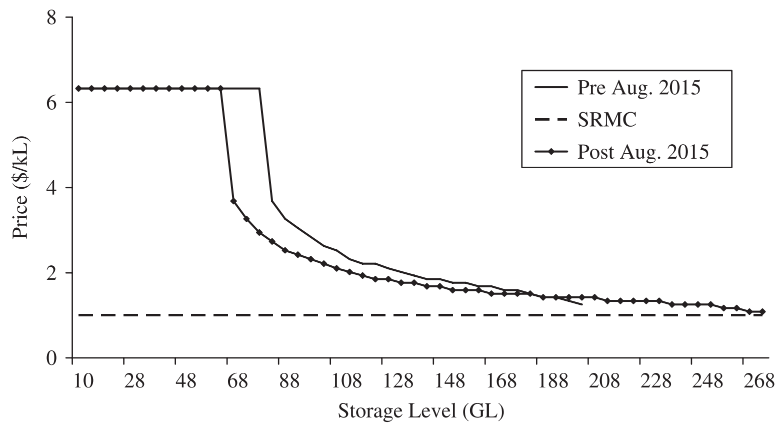

Figure 2 Rain dependent scenario, price policy function, Spring, 2015.

maximum price is dependent on the season, being highest in summer and lowest in winter. As discussed it may not be practical to use scarcity pricing in emergency situations, as such these maximum prices can 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 post the completion of an augmentation project (see Figure 2).

When interpreting Figure 2 note that the initial storage capacity of 200 GL increases to 270 GL following augmentation. The estimated prices are lower pre augmentation, around 200 GL, given the higher probability of spills at this storage level.

Figure 3 shows the estimated investment policy rule as a function of time and the storage level.

For each point in time the investment rule defines a storage trigger point: for storage levels below this point investment is executed. Over time the

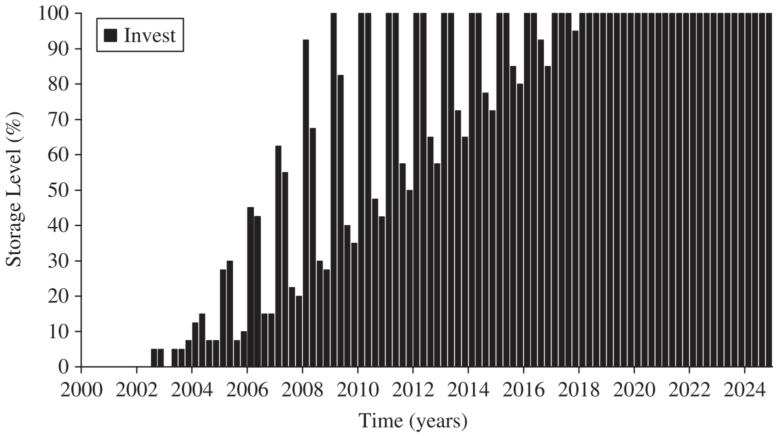

Figure 3 Rain dependent scenario, investment policy function.

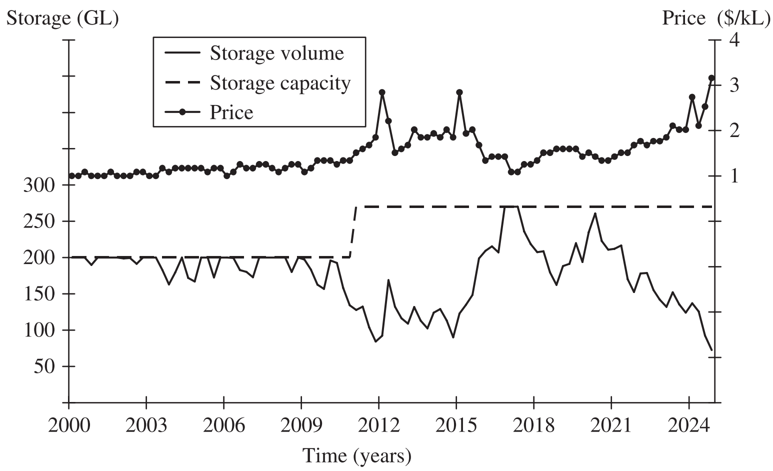

Figure 4 Rain dependent scenario, example stochastic simulation, price and storage level.

storage trigger point increases due to demand growth. The investment rule also displays strong seasonality, with the storage trigger point peaking in winter. Starting dam construction in winter ensures new dam will come online in time for the winter season in two years time and will be able to capture the typically strong winter inflows. Clearly an empty new dam has little value in summer when inflows are likely to be low. This result is dependent on the assumption of a fixed 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 4 displays a

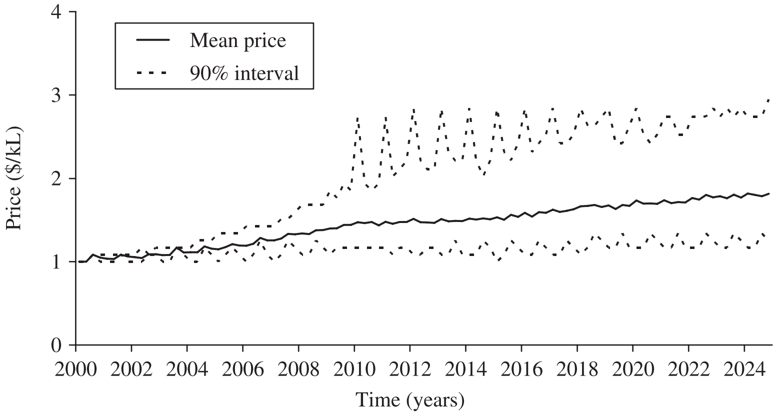

Figure 5 Rain dependent scenario, mean price level with 90 per cent confidence interval.

single example of a stochastic simulation, the increase in storage capacity represents the supply augmentation project coming online.

The simulated timing of investment varies depending on the realised conditions, with a mean execution time of eight years. The variability of investment timing for rain dependent augmentation is relatively low compared with that of rain independent augmentation, see Figure 8. Figure 5 displays the mean price level with 90 per cent confidence interval. The mean price level is increasing in time due to demand growth. The growth in the mean price level slows around the time of supply augmentation. Figure 5 also displays how the variability in price increases with the mean level of scarcity (mean price level).

4.2 Rain independent scenario

The rain independent scenario assumes a rain independent augmentation project as defined by the following parameters (Table 3).

Table 3 Rain independent augmentation option

Capital cost, *c*	$200 million
Ongoing cost, *a*	$10 million a year
Additional inflow, *nrin*	6000 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, in that it involves high capital and operating costs and a fixed supply of water.

The estimated price policy functions for the rain independent scenario, given the initial supply capacity are essentially identical to those estimated

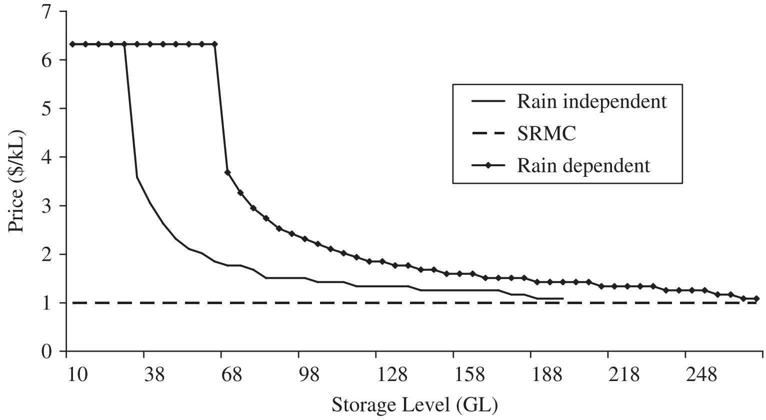

Figure 6 Rain independent scenario, price policy function, Spring 2015.

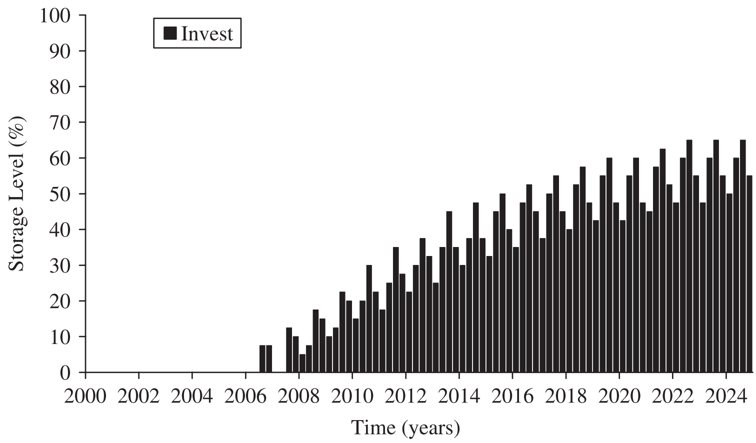

Figure 7 Rain independent scenario, investment policy function.

for the rain dependent scenario. However post augmentation the estimated optimal prices are significantly lower in the rain independent scenario, see Figure 6. While the rain independent option provides a smaller increase in mean inflows, it results in a substantial increase in the reliability of inflows. For a given storage level this increase in reliability substantially reduces mean water scarcity. The estimated prices in Figure 6 do not however, reflect the higher operating and capital costs of rain independent augmentation. In practice, given the need to recover costs, average water prices may be higher under rain independent augmentation.

The estimated investment policy function is shown in Figure 7. The storage trigger points remain lower than in the rain dependent scenario. 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

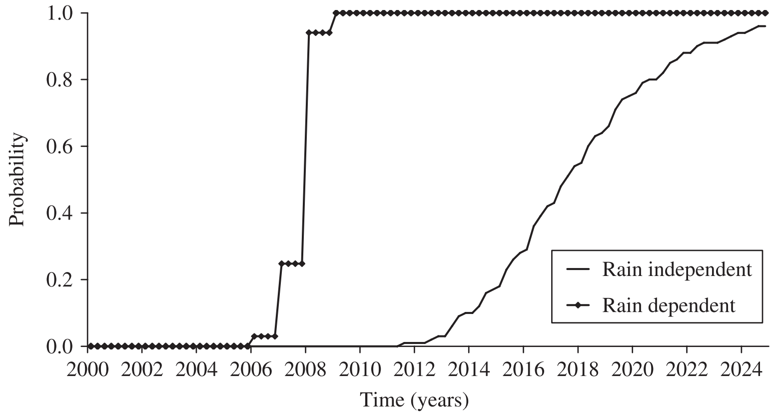

Figure 8 Cumulative probability distribution of investment timing.

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 insure the essential water supply is maintained.

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 online just in time for the critical summer demand period in exactly two years time.

Figure 8 displays the cumulative probability distribution over investment timing for rain dependent and rain independent augmentation. Rain dependent augmentation occurs earlier on average (8.0 years compared with 17.7 years) and is less variable. The timing of rain independent augmentation is highly variable, being strongly dependent on realised inflow levels. There remains a positive probability that a series of inflows is realised which allows the rain independent augmentation project to be delayed beyond the simulation period.

The results demonstrate the benefits of delaying costly investment in rain independent supply in the face of extreme climate risk. In practice urban water utilities can use a number of alternative measures to manage risk and delay investment including investing in lead time reduction, adopting smaller upgradeable investment projects (where the risk savings outweigh economies of scale) and pursuing temporary supply options such as water trade with rural water holders.

Where not shown here, a sensitivity analysis over model parameters was conducted. One of the key results of this analysis was that investment in rain independent supply is highly marginal, since small increases in the costs or decreases in the benefits (more elastic demand, higher mean inflows, lower penalty for system failure) result in a large reduction in the probability of investment.

Figure 9 displays the mean price for the rain independent scenario. In this scenario mean price rises quickly at first given augmentation is occurring on

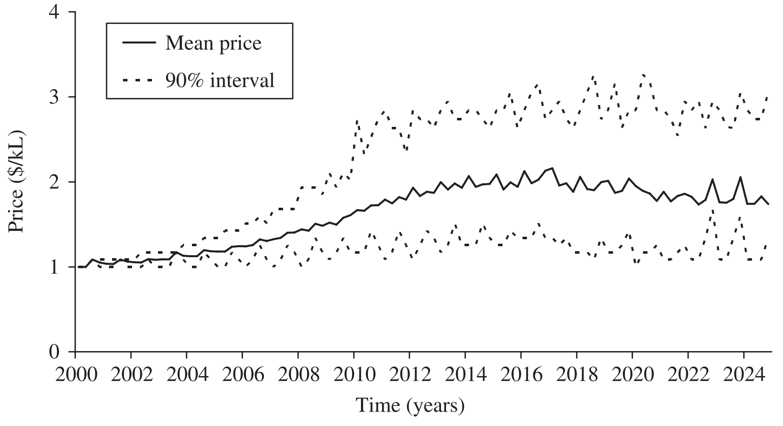

Figure 9 Rain independent scenario, mean price level with 90 per cent confidence interval.

average later than in the rain dependent scenario. The mean price falls gradually after year 17 given augmentation is more likely to have occurred.

4.3 'Staged' scarcity pricing

As discussed, scarcity pricing could potentially be implemented using a system of stages similar to that used for water restrictions. 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. A reduction in the number of price points yields a reduction in mean welfare, however, this reduction is relatively small (–0.4 per cent for the 12 point grid and –1.8 per cent 6 point grid). An example of a 'staged' price policy function is shown in Figure 10.

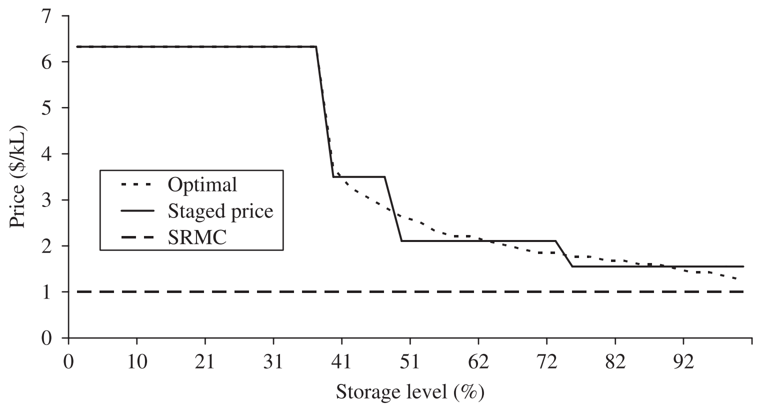

Figure 10 Example 'staged' price policy function.

5. Conclusion

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. Scarcity pricing is 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. Such a scarcity pricing system could be potentially be implemented under a system of price stages similar to the current system of water restrictions.

In this article a stochastic dynamic optimisation model of an urban water market was used to demonstrate how a scarcity pricing system would operate in theory, with the optimal price inversely related to storage levels, increasing in time with demand growth and decreasing with the introduction of supply augmentation. 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. Given this reality, policy makers should be considering ways to improve the efficiency of demand management and supply augmentation policies. Scarcity pricing is one approach which warrants further consideration.

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