

A photograph showing a close-up of a water treatment facility, with a large, turbulent flow of water cascading over a series of dark, slanted metal bars or filters. The water is white with foam, indicating high flow and turbulence.

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

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Summary

- Recent drought conditions across Australia have significantly depleted water storages in most urban centres. 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 storage, increasing demand because of population growth and minimal additions to supply capacity.
- Prior to the recent spate of supply augmentation activity, urban water scarcity was dealt with primarily through demand management measures, including the imposition of water restrictions.
- Supply augmentation, in response to long-run demand growth, has traditionally involved the periodic construction of new dams. However, concern over environmental impacts, a lack of suitable sites and potential climate change effects, have forced water utilities to consider alternative supply options such as desalination and recycling. These new supply options provide a more reliable supply of water but involve substantially higher capital and operating costs.

Urban water policy

- Urban water utilities have two main policy instruments at their disposal: demand management policy and supply augmentation policy. Demand management policy includes the use of water restrictions and pricing as well as advertising campaigns and incentives for improvements in water use efficiency. Supply augmentation policy is concerned with the nature and timing of additions to water supply infrastructure.
- Urban water policy can be considered to have both short and long-run contexts. In the short run, when supply infrastructure is fixed, the water utility must rely on demand management policies such as water restrictions to ration available water in the event of any scarcity (as may arise under drought conditions). In the long run, water utilities can influence the supply of water by undertaking supply augmentation. The optimal long run demand management policy (for example, the long-run mean frequency of restrictions or mean price level) will need to maintain the optimal balance between the benefits of water consumption and the costs of supply augmentation.

A potential role for scarcity pricing

- Water restrictions involve complex rules that govern the use of outdoor water by urban households. Water restrictions are a relatively inefficient method of demand management, as they impose inconvenience

costs, generate allocative efficiency losses and require substantial enforcement effort.

- Currently in Australia, urban water prices are set by regulators. Current practice involves setting urban water prices to match estimates of long-run marginal cost (LRMC). A fixed LRMC price does not respond to changes in scarcity levels and will be lower than optimal when storage levels are low, necessitating a rationing of demand through alternative measures such as water restrictions.
- In this report, scarcity pricing is proposed as an alternative to water restrictions. A scarcity price system would involve adopting a variable price that responds to changes in water scarcity where, for example, the price varies inversely with storage levels. In July the National Water Commission (2008) released a position statement recommending that scarcity pricing receive further consideration as an alternative approach to urban water demand management.
- Scarcity pricing is a potentiality more efficient demand management tool than water restrictions. With any scarcity pricing system it would be necessary to ensure that any equity considerations were adequately addressed, such as the need to ensure essential water supply remains affordable for all households. One way to achieve this could be to adopt a two-block price scheme, where a low (or zero) constant price would apply to the first block of consumption and a variable scarcity price would apply to consumption above this level.
- Scarcity pricing could also assist in supply augmentation decisions. Historically, urban water utilities have made relatively arbitrary judgments on the timing of supply augmentation, often involving the targeting of an 'acceptable level' of reliability as measured by the expected duration of water restrictions. Scarcity pricing would provide a more accurate measure of society's willingness to pay for urban water, which could be directly compared with the costs of supply augmentation.

Issues in implementing scarcity pricing

- There are a number of practical considerations associated with adopting a scarcity pricing system that would need to be addressed. For example, there would be a need to maintain some form of regulatory effort to prevent abuse of monopoly power by urban water utilities. There may also be a need to improve current water metering practices and technologies.
- Urban water utilities may also face an information problem when administratively setting prices. For example, utilities have incomplete information on the distribution of future inflows and the community's willingness to pay for urban water. However, this information problem is not necessarily more burdensome than that faced under a system of water restrictions. Further, the use of scarcity pricing may, over time, reveal more information, particularly on consumers' willingness to pay.

- One approach to setting scarcity prices would be to adopt a system of price stages similar to that used for water restrictions. A number of price stages could be defined, with each stage aiming to achieve a specific reduction in water consumption and having an associated trigger point.

Modelling urban water policy under climate variability

- One of the main difficulties in designing urban water policy, particularly in Australia, is the extreme variability of rainfall and dam inflows. This report considers the design of optimal demand management and supply augmentation policies under climate variability, by constructing and applying a stochastic dynamic model of an urban water market. This model is used to demonstrate how a scarcity pricing system would operate and to evaluate the basic factors governing the optimal timing of supply augmentation investment.
- A stochastic dynamic programming model of an urban water market was constructed using data on urban water supply and demand in the Australian Capital Territory. The model estimates optimal price and investment policy functions, given a theoretical probability distribution over future dam inflows.
- The model results demonstrate 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 examined. Substantial differences were observed between the estimated optimal investment rules of rain-dependent and rain-independent augmentation options. The higher costs and the certain inflows associated with rain-independent augmentation may mean that water utilities are likely to adopt an opportunistic approach: where investment is delayed until substantial decline in storage levels occurs.

Conclusions

- Urban water restrictions impose significant costs on consumers in the form of allocative efficiency costs and inconvenience costs. Scarcity pricing is an alternative to water restrictions which could potentially avoid many of the costs of water restrictions. This report provides a detailed qualitative discussion of the various benefits and costs of adopting scarcity pricing.

- The main focus of this report has been to consider how a scarcity pricing system could potentially operate. This has involved economic modelling to demonstrate how an urban water scarcity price would typically vary, given a specific set of assumptions, over time and in response to changes in storage levels. This also involved considering a range of practical implementation issues, including the possibility that scarcity pricing could be implemented using a system of stages similar to that used for water restrictions.
- 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 that warrants further consideration.

1 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 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 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 has received significant research attention in recent times, see for example: The Productivity commission (2008), Grafton and Kompas (2007), Sibley (2006) and Frontier Economics (2008). In July the National Water Commission (2008) released a position statement recommending that scarcity pricing receive further consideration as an alternative approach to urban water demand management.

One of the main difficulties in designing urban water policy, particularly in Australia, is the extreme variability of rainfall and dam inflows. This report 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 demonstrate how a scarcity pricing system would operate and to evaluate the basic factors governing the optimal timing of supply augmentation investment.

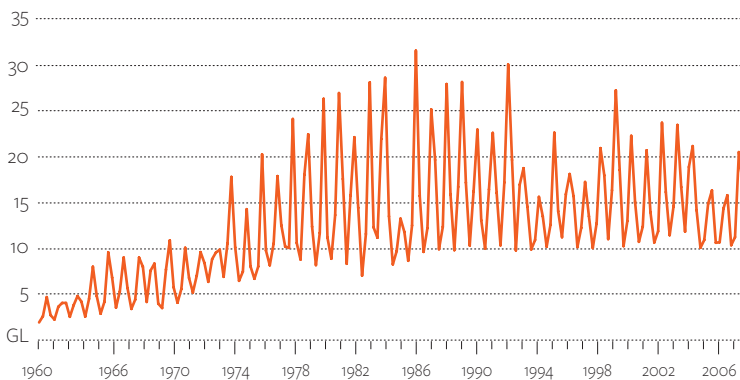
Background information on the demand and supply of urban water in Australia is outlined in chapter 2. Current Australian urban water policy and the potential for reform are outlined in chapter 3. An illustrative model of an urban water market is described in chapter 4 and a discussion of the modelling results is contained in chapter 5. Conclusions are outlined in chapter 6.

2 Urban water in Australia

Demand for urban water

Householders are the primary consumers of urban water. The Water Services Association of Australia (2005) estimates households accounted for approximately 62 per cent of total urban water use in 2000–01. Figure a displays urban water consumption in the ACT since 1960. ACT water consumption displayed strong growth during the 1960s and 1970s before peaking in the early 1990s. Urban water consumption is highly seasonal, with demand highest in summer and lowest in winter.

a Quarterly ACT water consumption
winter 1960 to winter 2007



Source: Actew, personal communication, 2006.

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). The responsiveness of urban water demand to changes in price has been the focus of a substantive volume of economic literature. While estimates of price responsiveness vary substantially, a number of recent Australian studies have found that demand is relatively responsive to changes in price (see box 1).

box 1 The price elasticity of urban water demand

The responsiveness of demand to changes in price can be measured in terms of price elasticity. The price elasticity of demand refers to the percentage change in the quantity demanded of a good in response to a given percentage change in price. Econometric techniques are commonly used to estimate price elasticities based on historical data on quantities and prices. A large number of econometric studies have attempted to estimate the price elasticity of urban water demand both in Australia and overseas. A wide range of elasticity values has been estimated, generally from 0 to -1, where an elasticity of -1 means that a 10 per cent increase in price results in a 10 per cent reduction in demand. As noted by the Productivity Commission (2008), a large amount of the variation among different studies can be explained by differences in study methodologies.

Dalhuisen et al. (2003) present a comprehensive meta-analysis of 64 US econometric studies, estimating a mean price elasticity of -0.41. A study by Graham and Scott (1997) estimated the price elasticity of residential water demand in the ACT region to be in the range of -0.15 to -0.39. Grafton and Kompas (2007) estimated the price elasticity for urban water in Sydney to be -0.35. Hoffman et al. (2006) conducted a panel data study (data across multiple regions and over time) of urban water demand in Brisbane and estimated a contemporaneous price elasticity of between -0.67 and -0.55. Another panel data study, by Xayavong et al. (2008) for Perth, estimated an indoor elasticity of between -0.70 and -0.94, and an outdoor elasticity of between -1.30 and -1.45.

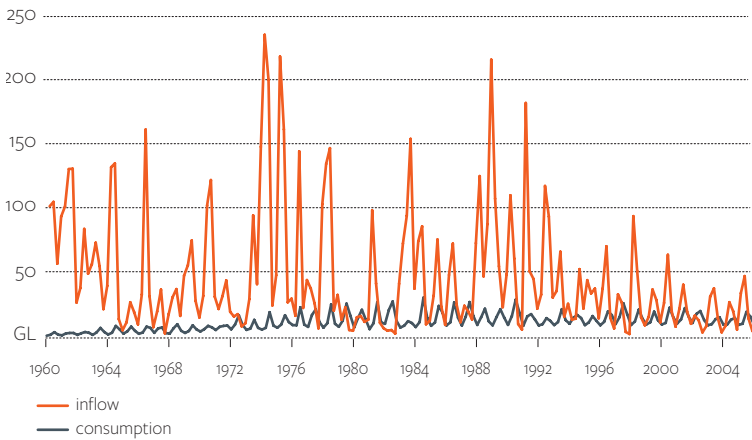
Supply of urban water

In Australia the majority of water supplied to urban consumers is captured in large surface water storages, which are reliant on catchment rainfall and runoff. Australian urban water storages are large by international standards as a result of the relatively high variability of rainfall. Figure b shows storage inflows and demand in the ACT since 1960; inflows display extreme variability relative to demand.

Figure c displays ACT total storage capacity and actual storage volumes since the 1960s. Increases in storage represent the construction of new dams. Traditionally, growth in Australian water demand has been met by the periodic construction of new dams. Until recently, much of urban Australia had received very little in the way of new water supply infrastructure for several decades. Currently, substantial investment in supply augmentation is occurring in most capital cities.

In most capital cities, a lack of suitable sites and concern over adverse environmental impacts has reduced the attractiveness of investment in new dams. The potential for climate change to result in a reduction in future

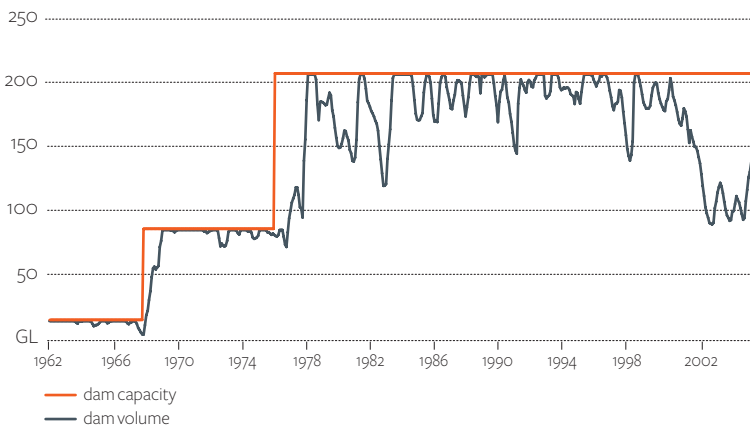
b Quarterly ACT water storage inflows and consumption
1960 to 2006



Source: Actew, personal communication, 2006.

rainfall and runoff has raised further concern over the effectiveness of 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^{*}). However, both options involve substantially higher capital and operating costs.

c Monthly ACT total storage capacity and actual storage level
1960 to 2006



Source: Actew, personal communication, 2006.

* Water recycling may have some limited exposure to rainfall variability, as waste water is supplemented by stormwater inflows and infiltration.

Although not the focus of this report, another option for sourcing urban water is to acquire it through trade with rural water holders. This depends, of course, on the existence of a physical connection between rural and urban water systems, which in some cities would require investment in pipe and pumping infrastructure. CSIRO and the Centre of Policy Studies (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 is considered by Page and Hafi (2007).

3 Urban water policy

Urban water is typically provided by a monopoly supplier. An unregulated monopoly supplier of urban water would have an incentive to increase prices to excessive levels, resulting in an inefficient allocation of water. In Australia, urban water is typically supplied by government owned and/or operated organisations, subject to independent regulation including price control.

In this report it is assumed that the combination of government ownership and regulation effectively ensures monopoly water utilities act in the public interest. Competition in the provision of urban water is not considered in this report. For a discussion of the potential for competition in urban water provision, see Productivity Commission (2008).

In pursuing the public interest, the urban water utility seeks to maximise the net benefits of water use in the long run, subject to water availability constraints. In achieving this objective, the water utility has two main policy tools: demand management and supply augmentation. Demand management is a term used to encompass a range of policies designed to restrict or reduce water use in times of scarcity. Given the regulatory control over urban water prices, water utilities 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. Supply augmentation policy is concerned with the nature and timing of additions to water supply infrastructure. In this report 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, the water utilities' primary response to low inflow (drought) conditions is to limit water use through demand management measures (for example, water restrictions). Such short-term rationing of demand may be optimal in an intertemporal context — that is, if we use less water today we will have more water for future periods.

In the long run, supply infrastructure can be altered and demand management policy and supply augmentation policy are simultaneously

determined. This involves a trade-off between the consumer benefits associated with non-essential water consumption and the costs of supply augmentation. In Australia, urban water utilities accept that ‘gold plating’ supply infrastructure (so that all demand for urban water can be met at all times) would be unnecessarily costly. The optimal long-run demand management policy (for example, the long-run mean frequency of restrictions or the mean price level) will maintain the ideal balance between the benefits of non-essential 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 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 an economic welfare perspective, a scarcity price yielding the same reduction in consumption would be preferable, as it would involve a transfer of rent to the utility/government rather than imposing irrecoverable time and inconvenience costs. A scarcity price would, however, result in some distributional changes. For example, it would tend to benefit consumers who valued their time more highly.

Water restrictions in their more severe forms involve complete bans on outdoor water uses. Where the willingness to pay for water varies across individuals, prescriptive rationing will result in an inefficient allocation of resources where water is not necessarily directed to its most valued uses. In contrast, price-based rationing ensures that water use is directed to its highest value uses and that the marginal value of water use is equalised across households and across different water uses within households.

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 which override private

* McIntyre et al. (2003) note that the Australian Capital Territory Government has received complaints from elderly customers regarding the physical effects of hand watering during early morning or late evening times, particularly during winter.

valuations (Edwards 2006). For example, water restrictions are limited to outdoor residential water use (for reasons of enforcement) and do not directly limit indoor 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 which is not attempted in this report. A number of studies have been undertaken to estimate the costs of restrictions using varying techniques, including Hensher et al. (2006), Brennan et al. (2007) and Grafton and Ward (2007).

Other demand management measures

Water utilities also employ a range of other non-price-based policies aimed at reducing the long-term consumption of urban water, including advertising campaigns and subsidies for water saving equipment. Advertising campaigns typically involve advertising across various mediums promoting water conservation and providing advice on how to improve water use efficiency. Such campaigns can be costly while their actual impact on water consumption is difficult to measure.

Government subsidies are also commonly offered for a range of water-saving products, including residential rainwater tanks. One of the problems with government subsidies for water-saving devices is that they may induce over-investment in products which 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.

Ideally, water conservation efforts and investments in water use efficiency should be motivated by water prices which accurately reflect scarcity. Under these conditions, subsidies or publicly funded advertising campaigns would not be required.

Current pricing regime

In Australia urban water pricing is regulated by state and territory government agencies. These agencies make price determinations specifying water charges over three to five year time frames. 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. Here the SRMC refers exclusively to the direct marginal costs associated with transferring water from storages to households for consumption, such as the costs of water pumping and treatment.

In the presence of demand growth, scarcity and capacity constraints become inevitable in the long run. Australian water utility price regulators generally advocate some form of long-run marginal cost (LRMC) pricing. For more details on the various definitions and methods of estimating LRMC see Sibley (2006) or Productivity Commission (2008). A fixed LRMC price does not explicitly consider the variability of 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 storages 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. For example, in the ACT in 2007–08 a fixed annual supply charge of \$75 applied for each parcel of land. In this paper we focus the marginal price of water rather than the average price. The impact of different price and investment policies on revenue and cost recovery is not considered in detail in this paper.

In the ACT, as in most capital cities, an inclining block pricing scheme applies to urban water consumption. In 2007–08 a three-block pricing structure applied, involving a price of \$0.75 a kilolitre for the first 100 kilolitres, \$1.67 between 100 and 300 kilolitres and \$2.57 for consumption over 300 kilolitres. Inclining block pricing schemes are economically inefficient relative to a single uniform price (Edwards 2006; Brennan 2006).

Scarcity pricing

The scarcity price is the price which 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 will be state-dependent, meaning it will vary depending on the prevailing conditions. For example, a scarcity price would vary inversely with storage levels. Put simply, when water is scarce the price of water is higher; as water storages fill (water becomes less scarce), price falls. A scarcity pricing system represents an alternative approach to demand management policy, which could potentially avoid many of the efficiency costs associated with water restrictions.

The adoption of scarcity pricing of urban water is sometimes opposed on the grounds of equity. However, equity concerns can be adequately addressed through any number of policy measures. For example, this could involve targeted subsidies to low-income households. Additionally, a two-block price scheme could be adopted to ensure essential water is provided at all times at an affordable cost to all households.

Under a two-block price scheme a low (or zero) constant price would apply to the first block of consumption to cover essential water needs, while a variable scarcity price would apply to consumption above this level. A two-block price scheme would involve some loss of efficiency, but it would represent a substantial improvement over a three-block system (such as that imposed in the ACT) (Edwards 2006). Ideally, the threshold between the two pricing blocks would ensure all non-essential water demand would be exposed to the scarcity price. In practice, setting the threshold point would involve a trade-off 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.

It is also worth noting urban water charges represent a relatively small proportion of household expenditure. ABS (2006) statistics show water and sewerage charges represent only 0.7 per cent of average weekly household expenditure in Australia, and the Organisation for Economic Cooperation and Development (1999) has demonstrated that Australia has relatively affordable water charges in comparison with other OECD countries. Finally, as noted by the Productivity Commission (2008), water restrictions are not devoid of their own equity concerns.

An alternative to scarcity pricing of urban water would be a system of tradable water entitlements. However, such a system would be subject to substantial administration costs and transaction costs. This approach is not considered in this report.

Practical considerations

A number of important practical considerations need to be considered before a scarcity-based pricing system could be implemented. Firstly, a scarcity pricing system would require a relaxation of current water price regulation. Regulators could, however, continue to monitor total water utility revenue and profits in order to avoid misuse of monopoly power. Ideally, a regulator would influence the setting of the annual access charge or the price applying to the initial consumption block while allowing the scarcity price to be set appropriately by the water utility. The regulator may, for example, reduce annual access charges to offset the impact of increases in variable charges.

Scarcity pricing could potentially be implemented using a system of stages similar to that used for water restrictions (see table 1). A number of price stages could be defined, each corresponding 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. The water utility could simply replace each stage of restrictions with a scarcity price, based on its estimate of what price will achieve an equivalent reduction in consumption.

In reality, the water utility may not have full information on the exact distribution of future inflows, the long-run growth rate of demand and the price elasticity of the demand for water. This means setting optimal prices would not be a simple 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 require much 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 is more flexibility regarding 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. The adoption of a scarcity pricing system would not increase the risk faced by urban water consumers; it would merely replace existing restriction risk with price risk.

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 (personal communication, David Graham, 15 May 2007) it is currently not possible to read all meters on the same day, so 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 recently endorsed a pilot smart metering project (Actew 2007). Any scarcity pricing system would also require all households to be made aware of any changes in price as they occur. This may require some form of advertising, as with water restrictions at present.

Scarcity pricing may not be practical in an extreme water scarcity situation, where it may be necessary to reduce water consumption to essential levels. Particularly where a two-block pricing scheme is adopted, it may simply not be possible to limit all non-essential water consumption for all users. It

1 ACT water restriction storage level triggers and target annual reductions in water consumption

	stage 1	stage 2	stage 3	stage 4	stage 5
	%	%	%	%	%
Storage volume trigger	55	45	40	35	30
Target annual reduction	15	25	40	55	60

Source: Actew (2004).

may be necessary in such an emergency situation to revert to prescriptive restrictions. It may therefore be advisable to retain water restrictions in some form as a backup option, to be used only in worst case situations.

Supply augmentation

This report focuses specifically on the timing of supply augmentation investment under climate variability and not on making comparisons between specific supply projects. Decisions between alternative supply augmentation projects should be guided by comprehensive cost–benefit analyses that 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 with the expected net benefits of delaying investment. Such decisions are complicated by the substantial variability in the demand for water and, more importantly, in 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, 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. Urban water utilities typically maintain supply infrastructure so as to ensure that the probability of such a system failure is 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 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 consumers’ preferences (Hensher, Shore and Train 2006)*. One of the reasons for this is 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. Scarcity pricing may assist water utilities to make supply augmentation decisions, as it would provide a more accurate measure of society’s willingness to pay for urban water, which could be directly compared with the costs of supply augmentation.

* In recent years, though, ACTEW has incorporated in its modelling estimates of willingness to pay derived from stated choice experiments (Hensher et al. 2006).

Environmental flows

An additional aspect of urban water policy not considered in detail in this report 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 systems. The ACT government (2006) maintains guidelines outlining 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 is a clear trade-off 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 which 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).

4 The model

This chapter contains a brief description of an economic model of urban water supply and demand. A more detailed discussion of the model is contained in appendix A.

The model is a single region model of the water market in an urban centre. The model is a stochastic dynamic programming model, which estimates the optimal pricing and investment policies of the water utility.

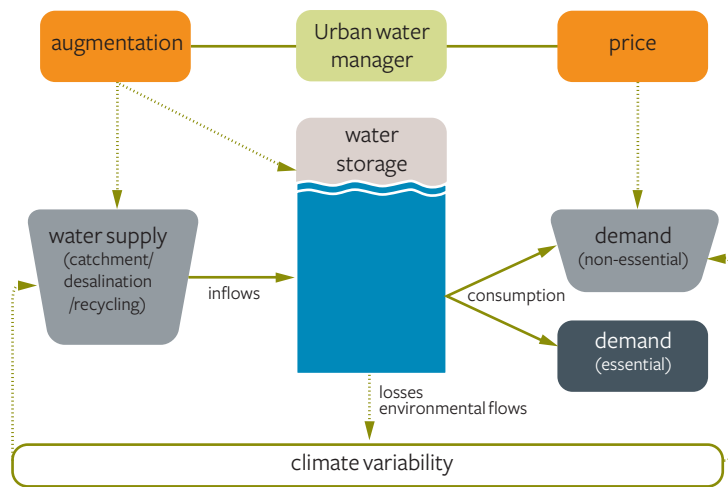
The model is based on the ACT region and incorporates data on the demand and supply of urban water in the region, provided by the Actew Corporation. An attempt has been made to incorporate a degree of realism into the model. However, a number of simplifying assumptions are made, particularly on the supply side of the model, in order to keep the level of hydrological and engineering detail to a minimum. The model is not designed to forecast or estimate the likely impacts 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 climate variability.

Figure d summarises the main features of the model. The model estimates the price and investment policy rules that maximise the expected discounted value of economic welfare over a predetermined time horizon. In this instance, economic welfare refers primarily to the expected discounted sum of consumer surplus from non-essential water consumption less the costs of supply augmentation, less penalties imposed for any inability to meet essential demand. The model comprises two main components, one specifying the evolution of water demand and the other specifying water supply.

The demand component involves an aggregate urban water consumption function which accounts for long-term growth of demand, seasonal variation, response to stochastic climate variability and response to price changes. The seasonal variation of demand and the response of demand to climate variability are estimated econometrically. Inflows were used as a proxy for prevailing weather conditions (such as rainfall and temperature), as this allows the model to have a single source of risk. Demand is separated into a non-essential or price-responsive portion and an essential portion unresponsive to price. 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.

The supply component of the model assumes a single water storage with stochastic seasonal inflows. A single storage model can be interpreted as an approximation of a multiple reservoir system. Seasonal inflow probability distributions were estimated using historical ACT data. The supply side of the model also accounts for evaporation from storages and environmental flow

d Conceptual diagram of the Urban Water Model



The supply side of the model also accounts for the impact of supply augmentation on total water storage capacity and inflow levels. The model allows for two forms of supply augmentation: rain-dependent (representative of new dams) and rain independent (representative of desalination or recycling). Rain-dependent augmentation is modelled as providing additional storage capacity and additional stochastic inflows. Rain-independent augmentation is modelled as providing additional certain inflows but no additional storage capacity.

Finally 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. An arbitrary value of \$1 per kilolitre (kL) is assumed for the SRMC.

5 Results

It is important to note the quantitative results generated by the model (such as the realised price levels and the timing of supply augmentation) are a function of model assumptions and are not intended to be interpreted in any way as predictions or forecasts. A sensitivity analysis contained in appendix B demonstrates how the results change when certain parameter assumptions are altered.

Two scenarios are evaluated with the model: a rain-dependent augmentation scenario and a rain-independent augmentation scenario. This approach was necessary because of the ‘curse of dimensionality’ problem, which meant the inclusion of multiple investment projects would make the problem unfeasibly large. These scenarios are intended to be illustrative and are not meant to represent forecasts of specific ACT circumstances. The model time scale is seasonal (quarterly) and each scenario is run over an arbitrary 25-year time horizon, notionally the period 2000 to 2025.

Scenarios involving a single augmentation option will tend to overstate the extent of water scarcity relative to the case of multiple investment projects. This is because 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 parameters set out in table 2.

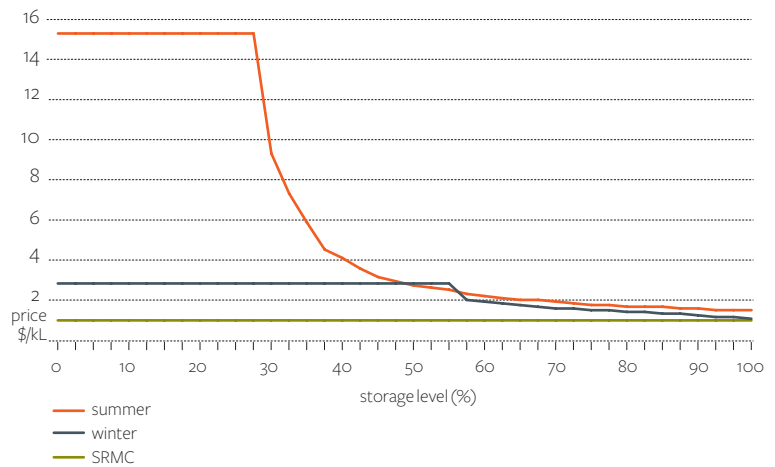
The estimated price policy function specifies the optimal price given the time period, the prevailing storage level and the state of supply augmentation (that is, pre augmentation, during augmentation, or post augmentation). Figure e shows the estimated pre augmentation price policy function for an arbitrary time period (2015). 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, the price approaches, but does not necessarily reach, the SRMC. The optimal price is seasonal: 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 non-essential

2 Rain-dependent augmentation option parameters

Capital cost	\$100 million
Ongoing cost	\$1.5 million a year
Proportional increase in mean inflow	0.20
Additional storage capacity	70 000 ML
Lead time	2 years

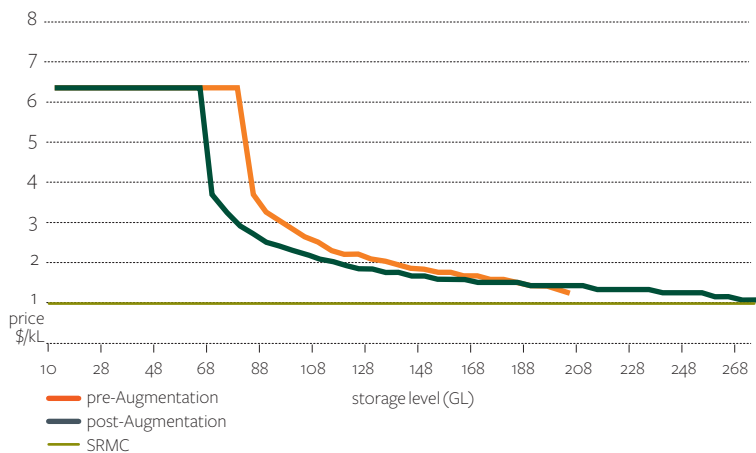
e Price policy function, pre-augmentation
summer and winter 2015



demand is reduced to zero. This maximum price is dependent on the season, being highest in summer and lowest in winter. As discussed earlier, it may not be practical to use scarcity pricing in emergency situations where it is necessary to reduce consumption to essential levels. These maximum prices should therefore be interpreted more as shadow prices, representative of high-level water restrictions. In any event the probability of such prices being realised in the model is extremely low, see for example figure i.

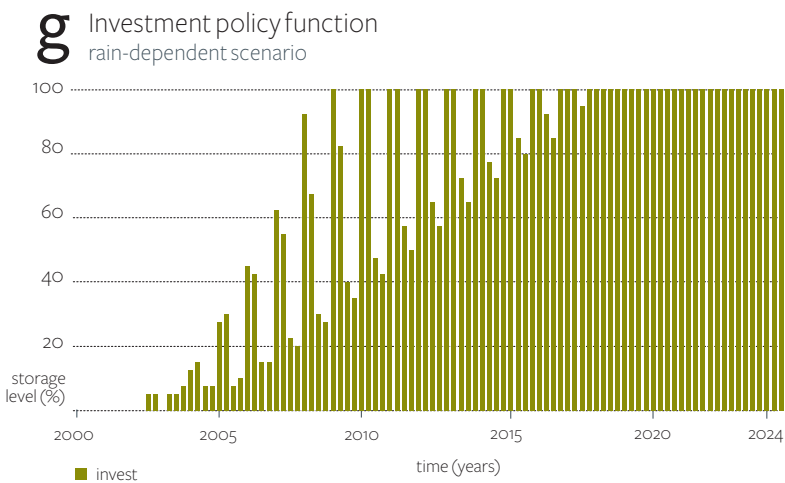
The estimated optimal price is (for a given storage level and augmentation status) increasing in time as a result of demand growth. The optimal price is also (for a given time and storage level) lower post the completion of an augmentation project. Figure f shows the price policy function (pre and post augmentation for the time period spring 2015).

f Price policy function, pre and post-augmentation,
rain-dependent scenario, spring 2015



When interpreting figure f, note the initial storage capacity of 200 gigalitres increases to 270 gigalitres following augmentation. The estimated prices are briefly lower pre augmentation, at around 200 gigalitres, given the higher probability of spills at this storage level.

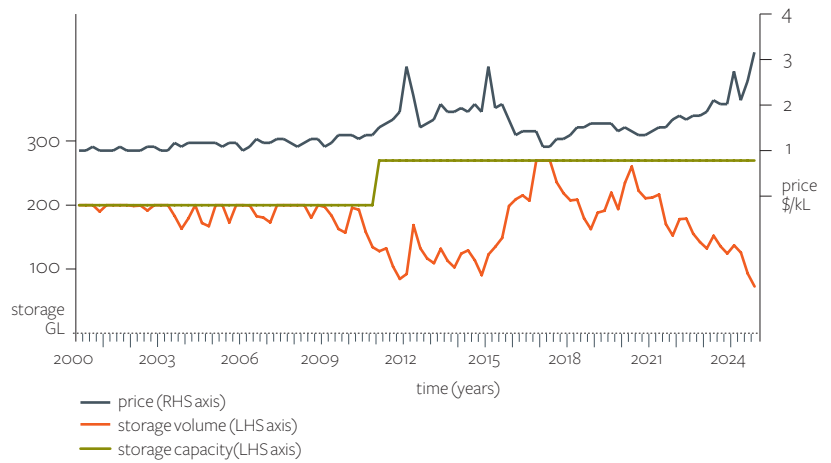
Figure g shows the estimated investment policy rule as a function of time and the prevailing storage level. For each point in time the investment rule defines a storage trigger point: for storage levels below this point the investment is executed. Over time the storage trigger point increases because of demand growth. The investment rule also displays strong seasonality. The storage trigger point peaks in winter when the project (new dam) will come on line, 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.



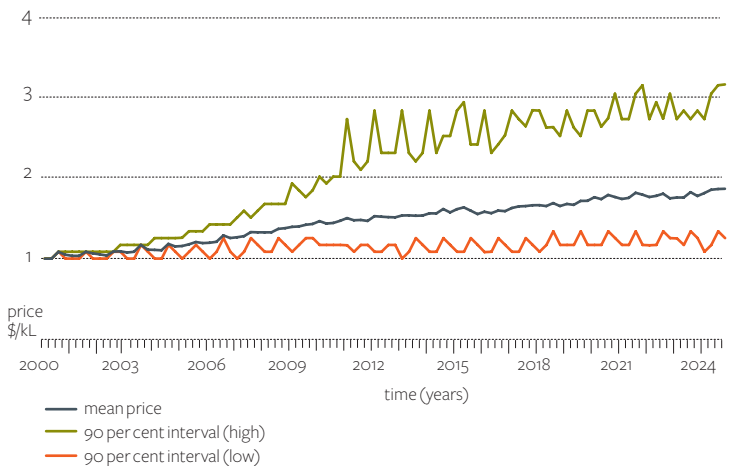
Given the estimated policy functions, model simulations can be generated by drawing a series of inflow observations from the defined probability distributions. A Monte Carlo analysis can be performed by generating a large number of such simulations and combining the results. Figure h displays an example of a single stochastic simulation. In figure h the increase in storage capacity represents the supply augmentation project (new dam) coming online. The timing of investment varies across simulations depending on the realised conditions (the stochastically generated inflows). The mean year of investment is 2008. Variability in the timing of investment for rain-dependent augmentation is relatively low compared with that of rain-independent augmentation (discussed in the next section).

Figure i shows the mean price level and 90 per cent confidence interval estimated by Monte Carlo analysis. The mean price level is increasing in time because of demand growth. The growth in the mean price level slows around the time of supply augmentation. Figure i also shows how the variability in price increases with the mean level of scarcity (mean price level).

h Example stochastic simulation
rain-dependent scenario



i Mean price level with 90 per cent confidence interval
rain-dependent scenario



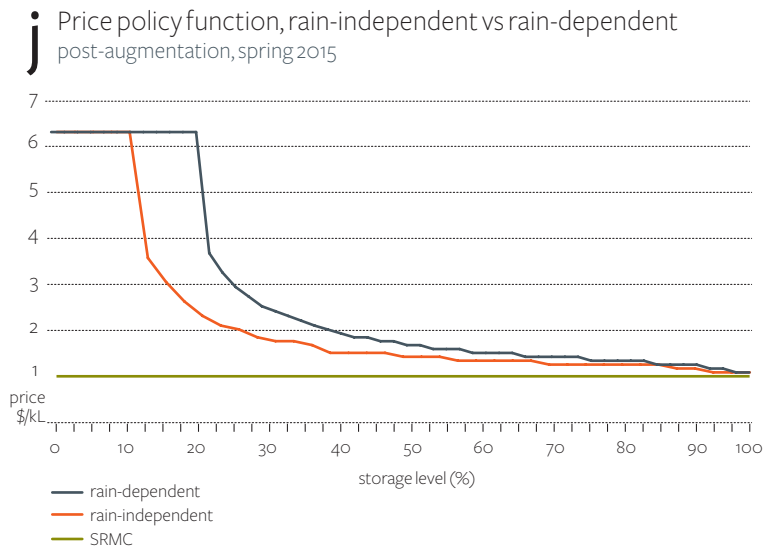
3 Rain-independent augmentation option

Capital cost	\$200 million
Ongoing cost	\$10 million a year
Additional inflow	6000 ML a season
Additional storage capacity	0
Lead time	2 years

Rain-independent scenario

The rain-independent scenario assumes a rain-independent augmentation project as defined by the parameters set out in table 3. 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.

The estimated pre-augmentation price policy function for the rain-independent scenario, is essentially identical to that estimated for the rain-dependent scenario. However, post augmentation the estimated optimal prices are lower in the rain-independent scenario (see figure j).



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. It should be noted that the estimated prices in figure j do not 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 k. The storage trigger points remain lower than in the rain-dependent scenario, 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 until storage levels decline substantially. There are two reasons for this. Firstly, rain-independent augmentation is more expensive and therefore there is more to be gained by delaying its introduction. Secondly, 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 project will provide inflows sufficient to improve storage levels and ensure 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, when the project will come on line in time for the critical summer period in exactly two years time.

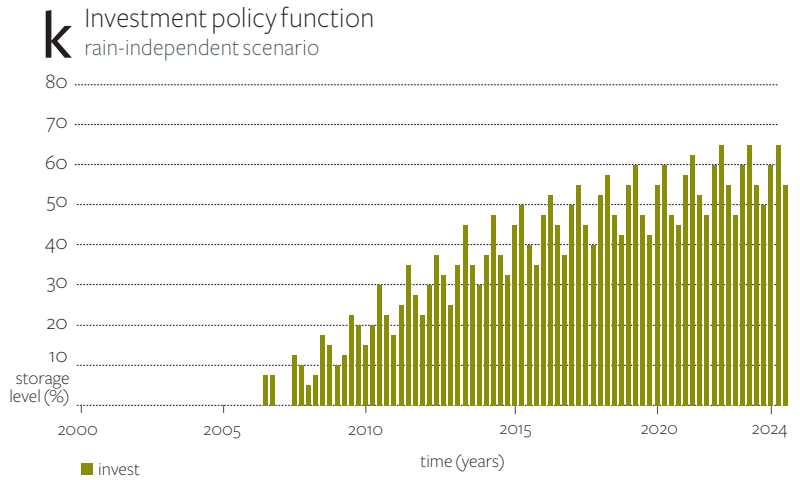


Figure l displays a single-example simulation for the rain-independent scenario, showing the realised price and storage levels as well as the augmentation time. In the rain-independent scenario simulations, a substantial drop in the price level is often observed following the introduction of the augmentation project.

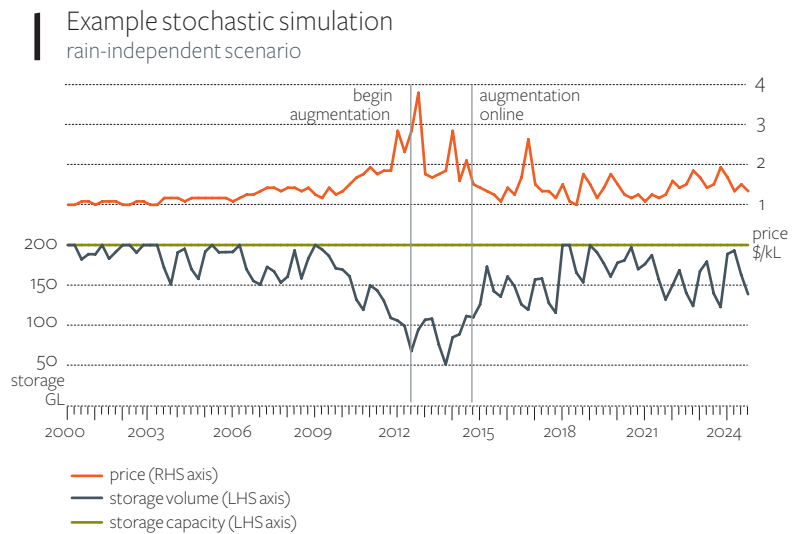
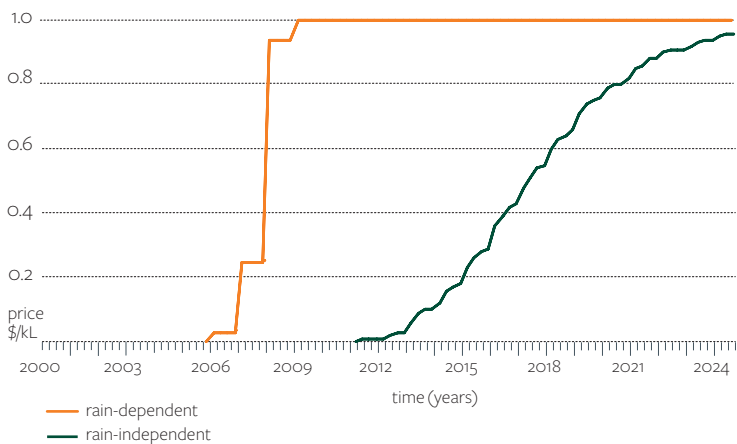


Figure m shows the cumulative probability distribution over investment timing for rain-dependent and rain-independent augmentation. Rain-dependent augmentation occurs earlier on average (2008 compared with 2018) and is less variable. The timing of rain-independent augmentation is highly variable, being strongly dependent on realised inflow levels. For

example, there remains a positive probability 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 investment in rain-independent supply in the face of significant inflow risk, consistent with a real-options approach to irreversible investment under uncertainty. A real-options approach to water infrastructure investment has previously been advocated by Acil Tasman (2007). While not modelled here, 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.

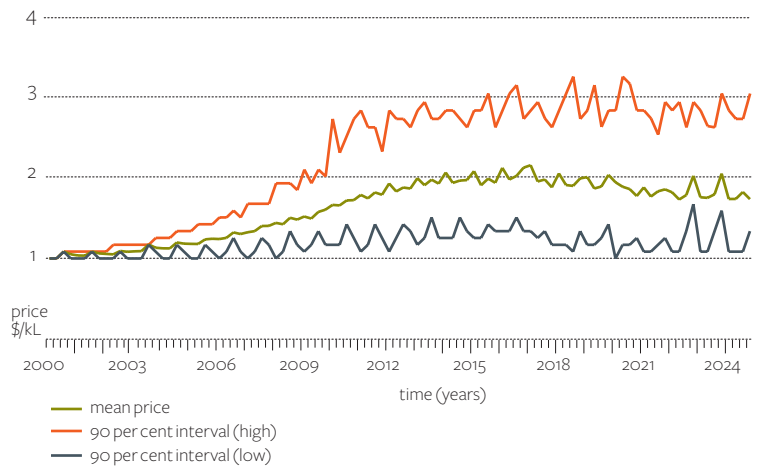
m Cumulative probability distribution of investment timing



The results are also to some extent consistent with the behaviour of Australian water utilities in that demand management and other supply alternatives have generally been pursued prior to rain-independent augmentation. For example, the NSW Government did at one point have a stated policy that investment in desalination would occur only if storage levels dropped below 30 per cent (NSW Government 2006). However, in recent times most capital cities (including Sydney) have subsequently approved investments in rain-independent supply, although this has not been without controversy (see for example Brennan 2008).

Figure n displays the mean price for the rain-independent scenario. In this scenario the mean price rises quickly at first, given that augmentation is occurring later than in the rain-dependent scenario. The mean price falls gradually after year 17 as the probability of augmentation increases.

n Mean price level with 90 per cent confidence interval rain-independent scenario



A sensitivity analysis over a number of model parameters was also conducted (the details are contained in Appendix B). One of the key results of this analysis is that investment in rain-independent supply is highly marginal, as small increases in the costs (capital or operating) 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.

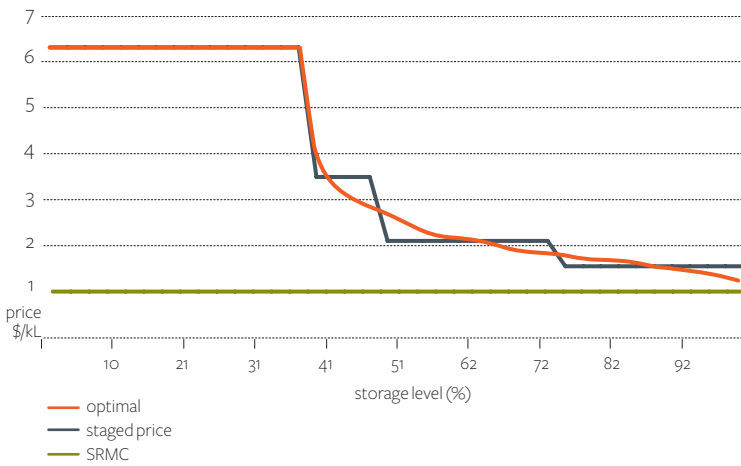
‘Staged’ scarcity pricing

As discussed earlier, 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. These limited price point simulations should not be interpreted as an implicit representation of water restrictions. 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 mean welfare, as measured by the objective value in the model. However, this reduction is relatively small (–0.4 per cent for the 12-point grid and –1.8 per cent for the 6-point grid). An example of a staged price policy function is shown in figure o.

A staged scarcity pricing system could be implemented under a similar framework to that used for water restrictions at present, in terms of the number of stages, the storage trigger points and the quantity targets (see,

for example, table 1). The only real difference is that price is used to achieve the quantity targets rather than water restrictions. A staged scarcity pricing system would be simpler for the utility to implement than a fully flexible price, significantly reducing the frequency of price changes required.

O Limited price grid, price policy function
rain-dependent, spring 2015, pre-augmentation



6 Conclusion

In Australia the predominant approach to demand management in urban water is the imposition of water restrictions. Water restrictions are a relatively limited and inefficient method of rationing demand, imposing inconvenience costs and allocative efficiency costs and also involving significant enforcement costs. In this report 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: when storage levels were lower, prices would be higher. Scarcity pricing could be implemented under a two-block price scheme that ensured essential water consumption remained affordable at all times. Scarcity pricing may also assist water utilities to make supply augmentation decisions, as it would provide a more accurate measure of society's willingness to pay for urban water, which could be directly compared with the costs of supply augmentation.

A number of practical considerations associated with adopting a scarcity pricing system would need to be addressed. For example, there would be a need to maintain some form of regulatory effort to prevent abuse of monopoly power. There may also be a need to improve current water metering practices and technologies. One way to implement scarcity pricing could be to adopt a system of stages similar to that used for water restrictions. A number of price stages could be defined, each corresponding to a different level of scarcity and each aiming to achieve a specific reduction in water consumption and having an associated trigger point.

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 optimal price and investment policy functions, 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 model results illustrated that a staged price system would result in a minimal loss of efficiency relative to a more flexible price system.

The nature of optimal investment policy, involving the execution of investments once storage levels decline below specific storage trigger points, was also examined. 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 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 to improve the efficiency of demand management and supply augmentation policies. Scarcity pricing is one approach that warrants further consideration.

appendix **A** The model in detail

The model in context

The urban water model is formulated as a stochastic dynamic programming problem. 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, 1971b), 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 to 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.

The demand for urban water

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 of demand to weather variability are estimated econometrically. A simple explanatory equation for urban water consumption was estimated based on quarterly ACT data over the period 1960 to 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

4 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
<i>Standard error</i>	0.0248	
<i>Adjusted R squared</i>	0.91	

used as a proxy for prevailing weather conditions (such as rainfall and temperature), as this allows the model to have a single source of risk.

In the model demand is projected over an arbitrary 25-year time horizon, notionally the period 2000 to 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. The modelled growth rate is, however, broadly in line with the ‘high growth’ scenarios developed by Actew (2004). Equation 1 specifies the evolution of demand for water over time given a fixed short-run marginal cost price.

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

Where:

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

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 which is essential and hence 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.

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

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

Where:

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

The supply of urban water

For the supply side of the model it is assumed there is a single storage with stochastic inflows. No attempt has been made to incorporate multiple connected storages, distribution networks or water treatment services. In reality the ACT maintains three (soon to be four) major water storages. However a single storage model can be interpreted as an approximation of a multiple reservoir system. Perera and Codner (1988) demonstrate the use of a single storage model as a way of limiting the complexity of multiple storages and minimising 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 to 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 5.

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.

$$\text{Equation 3} \quad S_t = S_{t-1} + TotIN_t - E_t - Q_t$$

5 Log normal inflow distribution parameters

	mean inflows (ML)	m	s
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

Where:

- S_t = the storage level
- $TotIn_t$ = total inflows (dependent on supply augmentation)
- E_t = total storage losses (dependent on supply augmentation)
- K_t = total storage capacity (dependent on supply augmentation)
- S_{MIN} = 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. In the model rain-dependent augmentation implicitly assumes that a new dam generates additional inflows by capturing water from a stream/catchment that was previously not captured. This is again a simplifying assumption: in an interregional context new dams (and even extensions to existing dams) may involve capturing water that would otherwise be captured (at least partially) by other dams or water users downstream.

For simplicity the model assumes a single storage, to maintain this assumption rain dependent augmentation (i.e. a new dam) is modelled as an increase in storage capacity and inflows into the representative single storage. As noted above a single storage model can be interpreted as an approximate representation of a multiple storage system. For simplicity it is also 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.

$$\text{Equation 4} \quad TotIN_{t,s} = (1-ef) \left(IN_s + \sum_{i=1}^I \mathbf{\hat{A}}_{t-LT_i,i} (\mathbf{f}_i / IN_s) \right) + \sum_{i=1}^I \mathbf{\hat{A}}_{t-LT,i} nrin_i$$

$$\text{Equation 5} \quad K_t = k_o + \sum_{i=1}^I \mathbf{\hat{A}}_{t-LT_i,i} ik_i$$

Where:

- $I_{t,i}$ = 1 for all $t > T$ where T is the time of execution for investment i (and 0 otherwise)
- ef = the proportion of inflows released to the environment
- $nrin_i$ = fixed non rain-dependent inflows of investment i (ML)
- \mathbf{f}_i = proportional increase in rain-dependent inflow for investment i
- ik_i = additional storage capacity of investment i (ML)
- LT_i = 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. An arbitrary 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 (consumer and producer) 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.

$$\text{Equation 6} \quad E \left(\sum_{t=0}^T \mathbf{b}^t (MS_t(Q_t, Q_t^{min}) - TC_t - PENALTY_t) \right)$$

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

Where:

MS_t = the market surplus (consumer and producer)

Q_t^{min} = the level of essential water demand at time t

TC_t = the 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

\mathbf{b} = is the 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 continuous 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.

appendix **B** Sensitivity analysis

This appendix displays results of a sensitivity analysis of key model parameters. Sensitivity analyses were performed for four parameters: augmentation capital cost c , demand price responsiveness (**a**), net inflows (environmental flows — ef) and the penalty for failure to meet essential demand (*PENALTY*). Each sensitivity analysis involves solving the model and running Monte Carlo simulations for each of a range of parameter values, bracketing the base case value. The results of these simulations are summarised by calculating the mean (over the entire simulation period) of key variables such as: the price, the timing of investment and the volume of water consumption. The mean discounted value of the objective function is also reported.

Capital cost

Results of a sensitivity analysis on augmentation capital cost are shown in table 6 and table 7. Increasing the capital cost of augmentation results in an increase in the mean investment time for both rain-dependent and rain-independent scenarios. In the rain-independent scenario, increasing the cost of investment also reduces the probability of investment occurring within the 25-year simulation period. As would be expected with a delaying of supply augmentation, an increase in mean price and a reduction in mean consumption are observed in both scenarios.

6 Sensitivity analysis: augmentation capital cost

rain-independent scenario

Investment cost (\$ million)	120 (-40.0)	160 (-20.0)	200 (0)	240 (20.0)	280 (40.0)
Probability of investment occurring in simulation	1.00 (3.1)	0.99 (2.5)	0.97 (0)	0.90 (-7.6)	0.72 (-26.0)
Mean investment time t	15.3 (-13.7)	16.5 (-6.4)	17.7 (0)	18.6 (5.2)	19.6 (10.8)
Mean discounted objective value (\$ million)	1,316 (1.9)	1,303 (0.9)	1,290 (0)	1,283 (-0.7)	1,283 (-0.7)
Mean price (\$ per kL)	1.54 (-5.7)	1.59 (-2.6)	1.64 (0)	1.69 (3.8)	1.78 (8.8)
Mean consumption (ML per season)	24.2 (2.2)	23.9 (1.0)	23.7 (0)	23.4 (-1.3)	23.0 (-3.0)

Note: Percentage change shown in parenthesis.

7 Sensitivity analysis: augmentation capital cost

rain-dependent scenario

Investment cost (\$ million) c	60 (-40.0)	80 (-20.0)	100 (0)	120 (20.0)	140 (40.0)
Probability of investment occurring in simulation	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Mean investment time (years)	6.1 (-23.7)	7.1 (-12.0)	8.0 (0)	9.0 (11.8)	9.8 (21.9)
Mean discounted objective value (\$ million)	1360 (2.0)	1350 (13)	1333 (0)	1320 (-1.0)	1310 (-1.7)
Mean price (\$ per kL)	1.43 (-2.1)	1.44 (-1.0)	1.46 (0)	1.49 (2.4)	1.51 (3.7)
Mean consumption (GL per season)	24.9 (0.9)	24.8 (0.4)	24.7 (0)	24.5 (-0.8)	24.4 (-1.3)

Note: Percentage change shown in parenthesis.

Price elasticity

Results of a sensitivity analysis on the demand elasticity parameter (**a**) are shown in table 8 and table 9. When the demand for water is less (more) elastic, the associated surplus per unit of water consumed is higher (lower) and as a result investment occurs earlier (later). Rain-independent investment is particularly sensitive to a change in price elasticity.

All else held constant, a smaller price elasticity would be expected to result in substantially higher mean prices. However, increased (earlier) investment limits the increase in price by providing an increase in supply, which results in increased mean consumption. In the rain-dependent case the price is more sensitive to changes in demand elasticity.

8 Sensitivity analysis: demand elasticity parameter

rain-independent scenario

Elasticity parameter, a	1.33 (-40.0)	1.78 (-20.0)	2.22 (0)	2.67 (20.0)	3.11 (40.0)
Elasticity (1/a)	0.75	0.56	0.45	0.37	0.32
Probability of investment occurring in simulation	0.03 (-96.8)	0.31 (-68.2)	0.97 (0)	1.00 (3.6)	1.00 (3.6)
Mean investment time t	21.7 (23.1)	20.9 (18.4)	17.7 (0)	15.1 (-14.6)	13.0 (-26.5)
Mean discounted objective value (\$ million)	525.4 (-59.2)	844.0 (-34.5)	1290.0 (0)	1968.7 (52.7)	2951.7 (129.0)
Mean price (\$ per kL)	1.48 (-9.6)	1.65 (1.0)	1.64 (0)	1.7 (3.7)	1.77 (8.3)
Mean consumption (GL per season)	22.2 (-6.3)	22.5 (-5.1)	23.7 (0)	24.1 (2.0)	24.4 (3.1)

Note: Percentage change shown in parenthesis.

9 Sensitivity analysis: demand elasticity parameter

rain-dependent scenario

Elasticity parameter, α	1.33 (-40.0)	1.78 (-20.0)	2.22 (0)	2.67 (0)	3.11 (40.0)
Elasticity ($1/\alpha$)	0.75	0.56	0.45	0.37	0.32
Probability of investment occurring in simulation	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Mean investment time t	13.0 (61.3)	9.9 (23.0)	8.0 (0)	6.6 (-17.3)	5.2 (-35.0)
Mean discounted objective value (\$ million)	512 (-61.7)	853 (-36.2)	1333 (0)	2017 (50.9)	3002 (124.6)
Mean price (\$ per kL)	1.3 (-10.3)	1.38 (-5.0)	1.46 (0)	1.57 (8.1)	1.71 (17.8)
Mean consumption (GL per season)	24.0 (-2.9)	24.5 (-1.1)	24.7 (0)	24.8 (0.1)	24.7 (-0.1)

Note: Percentage change shown in parenthesis.

Net inflows

Results of a sensitivity analysis on the environmental flow parameter (ef) are shown in tables 10 and 11. The environmental flow parameter specifies a proportion of rain dependent inflows which are assumed to be released downstream. A sensitivity analysis over this parameter is effectively a sensitivity analysis over mean net inflows. A reduction in mean net inflows results in a bringing forward of investment. A decrease (increase) in net inflows in general results in an increase (decrease) in mean price and a fall (rise) in mean consumption. In the rain-independent scenario the changes in price and consumption are relatively small, while in the rain-dependent case price and consumption are much more sensitive to variations in mean net inflows.

10 Sensitivity analysis: net inflows

rain-independent scenario

Environmental flow parameter, ef	0.15 (-40.0)	0.20 (-20.0)	0.25 (0)	0.30 (20.0)	0.35 (40.0)
Effective change in mean inflow	(13.3)	(6.7)	(0)	(-6.7)	(-13.3)
Probability of investment occurring in simulation	0.03 (-97.4)	0.59 (-39.3)	0.97 (0)	1.00 (2.3)	1.00 (2.4)
Mean investment time t	22.4 (26.0)	20.4 (14.8)	17.7 (0)	14.9 (-16.4)	12.4 (-30.1)
Mean discounted objective value (\$ million)	1375 (6.6)	1333 (3.3)	1290 (0)	1258 (-2.5)	1220 (-5.4)
Mean price (\$ per kL)	1.6 (-2.15)	1.64 (0.40)	1.64 (0.00)	1.68 (2.86)	1.78 (8.84)
Mean consumption (GL per season)	24 (137)	23.7 (0.00)	23.7 (0.00)	23.3 (-1.36)	22.8 (-3.73)

Note: Percentage change shown in parenthesis.

11 Sensitivity analysis: net inflows

rain-dependent scenario

Environmental flow parameter, <i>ef</i>	0.15 (-40.0)	0.20 (-20.0)	0.25 (0)	0.30 (20.0)	0.35 (40.0)
Effective change in mean inflow	(13.3)	(6.7)	(0)	(-6.7)	(-13.3)
Probability of investment occurring in simulation	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Mean investment time <i>t</i>	11.8 (47.4)	9.8 (22.5)	8.0 (0)	6.3 (-21.8)	4.6 (-42.1)
Mean discounted objective value (\$ million)	1370 (3.0)	1360 (2.3)	1333 (0)	1300 (-2.3)	1260 (-5.3)
Mean price (\$ per kL)	1.29 (-12.11)	1.36 (-7.43)	1.46 (0)	1.6 (9.45)	1.81 (23.75)
Mean consumption (GL per season)	26 (5.27)	25.4 (3.07)	24.7 (0.00)	23.8 (-3.59)	22.7 (-8.06)

Note: Percentage change shown in parenthesis.

Penalty value

Results of a sensitivity analysis on the penalty for failure to meet essential water (*PENALTY*) are shown in table 12 and table 13. When storage levels reach low levels, the probability of a system failure (an empty dam) becomes significantly different from zero and the penalty value begins to influence the estimated price and investment policy functions. As shown in the sensitivity analysis, a higher penalty value results in higher prices on average and earlier investment on average in both scenarios. The impact of the penalty value on mean prices is relatively small, as it will tend to increase prices only during substantial droughts. The penalty value does, however, have a significant impact on investment timing in the rain-independent scenario. In the absence of a penalty for system failure, the rain-independent supply option is likely to be executed in only one in

12 Sensitivity analysis: penalty

rain-independent scenario

Penalty value <i>PENALTY</i>	0 (-100)	5×10^9 (-50)	1×10^{10} (0)	1.5×10^{10} (50)
Probability of investment occurring in simulation	0.24 (-75.2)	0.96 (-1.6)	0.97 (0)	0.98 (0.4)
Mean investment time <i>t</i>	21.0 (18.3)	18.0 (15)	17.7 (0)	17.4 (-2.1)
Mean discounted objective value (\$ million)	1356 (5.1)	1294 (0.3)	1290 (0)	1289 (-0.1)
Mean price (\$ per kL)	1.66 (1.08)	1.65 (0.82)	1.64 (0)	1.63 (-0.33)
Mean consumption (GL per season)	23.3 (-1.62)	23.6 (-0.30)	23.7 (0)	23.7 (0.10)

Note: Percentage change shown in parenthesis.

four simulations. A higher penalty value also decreases the probability of a system failure. However, given that this probability is very low, it is difficult to accurately measure it without increasing the number of simulations substantially.

13 Sensitivity analysis: penalty

rain-dependent scenario

Penalty value <i>PENALTY</i>	0 (-100)	5×10^9 (-50)	1×10^{10} (0)	1.5×10^{10} (50)
Probability of investment occurring in simulation	1.00 (0)	1.00 (0)	1.00 (0)	1.00 (0)
Mean investment time <i>t</i>	10.1 (26.3)	8.3 (3.2)	8.0 (0)	7.9 (-1.2)
Mean discounted objective value (\$ million)	1354 (1.6)	1337 (0.3)	1333 (0)	1333 (0)
Mean price (\$ per kL)	1.39 (-453)	1.46 (-0.12)	1.46 (0)	1.47 (0.65)
Mean consumption (GL per season)	25 (137)	24.7 (0.03)	24.7 (0)	24.7 (-0.20)

Note: Percentage change shown in parenthesis.

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