

# Final Report

## Enhancing water infrastructure provision with climate change uncertainty

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## Foreword

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This document consists of two parts—an introductory part (chapter 1) that sets out relevant issues in non-technical terms and a second part that consists of four technical papers (chapters 2–5).

This work has been presented at various academic and professional forums, which are summarised below.

All authors presented parts of their work to the *Mini-symposium on Urban Water Planning with a Risky Climate* at the *Australia Agricultural & Resources Economics Society (AARES) 56th Annual Conference* on 7–9 February 2012 in Fremantle, Western Australia. The Victorian Centre for Climate Change Adaptation Research (VCCCAR) sponsored the mini-symposium.

Clarke, Freebairn and Jayanath presented to the Annual Forum of the VCCCAR on 25 June 2012 in Albert Park, Melbourne, Victoria.

Clarke presented this work to the *World Natural Resources Modeling Conference* on 12 July 2012 at the University of Queensland, Brisbane, Queensland.

Jayanath presented three papers at La Trobe University, Wodonga, Victoria: ‘Water infrastructure, climate change and institutional reforms’ at the *Paper Bag Seminar* on 8 June 2012, ‘Embedding flexibility in urban water supply augmentation’ at the *Brown Bag Seminar* on 13 December 2011 and ‘Factoring uncertainty in infrastructure decisions’ on 29 July 2011.

Leroux presented at the *Monash Environmental Economics seminar series* in May 2012, the *European Association of Environmental Economists Annual Conference* in Prague on 29 June 2012 and the *Mannheim University and Heidelberg University joint seminar series* on 17 July 2012.

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## 1. Non-technical summaries

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### 1.1 Planning urban water investments with climatic uncertainty

*Harry Clarke*

Policies for assessing effects of climate change risk and uncertainty on water-supply provision are discussed. The emphasis is on analytical insights derived using option-pricing arguments. Attention is also paid to portfolio approaches, problems of uncertainty and catastrophic risk.

Water supply services are impacted by climate. Temperatures will rise with global warming although impacts on rainfall are much less determinate. Stream flow and rates of runoff will decrease. Climate change will also increase climatic variability with possibly more droughts and severe flood events.

Climate projections are notoriously non-specific. They often disagree markedly on the sign and magnitude of forecast precipitation. The best forecasting models are, moreover, unsuitable for making regional forecasts because of their coarse geographic resolution. Yet it is at the specific catchment level that water supply decisions are taken. Climate variability increases at the scale defined by the water supply catchments servicing urban areas because of topography, coastline features and land cover, as well as regional atmospheric and specific convection characteristics and the distinctive impacts of the El Niño Southern Oscillation (ENSO). These risks and uncertainties create an uncertainty cascade, with high overall uncertainty regarding forecast climate change impacts on water.

Until recently, water supplies to Australian capital cities were affected by a long-term drought that governments responded to with water restrictions and investments in desalination. A Productivity Commission inquiry argued that investments in large-scale desalination have achieved water supply security but at excessive cost compared to smaller scale desalination or alternative sources of urban supply. It was suggested that using a 'real options' or 'adaptive' approach to urban water planning would reduce costs of water supply augmentation.

The attractiveness of real option approaches is that they explicitly address the uncertainties and irreversibility of investments. The approaches enable explicit attention to be paid to the probabilities of different rainfall and stream-flow scenarios. The approaches facilitate a focus on flexibilities in making investment choices about the timing and types of investment choices made. Even if such policy options as rural–urban water trades are ruled out as politically unfeasible, there are also options for initially building smaller desalination plants and then moving to a larger plant if needed.

One approach to addressing risk is to use expected values or, accounting for risk aversion, to use expected utility theory. The real options approach generally assumes risk neutrality. It is

used when projects have risky returns but where information about risks improves through time and projects have differing degrees of performance flexibility.

Consider a desalination plant — which costs  $C$  but which yields benefits  $W$  at future time  $T$  if an adverse climate event (low rainfall) occurs but yields zero benefits otherwise. That zero benefits arise without the adverse climate event implies the project is irreversible, so capital cannot be retrieved and used to produce something else should desalination prove uneconomic. The decision to proceed with the plant involves purchasing an option that delivers  $W$  if exercised and 0 otherwise. With discount rate  $r$ , this option's value is:

$$V_1 = -C + e^{-rt}E[\max(0, W)]$$

(1.1)

where  $E$  denotes expectation when the project cost is incurred. Alternatively, since the plant involves an irreversible commitment, construction could be delayed until future climate is observed, saving sunk investment costs should the investment be unwarranted. The possible outcomes now are saved construction cost  $C$  assuming the adverse climate event does not occur and a loss incurred if the adverse event occurs that could have been mitigated,  $-W$ . The option of not developing is worth:

$$V_2 = C - e^{-rt}E[\max(0, -W)]$$

(1.2)

$V_1$  and  $V_2$  have opposite signs so the best choice is to select the alternative with positive expected value.

There can be incentives to delay irreversible investments, although depending on the scale of benefits and costs, there are also reasons to proceed with construction immediately. Generally there can also be incentives to proceed cautiously with irreversible investments. For example, a project can be developed in stages either through gradually expanding the project's scale as conditions turn toward favouring its completion, or at least by creating preconditions for production (land purchases, environmental approvals) that facilitate construction if warranted. Our focus is on the character of such decisions. Interest is on analytical insight not numbers. This is distinct from earlier studies that use simulation based on artificial 'data'. There is value in seeking an analytical feel for the qualitative factors impacting on decisions.

## Real options

Several models are developed. First the economics of desalination are examined when a desalination plant itself only becomes valuable when an alternative source of supply — stream-flow — fails because of an adverse climatic event. Then dam construction is examined when the construction is subject to uncertainty because of climate change — in certain 'states of the world' the dam is uneconomic. These problems are similar. Uncertainty in each case is attached to a particular technology even if for desalination it stems from

valuation uncertainties attached to an alternative technology. After this, a model of incremental expansion of both desalination and dam capacity is developed and finally modular expansions of desalination is discussed.

### **Portfolio issues**

A different way of thinking about impacts of risk on water supply planning is to analyse investments as a portfolio problem. For example, investors generally prefer a portfolio returning 10 per cent with certainty to one paying 0 per cent with probability 0.5 and 20 per cent with probability 0.5. These investors are risk averse and will pay an actuarially fair insurance option to fully insure against risk. Accounting for risk aversion in this way makes it optimal to diversify across sources of supply and include uncorrelated alternative sources of supply even with water productivity differentials.

One way of specifying risk aversion is to target a water supply reliability objective; for example, meeting water demand in 19 years out of 20. The higher the targeted probability the greater is risk aversion.

Then what average yield of a new source of water must be added to a pre-existing water supply to achieve reliability? If desalination yields supply with certainty, reliability can be met with lower mean water yields by scaling up the proportion of rain-independent desalination in the total. The probability distribution of supply outcomes is shifted to the right by adding riskless supply. Reliability objectives can be met with even lower mean water yields if new sources of supply are negatively correlated with pre-existing supplies.

### **Uncertainty**

A distinction is drawn between risk and uncertainty. Risk arises where all the possible outcomes, or states of the world, can be enumerated and probabilities attached to them. 'Uncertainty' arises when all possible states of the world can be enumerated but probabilities cannot be assigned. Still more complex situations arise where we also don't know either probabilities or states of the world that might arise — this is 'gross ignorance'. Then surprises can occur that were not *ex ante* anticipated to be possible.

Uncertainty issues can also be approached using 'minimax' and 'minimax regret' heuristics. The 'minimax criterion' involves choosing the supply option that minimises the worst that can happen given uncertainty — a form of the 'precautionary principle'. An unattractive feature of this solution is that it might turn out that taking no action to address water shortages makes sense if a costly policy might fail. Therefore a heuristic is considered in this setting to avoid this situation by computing the regret that would be experienced, and to minimise the maximum regret. This is the 'minimax regret decision rule'. Sometimes building a desalination plant involves less regret than doing nothing.

### **Catastrophes**

Climate change offers the possibility of 'catastrophic risks' when water supply is so affected by climate change that potable water becomes in extremely short supply for a segment of the population for an extended period. Then the problem of addressing climate change becomes



straightforward in a cost–benefit sense since policy actions, if available, will always be taken to offset the enormous possible social costs. The optimal extent of risk mitigation depends on the costs of mitigation compared to the benefits in terms of risk reduction.

Severe extended periods of drought have been experienced in Australia. The appropriate response has been and will continue to be a mix of temporary demand-management and supply-side options. There is a serious potential option pricing issue associated with the timing of a lumpy irreversible investment problem. This again involves issues of valuation at the margin — between postponing an irreversible investment when it might prove of low value and acting to realise it. There is not a substantial longer term sudden issue of avoiding potential catastrophic costs by making significant anticipatory investment actions. More plausibly there will be a conjunction of short-term emergency measures such as demand restrictions and a reactive investment response.

### **Final remarks**

Climate change risks raise option pricing issues. Investments in water supply augmentation can take the form of rain-independent technologies such as desalination or augmentation of rain-dependent technologies. The interaction of risk, irreversibility and possible learning generates a range of option pricing tasks. Risk aversion motivates insurance-based analytical approaches while uncertainty issues require the development of intelligent heuristics.

There are many important issues not addressed so far. One is determination of investment in wastewater treatment, where significant economies of scale arise. Here there are relatively low costs in installing additional drainage capacity to deal with extreme runoff events. It makes economic sense to include generous safety margins in making these types of capacity decisions.

Water quality issues and the prospects for technological advance in delivering water supply options such as desalination have not been considered. There are difficult issues of evidence here.

Finally an issue left unexplored is the integration of option pricing approaches with portfolio theories. Option pricing arguments suggest a case for delaying risky irreversible investments while portfolio arguments suggest diversifying them. Integrating these views is difficult because of the lumpy character of water-supply investments.

## 1.2 Risk aversion and urban water decisions

*John Freebairn*

This work sets out the general uncertainty facing managers of water and investors in infrastructure about increasing the availability and security of water supply. First, the sources and forms of imperfect information facing the water market are described. With this background, the work discusses some of the different decision strategies available to best respond to the uncertainty. Climate change is just one source of imperfect information. In general, to focus on just one source of uncertainty and to ignore other sources is likely to lead to less than best practice outcomes.

### Imperfect information

One way of describing the uncertainty facing the water industry, including water for households, irrigation, industry and the environment, is to consider imperfect knowledge about water demand, water supply and government policy.

Consider first demand, and by way of illustration the specific case of urban water demand. A conventional demand function relates quantity of water used per household to the water price, water supply regulations, household income, and variables such as housing density, climate and stochastic variation in terms of an error term.

In reality the error term is important, and seldom is more than two-thirds of the variation in quantity explained by the included explanatory variables. There are only sample estimates of the key parameters on the explanatory variables, and the estimates vary from study to study. For example, estimates of the price elasticity of demand vary from zero to 0.8, and in forecasting future demand, we have to use estimates of the explanatory variables.

From 1997 to 2010, Melbourne's per capita water consumption fell by 44 per cent. We do not know the relative contributions of higher prices, regulations, greater urban density and other factors to the fall in consumption. Further, we do not know whether current low consumption will be sustained, reversed or maintained in the future.

An important unknown about water demand is the willingness of households and other water users to pay for security of supply. It is a safe bet that the dollar sum varies across individuals, and that the marginal value falls with higher levels of security. Buyer preferences, and willingness to pay, for water security (and perhaps other characteristics of water) is important in deciding on a portfolio mix of relatively expensive but also secure water supply. Such water supply is provided by manufactured water and by cheaper but more variable rain-fed dam supply water. Few studies have made estimates of household willingness to pay to avoid water restrictions. These studies suggest that some households are willing to pay at least double the current water rates for supply security that avoids water restrictions.

Consider next imperfect information on the water supply side. Climate effects on rainfall, water inflows to dams and storm water catchments are variable. For example, the standard

deviation of inflows to Melbourne's dams is about 45 per cent of the average inflow. Looking to the future, these distributions, and not just the average flows but also the higher moments of the distribution, are anticipated to change with climate change. Also, it seems likely that the changes will vary by water catchment and region.

There are other important sources of uncertainty on the water supply side, particularly for infrastructure investment costs and the relative ranking of different investment options. These include developments in technology such as for manufactured water and the capture and treatment of storm water, relative input costs, and particularly for energy required to pump and manufacture water. The opportunity value of water for environmental amenity with increase with higher incomes; but by how much?

Uncertainty about future government policy can affect both water demand and water supply, which adds another layer of imperfect knowledge for water managers and investors. On the water demand side, will government policy continue to regulate prices? If so, on what criteria will it continue to impose water restrictions? A range of government policies will directly and indirectly affect future population growth and housing density, both of which are important components of the demand function (1). On the water supply side, government policy intervention is important for allocating limited water between uses that provide public amenity, and consumptive uses, which have private good properties and where markets can work. For the most part, this water use has public good properties (of non-rival consumption and high costs of exclusion) where markets fail and government intervention is required. Government policy in past decades has had a major influence on the conditions under which new dams, pipelines and manufactured water plants can be built.

For people making decisions on managing and investing in water, there are some important characteristics of the imperfect information and the investments. In some cases fairly objective and generally agreed probabilistic information is available, but in many cases only subjective estimates are available. For each of these demand, supply and policy dimensions discussed, in almost all cases more information is revealed over time. This regular inflow of new information provides a rationale for adaptive decision-making. Most investments involve long lead times for government approval and construction. Also, because of economies of scale they are lumpy and large, and once completed they become sunk costs for many decades.

### **Decision strategies**

Several strategies to manage the allocation of water over time and across different users from a given supply infrastructure recognise imperfect information about both water demand and inflow. The current urban strategy sets a price that is invariant with the quantity of water in storage, and in the event of an impending shortage imposes restrictions, mostly on outdoor water use. In the case of irrigation water, allocations per entitlement are adjusted for water in storage, and a market sets the price.

Urban water use could consider an adaptive pricing strategy; this has been supported in the 2011 Productivity Commission study (refer to chapter 2 for details). Further, water restrictions imposed as a one-size-fits-all, but only to outdoor and not indoor use, involves

efficiency costs across different users with different preferences regarding security of water supply. The electricity industry provides examples of more flexible and efficient arrangements with different product characteristic packages and costs for handling uncertainties of demand and supply.

An important question facing the future water industry should be the choice of portfolio of different sources of water supply with different characteristics to match buyer preferences for water with different characteristics. Of particular interest are the two characteristics of average cost and security of supply; other attributes include health risks, taste and perceived 'yuk' factor for recycled water. At a cost, greater security of supply can be achieved by a system with multiple dams where there is an imperfect correlation between inflows over time, by pipelines interconnecting systems adding manufactured water, and by adopting more conservative inter-year storage carryover rules. Societal welfare would be maximised with a portfolio choice that equates the buyer marginal rate of substitution for characteristics with the relative marginal costs of the characteristics. The answer will vary across different communities with different preferences and available production possibilities.

With a growing population and likely reductions in inflows with climate change, a key set of investment questions is when to invest in a supply capacity expansion, in what form and of what size? To take the time of an investment decision, an early start reduces the probability that demand shifts run ahead of supply, but the early investment involves an additional cost in present-value terms. By contrast, a later investment time has a cost saving but increases the probability and cost of a water shortage, requiring very high scarcity prices and/or restrictions. A conventional decision-making model under risk would choose the time of investment to equate the expected marginal cost saving of delay with the expected marginal cost of less carryover water in storage (or, an expected utility model for risk averse decision-makers).

Better still, a real options analysis model recognises that information keeps rolling in about the uncertain demand, the uncertain supply and even uncertain government policy. New information provides a conditional option to delay the required time of investment, and this delay has cost-saving value to the investor.

At least two additional measures can be pursued to assist in making better water supply augmentation investment decisions, including using the real options model. First, shortening the government approval time for investment and/or the construction time allows more up-to-date information on the uncertain demand and supply factors to be used to delay the time of expansion. This will also reduce the probability that the extra infrastructure will provide excess capacity. In short, there is a return on investment in preplanning and regularly revising plans in response to new information. Second, investment in actively collecting and evaluating information to reduce the uncertainty about demand and supply results in better decisions on average. Information includes meteorology and hydrology data, understanding consumer demand, relative costs of different inputs or investment options and engineering developments, better investment and water management methods, and better understanding of the relative merits of different government policy options.

An interesting and potentially large cost saving strategy to accommodate the variability of rainfall and water inflows to dams involves better integration of water use for consumption and for environmental amenity. To some extent many of the required environmental flows vary from year to year, much as happened with pristine river flows. By contrast, many of the consumptive uses, including by households, industry and perennial crop irrigation, require more stable water flows. For example, if the environmental water manager (EWM) is provided with identical water property rights as the consumptive users, including the right to buy and sell water, the EWM might sell water at a relatively high price in times of limited storage and then buy back several times the quantity of water for flooding environmental assets in years of plentiful and relatively low cost water.

### **Concluding remarks**

Imperfect knowledge and uncertainty are endemic features of the water industry. Both the demand and supply sides are sources of uncertainty. Where government continues to intervene, changes in government policy are another source of uncertainty. Also important is that new information about variations in water demand and supply becomes available to decision-makers. More effective decision-making recognises the inflow of new information for decisions about water management and for investment in water supply expansion infrastructure.

## **1.3 Institutional reforms to enhance urban water infrastructure with climate change uncertainty**

*Jayanath Ananda*

Climate change adds another layer of uncertainty to the complex issue of urban water infrastructure provision. Current institutional configurations in the urban water sector are deemed inflexible and ill-equipped to deal with climate uncertainty. This research examines the regulatory and planning frameworks surrounding providing urban water infrastructure in Victoria. There is a clear need for institutional reforms that facilitate better infrastructure decisions under uncertainty. They include reforms relating to the current:

- regulatory setting that discourages adaptive decision-making
- dispersed and opaque responsibility for water supply security
- impediments to consider least cost supply augmentation options including (rural–urban water transfers
- information asymmetries relating to customer preferences and climate change impacts
- lack of guidelines on incorporating uncertainty into infrastructure investment evaluations
- lack of clarity in roles and objectives of the agencies surrounding urban water management.

## 1.4 Optimal portfolio of urban water supply assets under climate change

*Anke Leroux (with Vance Martin)*

Many urban centres around the world are in danger of running out of water in the near or medium term because of greater demand from growing populations and reduced supply from conventional surface and groundwater sources. Projected climate change impacts, which include reduced inflows into dams, will only exacerbate the problem. This situation has resulted in a global surge in actual and planned investments to augment urban water supply and ensure future supply security. Some have invested in desalination and recycling technologies, others have fostered stormwater harvesting.

The questions we are answering in this research project are: what is the optimal mix of water supply technologies and capacities, given historic precipitation and inflow patterns? How is this portfolio likely to change if climate change impacts on water supply are taken into account?

We adapt a dynamic portfolio model to the water sector. In particular, we model returns on investment as water flows per investment dollar and allow supply uncertainty from conventional reservoirs and decentralised stormwater harvesting initiatives to follow realistic gamma distributions. We derive closed-form solutions to urban water consumption and contributions to a given total annual water supply for each of three types of water supply assets:

1. conventional surface and/or groundwater sources
2. desalination and recycling technologies
3. stormwater harvesting.

We find that these depend on the mean and variances of rainfall and reservoir inflows as well as the level of risk aversion, rate of discount and total annual water supply.

The model is calibrated to Melbourne, using 95 years of monthly precipitation data and 95 years of inflows into Melbourne's four major reservoirs. The model uses cost and supply characteristics from these reservoirs, the Wonthaggi desalination plant and four local pilot stormwater harvesting projects. We find that averaged over a year, reservoirs should optimally supply 60 per cent of the total water supply, with stormwater harvesting and desalination each supplying 20 per cent. However, we find that these optimal contributions vary significantly among months. Besides finding support for aggressive demand management we show that a water planner, who considers supply augmentation investments to overcome seasonal shortages in water supply, may target a different mix of water supply assets. All optimal portfolios are subjected to a 'value at risk' analysis. It is shown that portfolios perform better than the current mix.

Climate change is considered in a preliminary way using the medium climate change impact scenario from the 2005 Melbourne Water Climate Change study (for details, refer to chapter 5). We found that greater variation in rainfall and inflows and a reduction in inflows by 7 per cent will lead to a chronic shortage of water supply even if an increase in mean rainfall by 10 per cent is assumed. Investments to further augment water supply will become necessary, with comparatively greater emphasis on desalination. However, an optimal contribution of 20 per cent harvested stormwater remains optimal. This suggests that encouraging investments to increase stormwater harvesting capacity represents a 'no-regrets policy' for Melbourne.



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## 2. Planning urban water investments with climatic uncertainty

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**Harry Clarke**

*School of Economics, La Trobe University*

### 2.1 Synopsis

Policies for assessing the effects of climate change risk and uncertainty on water supply provision are discussed with reference to recent Australian experience. The emphasis is on analytical insights derived from use of low-order stochastic dynamic programming models to address risk management. Attention is also paid to portfolio approaches and problems involving uncertainty and gross ignorance with respect to catastrophic risks.

This material was presented at the World Natural Resource Modeling Conference (ref 2012)

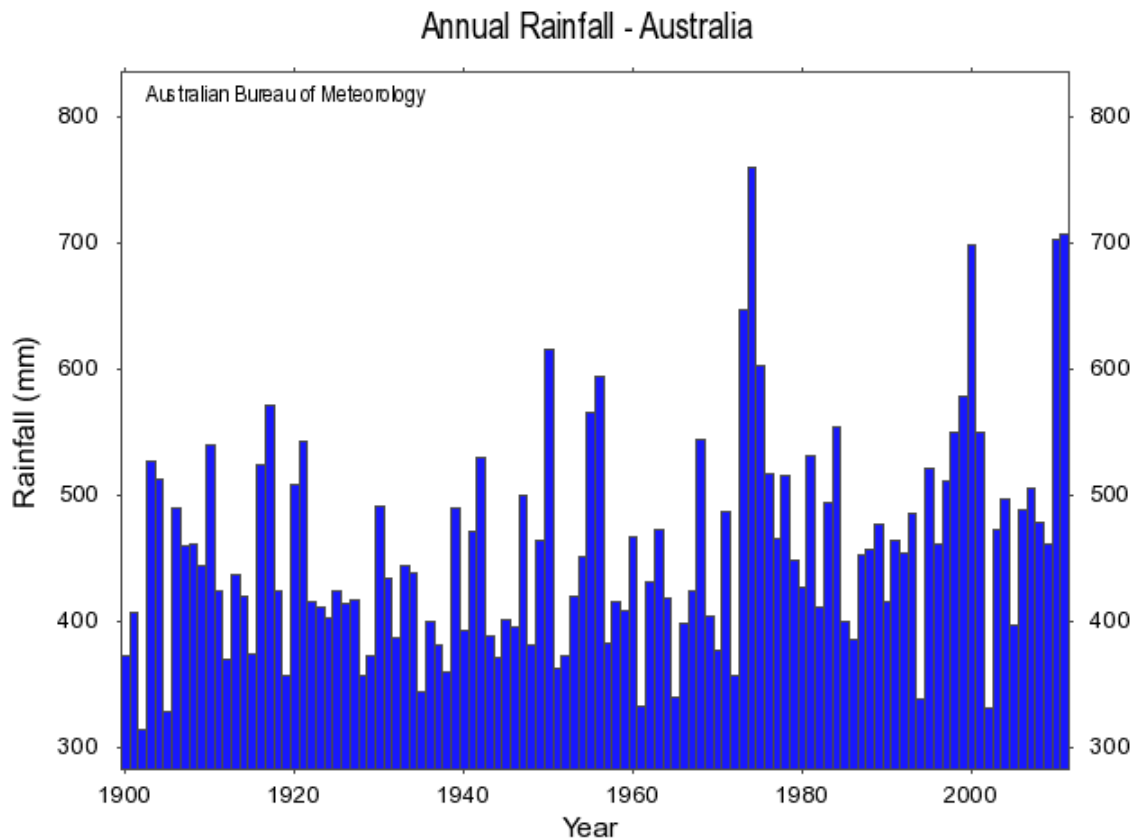
### 2.2 Introduction

The urban water sector provides drinking water and wastewater disposal services to urban communities. Drinking water must be harvested or manufactured using technologies such as dams and desalination plants. It must be stored, treated then distributed to users. Wastewater must then be removed and treated. The scale of the task can be assessed using a recent comprehensive Australian water audit — in 2009–2010, Australian total water consumption was 13 476 GL of which 6 987 GL (52 per cent of the total) was consumed in agriculture, 1 868 GL (about 14 per cent) by households and 658 GL (5 per cent) by manufacturing (Australian Bureau of Statistics (ABS) 2006). Most household and manufacturing consumption is in urban areas (CSIRO 2008).

Water supply services are impacted by climatic uncertainty. This includes anthropogenic climate change but also the long-standing variability of climate that is a characteristic of Australia, which displays greater rainfall variability than any other continent (Fig. 2.1). The average annual Australian rainfall from 1900 to 1911 was 457.5 mm but maximum and minimum values covered a wide range of 759.65 to 314.5 mm, respectively. Temperatures typically will experience a secular rise with global warming but impacts on rainfall are much less determinate and will vary by location. Rates of stream flow and runoff, for given rainfall, will decrease with increased temperature. Another forecast effect of climate change is an increase in climatic variability. More extreme droughts and more severe floods are possible in some areas, although the extent to which this is likely is subject to controversy.

All climatic forecasts are highly uncertain. Climate change projections are notoriously non-specific and are based on models that have uncertain relevance. For example, predictions from different models often disagree markedly on the sign as well as the magnitude of forecast precipitation changes. Moreover, climate forecasts are contingent on both forecasts of emission mitigation and emission generation scenarios as well as imperfect hydrological

modelling. The best global climate forecasting models — the Atmosphere Ocean General Circulation Models — are unsuitable for making regional forecasts because of their coarse geographic resolution. Yet it is at the specific catchment level that water supply decisions are taken. Climate variability increases at the scale defined by the water supply catchments that service urban areas because of topography impacts, coastline features, land cover and regional atmospheric and specific convection characteristics. There are also distinctive impacts of the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) depending on geography (see Bates in Bates et al. 2010).



**Figure 2.1. Australian Rainfall 1900–2011 (BoM 2012).** This chart means that ‘downscaling techniques’ contingent on choice of global model must be used to forecast climate at a regional scale. These models must then be linked to the behaviour of water supply systems. In Australia this has mostly involved a focus on mean annual catchment runoff forecasts for surface water. There is little information about the impacts of climate change on the drought and flood events that are of particular concern to water supply planners. There is not much Australian work on groundwater impacts, saltwater intrusion issues associated with sea level rise, or water quality issues associated with climate change.

The different types of uncertainty mentioned here — climate change forecasts, emissions forecasts and hydrologic forecasts — create an uncertainty cascade. Thus, there are high levels of uncertainty regarding forecast climate change impacts on water supplies (CSIRO 2008).

Quite apart from climate change issues, the intrinsically variable character of the Australian climate — rainfall variability is greater than in any other continental region (Lindesay 2003) — creates difficulties for planning water supply provision. Increasing urban populations and aging water supply infrastructure in a dry continent compound these difficulties.

Until recently the supply of water to Australian capital cities was affected by a severe long-term drought. Governments responded to the drought with water restrictions and by large investments in rain-independent supply capacity. Specifically, desalination plants have been constructed, or are being constructed, in Sydney, Melbourne, south-east Queensland, Perth and Adelaide. A Productivity Commission (PC) inquiry was set up to examine the case for microeconomic reform of the urban water supply sector (PC 2011). The central claim of this report was that recent investments in technologies such as desalination have achieved security of water supply. However, this has occurred at excessive cost compared to use of interim measures such as smaller scale desalination plants or alternative sources of urban supply such as rural-to-urban trade, wastewater treatment and aquifers. One purpose of this chapter is to examine these claims.

A specific claim made is that using a 'real options' or 'adaptive' approach to urban water planning rather than traditional approaches to planning investments would have reduced the costs of water supply augmentation, hence enabling lower water prices for consumers. For Melbourne and Perth, using this approach would have reduced costs of supply by \$1.1 bn over 10 years (PC 2011, p.xxvi). Taking the combined population of these cities to be 5.8 million, and ignoring discounting, this corresponds to an annual additional annual cost of about \$19 per capita, which the PC saw as large. The potential extra costs of proceeding with desalination plants ahead of lower-cost alternatives for these same two cities is estimated to be \$1.8–2.4 bn over 10 years. The midpoint of this range at \$2.2 bn corresponds to an additional per capita cost of \$38 (PC 2011, p.xxv).

It can reasonably be questioned whether \$19 is large enough to justify substantive revisions in the methodological approach. Moreover, the cost of providing a rain-independent secure source of water supply — effectively a social insurance policy for cities like Sydney and Melbourne — does not seem excessive at \$38. The desalination technology provides an insurance option against severe drought or medium-term climate change effects. Further, it seems that that using more sophisticated evaluation techniques, such as real options analysis, might not provide very large gains. These techniques, after all, are relatively complex, require strong assumptions and are rather data intensive so that the size of gains matters. Alternatively, it is necessary to demonstrate that use of such techniques provides a firm basis for securing significant gains.

An alternative to any supply enhancement program is demand management. Economists generally favour managing the demand for water using price rather than quantity or rationing restrictions for widely recognised efficiency reasons. Quantitative restrictions on water use limit high- and low-valued uses of water and hence do not meet supply constraints at minimum cost. Governments often subscribe to the view that water has a unique status as an essential for human life that is in relatively inelastic demand. Governments are therefore often reluctant to allow water prices to spike in the short-to-medium term and prefer quantitative restrictions on use (e.g. restrictions on outdoor water use), which are essentially forms of rationing. Economists generally do not oppose such policies in the very short term since they are relatively flexible to devise, apply and impose inefficiency costs over only a short duration. Longer term, there are stronger arguments for allowing water prices to be flexible to clear water markets or for taking steps to augment supply.

The PC also saw the use of quantitative restrictions on water such as rationing schemes demands as particularly costly. They cite evidence (Grafton & Ward 2010) that Sydney in 2004–2005 incurred extra costs of \$275 M in 2010 dollars while Melbourne incurred costs of \$420–1500 M over a 10-year period. Taking Sydney’s population to be 4.6 million, these costs are around \$60 per capita while, ignoring discounting, Melbourne’s costs are \$10–37 per capita per year, which the PC again saw as large. These are significant annual costs for a household of four, amounting to \$240 yearly. They are, however, costs that permit greater flexibility for supply decisions.

State governments did not expect that the national drought would be so extended and originally saw restriction policies as short-term measures. Pricing would have been a preferable way of managing water demands medium term, but this view is somewhat glib given the benefit of the hindsight that the drought extended much longer than expected. Before the drought, it would be more difficult to reach such a conclusion.

The attractiveness of stochastic dynamic programming or real option approaches is that they explicitly address the uncertainties and irreversibilities in water investment planning. The approaches enable explicit attention to be paid to the probabilities of different rainfall and stream-flow scenarios. The approach also facilitates a focus on flexibilities in making investment choices about the timing and types of investment choices made. Even if such policy options as rural–urban water trades are ruled out, there remain options — for building smaller desalination plants and then moving towards larger plants if needed. The important issue is to assess the size of these gains from using this approach. The PC was so convinced of the value of the real options approach that it specifically suggested that governments direct water utilities to adopt real options or adaptive planning approaches to procurement as part of a charter in the draft version of their urban water report.

Given that major augmentations in rain-independent water supplies in some areas in Australia will not be called for until 2020, there is time to examine these issues in depth. Indeed for the next decade or so there is little immediate scope for realising efficiency gains through better supply options.

## 2.3 Accounting for risk

There are many economic approaches to addressing risk (e.g. Randall 2011). The simplest approach in many economic settings is to use the idea of expectation. Here a random variable, for example the return to a risky investment project, is computed by multiplying net benefits in different ‘states of the world’ by their probabilities and then aggregating these values. This gives the expected value to the project, or the average return if the project could be repeated in an environment where the probabilities prevailed.

A practical objection to this procedure involves adopting the ‘frequentist’ notion of probability. Investment projects typically are not repeated in a way that would enable probabilities computed on the basis of relative frequencies. In addition, decision-makers may seek to avoid extreme adverse events. A private company might be bankrupted by a project with a positive expected value but which delivered a large loss in an adverse state of the

world. Similarly, politicians might be expected to be extremely averse to citizens being left with extremely limited water supplies. Government might use strategies to avoid such states of the world, which is exhibiting risk aversion. This is the basis for using expected utility approaches to assessing risk impacts.

'Real options' is an alternative approach for selecting among risky prospects when projects have risky returns but when information about these risks improves through time, and have differing degrees of performance flexibility through time. For example, certain projects may yield high rates of return in certain states of the world but very large and irreversible losses in other states.

### Illustration of real options

This approach can be illustrated by an example adapted from Randall (2010 p.50–51). Consider a desalination plant, which costs  $C$  now but yields benefits  $W$  at future time  $T$  if an adverse climate event (low rainfall) occurs, but which yields zero benefits otherwise. That zero benefit arises without the adverse climate event implies the project is an irreversible investment; that is, the value of the capital cannot be retrieved and used to produce something else should the desalination plant prove uneconomic. The decision to proceed with the plant can be viewed as purchasing an option that delivers gain  $W$  if it is exercised and 0 otherwise. With discount rate  $r$  the value of this option is:

$$V_1 = -C + e^{-rt}E[\max(0, W)] \quad (2.1)$$

where  $E$  is expectation taken at the time the project cost is incurred. Alternatively, it might be supposed that since the plant involves an irreversible commitment of resources, construction could be delayed until the climatic outcome is observed, saving sunk investment costs should the investment be unwarranted. The possible outcomes now are the benefits of the saved construction cost  $C$  assuming the adverse climate event does not occur and the loss incurred if the adverse event occurs but could have been mitigated  $-W$ . The option of not developing now is worth:

$$V_2 = -C + e^{-rt}E[\max(0, -W)] \quad (2.2)$$

Since  $V_1 + V_2 = 0$ , and  $V_1$  and  $V_2$  will have opposite signs, both options will not be exercised. The best choice is to select the alternative with positive expected value.

This is broadly suggestive of the real options approach. A specific example is articulated more fully in the section 'Desalination economics' below. However, incentives can delay irreversible investments, and depending on the scale of benefits and costs, there can also be reasons to proceed with construction immediately. More generally there can also be incentives to proceed cautiously with irreversible investments. For example, a project can be developed in stages either through gradually expanding the project's scale as conditions turn toward favouring its completion or, at least, by creating preconditions for production (land purchases, environmental approvals) that help its construction should construction prove warranted in the future.

With real options problems, sequential decisions are taken through time where the current state of a system depends on current and past policy actions. The objective is to optimise a performance function defined by the performance of the system through time. If the system is subject to random shocks through time then such sequential decision problems can sometimes be solved using techniques such as stochastic dynamic programming (SDP) (Ross 1995).

### **Other real options studies**

A vast literature on planning for investment in water projects includes several books. This chapter is restricted to recent approaches using SDP and specific variants of this technique — real option techniques. Our focus is on the character of the investment decision rather than hydrological models, which emphasise temporal links between water stocks and flows and intertemporal demand patterns. The interest is on analytical insight not numbers.

Borison et al. (2008) discuss the use of real options approaches as a way of dealing with water augmentation where the benefits of distinct projects are uncertain, information about uncertainties improves with time, there is project flexibility within a portfolio of projects such as the ability to ‘stage’ the introduction of a large investment as a sequence of ‘modules’, and there is substantial investment irreversibility. The approach is illustrative rather than technology-specific and relies heavily on a hypothetical case study. It surveys the qualitative insights provided by such an approach. For example, it points out that desalination technologies are energy intensive so their economic evaluation depends on energy price uncertainty. Likewise modular expansion of desalination provides flexibility advantages at the possible expense of economies of scale.

The setting envisaged is one where flexibilities in project scale can be manipulated at some cost to offset significant investment irreversibilities. A key idea is that one-off irrevocable investment decisions can be improved by a flexible strategy involving incremental investment. This can involve initial preliminary work such as site clearing and environmental approval, which are the early stages of a modular design. These moves are only completed into a comprehensive irreversible project if states of the world favourable to the expansion eventuate. The exposition is based on several hypothetical examples but centres on a ‘risk-adjusted decision tree’ model of dam or desalination plant choices.

Hughes et al. (2009) developed a numerical experiment on a highly simplified water supply system based on Canberra water supply data. Both demand management policies and supply options are used to address a single source of uncertainty associated with water inflows to a single dam. A scarcity price — a price that, at each time, maximises the discounted expected utility of water consumption — is set to manage demand that grows secularly. Optimally this price varies inversely with the amount of water in the dam. Supply augmentation takes two forms: (1) rain-dependent augmentation obtained by building a new dam; or (2) rain-independent from building a desalination plant — the latter despite Canberra’s distance from the coast! These possibilities are considered in turn rather than as alternatives because of the ‘curse of dimensionality’ in solving the associated full-scale stochastic dynamic programming problem. The dam adds to storage capacity and stochastic inflows where the desalination

plant does not. That the options are considered separately as scenarios rather than jointly changes things. An important insight is that a water utility can be more relaxed about pricing if it knows that following a dam construction it can add on a desalination plant.

The rain-dependent scenario produces a scarcity price that varies with storage. At full storage it approaches short-run marginal cost but it otherwise deviates from this level with the seasons. It is higher in summer when storage levels are lower than in winter. The optimal price is lower with augmentation in place. The investment policy is initiated as a trigger on water storage levels that increases secularly with time due to demand growth. The trigger has a seasonal element.

The rain-independent scenario relies on desalination. The scarcity prices for given pre-augmentation supply capacity are the same as for rain-dependent augmentations but are lower post-augmentation since the variability of supplies is reduced. This claim ignores the recovery of fixed capital cost, which is not realistic. The investment triggers are much lower because of the higher aggregate costs, which create an incentive to delay introducing such technologies. In addition, desalination supplies extra water with certainty so that the trigger can be lower.

A key result is that rain-dependent technologies are introduced much earlier. There are benefits in delaying the more costly desalination option. A key result is the ‘trigger’ strategy is optimal.

These are valuable and suggestive studies although each is hypothetical and neither describes a realistic decision problem. There is value in trying to get an analytical feel for the various factors that impact on infrastructure decisions given different forms of uncertainty using the dynamic programming approach. We turn to this issue in the next section.

## **2.4 Real options approaches to water supply investments**

The formal theory of real investments under uncertainty is complicated and, in empirical applications, data intensive (Dixit & Pindyck 1994). Applied research has mainly set out to either use simple theoretical models to gain qualitative insights or suggest heuristic procedures that draw on the major insights of this approach. Some theoretical models are suggested below in relation to a simplified water investment project. Further heuristic approaches are then discussed.

### **Simple models**

The intention here is to provide the flavour of relevant literature than draw on real options or SDP approaches without sacrificing mathematical rigor. The trade-off is to provide simple models that can be solved exactly or nearly so. Because dam and desalination technologies involve significant irreversibilities, it is not always correct to pose the policy problem as involving choice between a reversible and an irreversible technology and then using real options theory. However, standard SDP works in this latter setting.

Four models are developed. First, the reference model for desalination economics is discussed. Here the economics of a desalination plant are examined when the plant only becomes valuable when an alternative source of supply, stream-flow, fails because of an adverse climatic event. Second, a dam model is examined when the construction is subject to uncertainty because of climate change — in certain states of the world the dam becomes economically nonviable. These first two situations are a priori analytically similar. In each, the uncertainty is attached to a particular technology even if in the case of desalination it stems from valuation uncertainties attached to other technologies. Third, joint dam and desalination capacity expansion is developed. Fourth, the modular expansion of desalination capacity is discussed.

### Desalination economics — reference model

The generic situation envisaged above is now spelt out using real options theory. It involves an irreversible investment that is only valuable, and worth net water supply benefits ( $NB_d$ )  $NB_d > 0$ , if a certain state of the world,  $\theta_1$ , favourable to the technology eventuates. This might be the state that severe climate change forces reliance on desalination. In the second state of the world,  $\theta_2$ , the irreversible investment in plant is a redundant and unnecessary cost since existing infrastructure can costlessly provide water.

Suppose the respective states of the world occur with probabilities  $\pi$  (the desalination plant is valuable) and  $1 - \pi$  (the plant incurs a net cost). This view of the world is discrete in two senses. First the decision horizon operates over two periods, 'now' ( $t = 0$ ) and the 'future' ( $t = 1$ ). Second, a discrete all-or-nothing investment option in desalination is the sole investment option. In particular it is impossible to proceed with the plant in modular stages as discussed below under joint dam and desalination capacity expansion. If the plant is constructed, this is done at its long-term desired scale without first constructing a smaller plant.

If stream-flow does provide an adequate water supply then the alternative event  $\theta_2$  that occurs with probability  $1 - \pi$  arises, and the desalination plant is underused, providing negative net benefits ( $NB_u < 0$ ). Note that uncertainty is only experienced 'now'. It is resolved completely in the future when better knowledge about the climatic determinants of water supply is available. The decision to proceed with the plant can be made 'now' or in the 'future'; however, once made, it is irreversible because capital costs cannot be redeployed. Let  $x_i$  be a binary variable that takes the value 1 if a decision is made to have a plant in period  $i$ , and which is zero otherwise. The decision problem addressed is to determine when the decision to proceed with the plant should be made so as to maximise expected returns when the per-period discount rate is  $\delta$ . These discounted expected returns are:

$$E \equiv x_0 NB_d + \pi y_1 NB_d / (1 + \delta) + (1 - \pi) y_2 NB_u / (1 + \delta) \quad (2.3)$$

where  $y_1$  is the choice of  $x_1$  at  $t = 1$  if  $\theta_1$  occurs and  $y_2$  is the choice of  $x_1$  at  $t = 1$  if  $\theta_2$  occurs. Suppose  $(\pi NB_d + (1 - \pi) NB_u) / (1 + \delta) > 0$  so that the expected value at  $t = 0$  of having a plant in the future is positive. In this case, a sufficient condition exists for the project to have



positive present value initially, so  $E > 0$  is simply that the plant provides positive initial benefits. This is so when  $NB_d > 0$  as assumed. In fact,  $y_1 = 1$  since, in the favourable state of the world for the plant, it always pays to install one second-period even if one was not installed first-period. In addition,  $y_2 = x_1$  since, in the unfavourable state of the world for the dam, the first period decision will be sustained and the plant not built. Therefore:

$$\begin{aligned} E &= x_0 NB_d + \pi NB_d / (1 + \delta) + (1 - \pi) x_0 NB_u / (1 + \delta) \\ &= x_0 (NB_d + (1 - \pi) NB_u / (1 + \delta)) + \pi NB_d / (1 + \delta) \end{aligned} \quad (2.4)$$

Thus the decision to proceed with the plant at  $t = 0$  (so  $x_0 = 1$ ) should be undertaken provided:

$$\begin{aligned} NB_d + (1 - \pi) NB_u / (1 + \delta) > 0 &\leftrightarrow NB_d > -(1 - \pi) NB_u / (1 + \delta) \equiv QOV > 0 \text{ on recalling} \\ NB_u < 0 \end{aligned} \quad (2.5)$$

If we had assumed that expectations taken at  $t = 0$  were acted on without allowing for learning then the plant would be undertaken if  $NB_d > 0$ .

With irreversibility and risk this condition must be strengthened so that net benefits from the plant must exceed the quasi-option value ( $QOV$ ) arising from the loss of flexibility in undertaking construction early rather than waiting for uncertainty to be resolved.  $QOV$  is larger the greater is  $1 - \pi$ , the probability that stream-flow would prove adequate in the future.  $QOV$  is also greater when losses associated with building a plant (when a cheaper alternative source of water remains viable) are greater, and the greater the current valuation of these losses, the lower is the discount rate.

This is a simple model. It is isomorphic with the Arrow and Fisher (1974) conservation model that was the seminal early application of SDP to irreversible investments in a conservation setting. The result summarises much of the literature, suggesting that conventional cost-benefit criteria need to be tightened on desalination projects given the irreversibilities and uncertainties involved. The results arise because cheaper water might be available in the future from pre-existing technologies. The  $QOV$  stems from the fact that investment in desalination is irreversible but the decision not to invest is reversible and that, with time, knowledge of the economic viability of a desalination plant will improve.

The uncertainty considered here is assumed to arrive from the continued viability of pre-existing water supplies. However,  $\theta_2$  could be defined to include situations where desalination becomes non-viable because of higher fuel prices, which are the largest variable cost input of this technology. The case for deferring desalination investments by extrapolating recent cost decreases is complex because in the past these improvements have partly reflected declining energy prices as well as improvements in reverse osmosis desalination technologies. These latter improvements may not continue because prices of membranes used in these technologies may stabilise or increase with increased raw material costs (Cooley et al. 2006, p.44).

Uncertainty arises from the effects of random climate on stream-flows but it is this uncertainty that drives returns on a desalination plant. There are also climate-dependent alternatives to desalination plant construction, such as dams. The economics of such alternatives parallel those of desalination where, as just discussed, the viability of a backstop water technology is uncertain.

#### **Dam economics — case for expanding rain-dependent technologies**

The previous example can be equivalently set out for a rain-dependent water technology (a 'dam') that yields positive net water supply benefits  $NB_d$  provided pre-existing capacity provides inadequate water supply. This is an event ( $\theta_1$ ) with probability  $\pi$ . If pre-existing capacity does provide an adequate water supply, an event  $\theta_2$  that occurs with probability  $1 - \pi$ , the dam is underused and provides negative net benefits  $NB_u < 0$ . Again suppose two periods with uncertainty are resolved in the future. The decision to proceed with the dam can be made 'now' or in 'the future'. However, once made, it is irreversible. The analytics are as above.

Ignoring learning, the dam would be undertaken if  $NB_d > 0$ . With irreversibility and risk this condition is strengthened so that net benefits from the dam must exceed  $QOV$ , which arises from loss of flexibility in undertaking construction early. Again  $QOV$  is larger when: (1) the greater is  $1 - \pi$ , the probability that stream-flow would prove adequate in the future; (2) the greater are the losses associated with building a dam when a cheaper alternative source of water remains viable; and (3) the lower is the discount rate involved.

This analysis is isomorphic to that of the previous section. Taken together the analyses show that caution is needed with respect to irreversible investment in both rainfall-dependent and rainfall independent-technologies when these are seen as water-supply augmentation options. A  $QOV$  arises in each case either because the rainfall-dependent technology may fail or because the rainfall-independent technology may prove unnecessary. A key question is to examine what happens if both supply augmentation options are available.

#### **Joint dam and desalination capacity expansions**

Suppose water can be produced in two ways. It is convenient to suppose both of these expansion options are continuous so that large and small desalination plants and dams are feasible, although incremental expansion of a supply option is ruled out by assumption.

The analysis is generalised by allowing differing capital intensities in each water supply augmentation sector.

Suppose rain-independent technology (desalination) provides assured water  $F_1(K_1(t))$  in period  $t$  using capital  $K_1(t)$ . Alternatively rain-dependent (dam) investment  $K_2(t)$  provides water  $F_2(K_2(t))$  in period  $t$  if the state of the world is benign — rainfall does not decrease dramatically — or lesser benefits  $(1 - \alpha)F_2(K_2(t))$  with  $0 < \alpha < 1$  (a constant) if the state of the world is non-benign.

Suppose  $F_1$  and  $F_2$  are strictly concave differentiable functions, with  $F_1$  strictly increasing.  $F_2$  is initially increasing but may eventually decrease, reflecting the idea that viable dam sites may be in limited supply. For an initial range of capital stocks too suppose  $F_1 < F_2$ . Thus for at least an initial range of outputs desalination technologies are more expensive in terms of capital costs than dam technologies in state of the world  $\theta_1$ .

As before, both investments are irreversible. Denote the benign and non-benign states of the world as  $\theta_1$  and  $\theta_2$ , respectively, and the respective probabilities as  $\pi$  and  $1 - \pi$ .

The two situations envisaged with respect to the technologies are described as 'unlimited dam' options and 'limited dam' options, respectively. These are illustrated in Figures 2.2 and 2.3, respectively.

In Figure 2.2, abundant water supply expansion options are available. However, these experience diminishing marginal productivity with respect to rain-dependent and rain-independent technologies. Clearly specialisation in rain-dependent technologies is a possible optimal supply arrangement here.

In Figure 2.3, there are cheap though uncertain dam options but they are exhausted after a few small projects. Specialisation in rain-dependent technology is less likely.

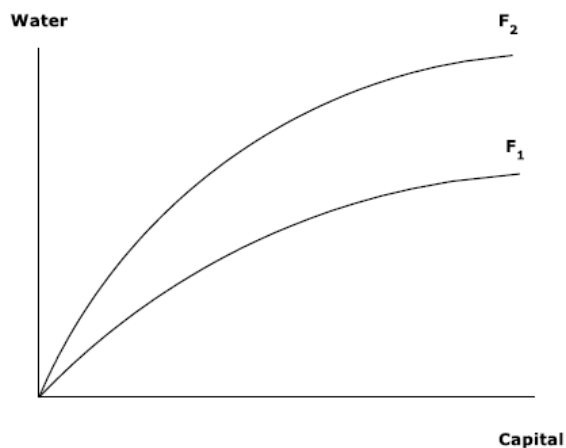


Figure 2.2. Unlimited dam options

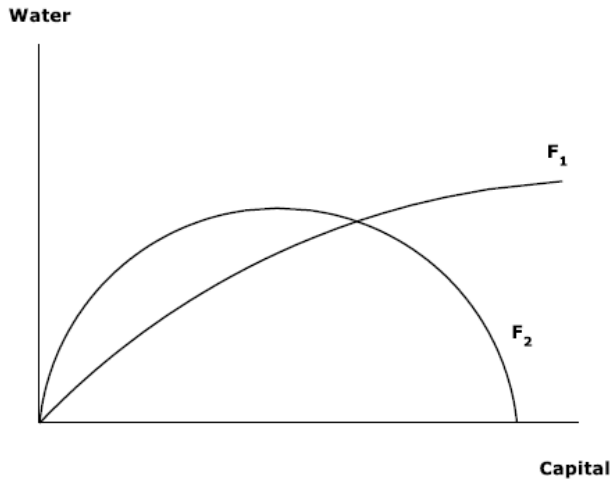


Figure 2.3. Limited dam options

Suppose the social utility gained from water is  $U(\cdot)$  a concave, differentiable function of supply in each period. In a simple way this introduces a demand side to the modelling. Water is assumed to be more valuable at the margin when it is scarce.

The cost of capital is  $r$  and the social discount rate  $\delta$ . Policy-makers seek an investment program maximising the discounted expected utility of water produced less the costs of capital. Thus policy-makers seek to maximise the expectation  $E$ , taken at  $t = 0$ :

$$E[U(F_1(K_1(0)) + F_2(K_2(0))) - rK_1(0) - rK_2(0) + U\{F_1(K_1(1)) + F_2(K_2(1))\} - rK_1(1) - rK_2(1)]\theta\pi + \{F_1(K_1(1)) + (1 - \alpha)F_2(K_2(1)) - rK_1(1) - rK_2(1)\}\theta(1 - \pi)] / (1 + \delta) \quad (2.6)$$

where  $x\theta y$  means that outcome  $x$  occurs with probability  $y$ .

Using the expected utility, equation 2.6 can be written:

$$U(F_1(K_1(0)) + F_2(K_2(0))) - rK_1(0) - rK_2(0) + \pi\{U(F_1(K_1(1)|\theta_1) + F_2(K_2(1)|\theta_1)) - rK_1(1)|\theta_1 - rK_2(1)|\theta_1\} / (1 + \delta) + (1 - \pi)\{U(F_1(K_1(1)|\theta_2) + (1 - \alpha)F_2(K_2(1)|\theta_2)) - rK_1(1)|\theta_2 - rK_2(1)|\theta_2\} / (1 + \delta) \quad (2.7)$$

where  $K_i(1)|\theta_j$  describes choice of  $K_i(1)$  when state of the world  $\theta_j$  eventuates for  $i, j = 1, 2$ .

It is natural to suppose here that  $K_1(1)|\theta_1 = K_1(0)$  since, when  $\theta_1$  occurs dam technologies deliver the desired water output, there will be no impulse to increase use of the more expensive desalination option. In addition, it is plausible to suppose  $K_2(1)|\theta_2 = K_2(0)$  since, if dams have reduced effectiveness because of climate change, there will plausibly be no interest in expanding use of such technologies in the future. Thus the theorem in equation 2.7 can be simplified to:

$$U(F_1(K_1(0)) + F_2(K_2(0))) - rK_1(0) - rK_2(0) + \pi\{U(F_1(K_1(0)) + F_2(K_2(1)|\theta_1)) - rK_1(0) - rK_2(1)|\theta_1\}/(1 + \delta) + (1 - \pi)\{U(F_1(K_1(1)|\theta_2) + (1 - \alpha)F_2(K_2(0))) - rK_1(1)|\theta_2 - rK_2(0)\}/(1 + \delta) \quad (2.8)$$

Equation 2.8 involves the decision variables  $K_1(0)$ ,  $K_2(0)$ ,  $K_2(1)|\theta_1$  and  $K_1(1)|\theta_2$ . Assuming second-order conditions for a maximum are satisfied and that interior solutions for both types of capital investments are obtained, the first-order necessary conditions for a maximum of equation 2.9 are:

$$U'F_1'(K_1(0)) = U'F_1'(K_1(1)|\theta_2) = U'F_1'(K_2(1)|\theta_1) = r \quad (2.9a)$$

where

$$U'F_2'(K_1(0)) = r + \Delta \quad (2.9b)$$

$$\Delta = \alpha U'F_2'(K_2(0))/(1 + (1 + \delta)/(1 - \pi)) > 0 \quad (2.9c)$$

Equations (2.9a–c) suggest the following. Investment initially in desalination capital and subsequently in the future, if climate change were to impact adversely on the ability of dam technologies, should earn competitive rates of return on capital equal to the cost of capital. The same prescription is true for future investments in dam technology should such technologies not be subject to adverse climate change effects. The value of these returns, however, is assessed at the gross marginal utility of water, which depends in part on water supply from dams. If this supply is low because low allocations are made to dam technology, then this marginal valuation will be high, promoting the case for alternative investments. The crucial optimality condition here relates to initial investments in dam technologies. These must exceed the competitive rate of return by  $\Delta$ , a factor that reflects the risk premium dam technologies must pay on first-period capital returns given the possibility of future underperformance of such technologies due to climate change. This is larger the greater is the future shortfall in water production from dams,  $\alpha$ , the greater is the probability of such an event  $1 - \pi$ , the lower the rate that future benefits are discounted and the greater is the value of the marginal product of water from dams.

The assumption of interiority here with respect to investment in dam technology is crucial. If only a limited or zero stock of extra dams could be constructed given the risk premium such technologies need to incur, then the supply of water from such sources would be limited and the marginal utility of such water increased. This would boost the case for investment in desalination technology.

### Modular expansion options and desalination

The model analysed in the section 'Accounting for risk', above, considers only a discrete all-or-nothing investment in desalination. Borison et al. (2008) and PC (2011) emphasise the case for constructing small rather than big desalination plants as a precaution for dealing with climate uncertainty. If expectations of climate impacts are uncertain it may make sense to defer the decision to construct a full-scale desalination plant in the future and use interim

policies (rationing and price-based demand management, temporary drawing down of groundwater resources, urban–rural trades) as a stop-gap. If climate change impacts ultimately prove less than catastrophic then the small plant is retained; if they are severe, the option remains to proceed to full construction in the future at the expense of some lost scale economies in construction.

To a limited degree this option has been used in the Wonthaggi plant discussed above. It has a designed capacity of 150 GL that can be expanded to 200 GL. It seems difficult to find information on the costs of achieving this type of flexibility. Evidence suggests there are significant economies of scale in all desalination technologies. Costs of producing water in small plants can be 50–100 per cent higher than in large plants. However at large scales these economies are still present but less important (Cooley et al. 2006, p.43). This does not in itself say much about the extra costs involved in constructing smaller plants that have the flexibility to be scaled up to larger plants. The core issue is the trade-off between realising economies of scale and flexibility (Sawhill 1989; Dixit and Pindyck 1994, p.51–54).

It is worthwhile delimiting the practical constraints on the case for desalination technologies. If current alternatives to desalination technologies, such as directly purchasing rural water, are much cheaper then it makes sense to select these simply because they are cheaper, and defer decisions on constructing desalination plants to the future when circumstances may change. In the case of the desalination plant constructed in Adelaide, the PC (2011) argued that water supply costs were 10 times those of directly purchased rural water. Purchasing rural water was presumably subject to political constraints imposed by interest groups associated with rural communities. However, the central issue is the existence of these constraints rather than ‘option value’ issues of deferring desalination investments until knowledge improves, supposing these rural sources of water remain available.

Now allow for a richer array of desalination investment options than we have yet considered. Initially, or first period  $i = 0$ , suppose a decision-maker can proceed with a full-scale desalination plant built to provide water flows  $W_{\max}$ , a smaller plant yielding water flows  $W_{\min}$ , or to build no plant at all. Ignore investment in other supply technologies so there is simply a backstop source of supply that is subject to climatic uncertainty. It is the effectiveness of this supply in the face of climate change that drives the viability of the desalination options. In the future, or second period  $i = 1$ , the same investment options arise subject to the constraint that disinvestment cannot occur and that an inefficiency arises if the desalination plant is scaled up. What choices should be made to maximise expected returns?

$W(i)$  here denotes the scale of installed water production capacity in the desalination plant in each of two periods  $i = 0$  and  $i = 1$ .

There are three possible future states of the world:

1.  $\theta_1$  occurs with probability  $\pi$ , and describes the state of the world where climate change effects are negligible in the future. If a desalination plant was not built initially it will not be built. If it was built initially at a low scale it will not be scaled up; if it was

- constructed at a large scale it will remain and will incur a net large sunk cost. Hence  $W(1) = W(0)$  and the future value of water from the desalination plant  $p(1) = 0$ .
2.  $\theta_2$  occurs with probability  $\beta$ , and describes the situation where moderate effects of climate change are experienced in the future. Construction only occurs on a small scale in the future if none was undertaken initially. If it was initially built at a small or large scale it will not be scaled up so  $W(1) = \max(W_{\min}, W(0))$ . The future value of desalination water  $p(1) = p > p(0)$ .
  3.  $\theta_3$  occurs with probability  $\gamma = 1 - \pi - \beta$ , and is the situation with severe climatic effects on stream-flow so dams provide significantly low water yields. Here  $W(1) = \max(W_{\max}, W(0))$ . This involves building a new large-scale plant from scratch, increasing a small-scale plant built initially to a larger scale or retaining a large plant. The future value of desalination water  $p(1) = p_{\max} > p$ .

The capital costs of installing a plant yielding water  $W_{\min}$  are  $c > 0$  and the costs of installing  $W_{\max}$  are  $C > 0$  if done as a single act of investment. However, the costs are  $c$  initially, then  $C' > C - c > 0$  if the plant is subsequently expanded from small to large scale.  $C' > C - c$  captures the loss of scale economies in not constructing the large plant as a single action.

A core trade-off here lies in the choice of flexibility over economies of scale. Building a small-scale desalination plant offers the prospect of not tying up very large amounts of capital if states  $\theta_1$  and  $\theta_2$  eventuate. However this saving must be offset against the loss of scale economies in carrying out the large-scale plant if state  $\theta_3$  eventuates.

The value of water from the desalination plant depends on initial water returns and investment decisions in the future. Suppose the world now is experiencing only moderate climate change so the per-unit value of water now is  $pW(0)$ . In the future when the state of the world is realised the value of water in state  $\theta_1$  is 0, in  $\theta_2$  it is  $pW(1)$  and in  $\theta_3$  it is  $p_{\max}W(i)$ . With discount factor  $d = 1/(1 + \delta)$  three development strategies are possible:

1. Build a large plant initially then inevitably retain that plant in the future. The net expected benefits are:

$$E1 = pW_{\max} - C + d(\beta pW_{\max} + \gamma p_{\max}W_{\max}) = W_{\max} (p + d(\beta p + \gamma p_{\max})) - C \quad (2.10)$$

2. Build a moderate-sized desalination plant immediately but reserve the decision on expanding the plant until the future state of the world is revealed. The net expected benefits from doing this are:

$$E2 = pW_{\min} - c + d(\beta pW_{\min} + \gamma p_{\max}W_{\max} - \gamma C') = W_{\min}(p + d\beta p) - c + d\gamma(p_{\max}W_{\max} - C') \quad (2.11)$$

The economics of this policy mean that large benefits and costs accrue immediately but there is low flexibility with respect to future investment decisions. Extra costs arise from the lost scale economies in constructing the desalination plant in a single stage.

3. Do nothing initially but wait to see how climate variability impacts. All costs and benefits from desalination are shifted into the future and maximum future flexibility are obtained. Net expected benefits are now:

$$E_3 = d(\beta p W_{\min} - \beta c + \gamma p_{\max} W_{\max} - \gamma C) = d\beta(p W_{\min} - c) + d\gamma(p_{\max} W_{\max} - C) \quad (2.12)$$

Here all current net benefits are foregone but future decisions can be taken optimally given the state of the world that emerges.

Here numerical methods and location-specific data must be used to make sensible judgements. It is difficult to come up with simple qualitative insights. The issues are the probabilities of moderate and the prospect of severe climatic responses. The costs and benefits of desalination technologies of different scales and the prospects of lost economies of scale in building smaller precautionary plants are important. Also important are the values attached to water in extreme states of the world.

Taking  $p = \$1$ ,  $p_{\max} = \$2$ ,  $W_{\min} = 50$ ,  $W_{\max} = 100$ ,  $\beta = 0.6$ ,  $\gamma = 0.2$  and  $d = 1$ , the nature of the restrictions on the various costs can be checked. It is easy to show  $E_3 > E_1$  if and only if  $C > 0.75c + 127.5$  so it is better to opt for total flexibility by deferring construction entirely until the future rather than building a large plant now if  $C > 0.75c + 127.5$  so if construction costs for a large plant now exceed a linear multiple of small plant costs. We have  $E_2 > E_1$  if  $C > 52 + c + 0.2C'$ . Thus a small plant now with the option to expand in the future is preferred to a large plant now if the costs of the large plant exceed a linear multiple of small plant costs and the cost of a plant upgrade.

These are stylised stories and other interpretations of the modular design issue are possible. For example, preliminary moves could be made to open the way for construction of a desalination plant in advance. Planning approvals could be established, land reserved for such uses and preliminary capital works undertaken. To the extent that such activities bring costs forward, they are ill-advised and destructive of present value. However, because such activities enhance flexibility by increasing the speed with which a sought-after project advanced once the evident need is made, they increase expected present value. These remarks are discussed further below.

### General insights and heuristic reasoning

The analytical examples provided highlight that risky irreversible investments must be cautiously approached. The case for making such investments upfront is not ruled out. However, this case must take into account that some circumstances may make such investments uneconomic. For the most part, the bias towards conservatism here has been interpreted above as a requirement that an irreversible investment must deliver an above-market rate of return.

Another way of looking at this issue is to think about taking actions that improve policy-maker flexibility. An example is to use the modular design option.



Important practical issues here involve the time to plan and construct a large capital project and the costs associated with these issues. If planning approvals and site purchase decisions can be taken at low cost but could take significant time to complete then they can be carried out in advance of possible construction. The cost of such investments in improving flexibility is the foregone present value.

The Wonthaggi Desalination Plant (WDP) being constructed in southern Victoria will supply 150 GL of water to urban Melbourne with the potential to expand production to 200 GL. Timing details on plant construction provide some perspective on flexibility issues. The decision to proceed with the plant was initiated by the Victorian Government in June 2007. Two years later the successful tenderer was announced for the project and construction began on 6 October 2009. The intention was for water output to be delivered in late 2011, about two years later. Bad weather has hindered construction so the starting date was extended to June 2012. Thus, the intended construction time was about equal to the time taken from deciding to proceed with the project and the appointment of the successful tenderer.

## 2.5 Portfolio issues

A different approach to thinking about the impact of risk on water supply planning is to analyse investment decisions as a type of portfolio problem. An investor holding a set of securities seeks a high expected rate of return but also low variance in the total return. Thus an investor typically prefers a portfolio that returns 10 per cent with certainty to a portfolio that pays 0 per cent with probability 0.5 and 20 per cent with probability 0.5. In this case the investor is risk averse and will pay a premium to avoid the risk. An investor with access to an actuarially fair insurance option will fully insure against risk. Alternatively, an investor that is indifferent concerning the two portfolios is risk neutral. In most — not all — option pricing literature, decision-makers are assumed to be risk neutral.

It is plausible to suppose water managers are risk averse since their customers are. Raucher et al. (2005) estimate the value of being able to access extra water during a severe water shortage in the USA at US\$3–20/kL.

It is straightforward to translate portfolio theories of finance into a water supply setting where yields reflect expected water supplies but where water authorities are averse to variability in supply. Accounting for risk aversion will make it optimal to diversify across sources of supply. Specifically, such accounting will include uncorrelated alternative sources of supply even if there are water productivity differentials. The difficulty is that many water options are discrete rather than continuous, so computational issues can become involved. Autocorrelation of supplies also imposes intrinsic dynamics on the management design task.

There are difficulties in specifying the appropriate degree of risk aversion. Often this is set out as the targeted probability of meeting a water supply reliability objective; for example, meeting a required minimum level of demand with a certain frequency such as 19 years out of 20. The greater the probability targeted, the greater the risk aversion. This is not entirely

adequate for specifying reliability since the extent of supply shortfalls matters as well as their frequency.

Ignoring this qualification we follow the discussion in Cooley et al. (2006, appendix D). First, define the reliability benefit sought. Take it to meet water demands in a large percentage of years. Think of the current portfolio of water supplies with mean annual average supply  $x$  and variance  $\sigma^2$  and assume these are normally distributed. If water supply must meet a minimum level of demand,  $D_{\min}$ , say 97.5 per cent of the time, then the mean supply  $x$  must satisfy:

$$x - 1.96\sigma = D_{\min} \quad (2.13)$$

Now distinguish old and new sources of supply with mean contributions  $x_0$ ,  $x_n$  and variances  $\sigma_0^2$  and  $\sigma_n^2$ , respectively. Suppose the correlation coefficient between new and old sources of supply is  $\rho$ . The mean aggregate water supply associated with new and old supplies is:

$$x = x_0 + x_n \quad (2.14)$$

The standard deviation of the new portfolio of new and old supplies is then  $\sigma^2$  given by:

$$\sigma^2 = \sigma_0^2 + \sigma_n^2 + 2\rho\sigma_0\sigma_n \quad (2.15)$$

We can ask what average yield of a new source of water  $x_n$  must be added to a pre-existing water supply to achieve the reliability standard (equation 2.13). In the case of a new desalination technology which yields water supply with certainty (so  $\sigma_0 = 0$ ), which is uncorrelated with pre-existing supplies (so  $\rho = 0$ ) from (equation 2.13), the reliability objectives can be met with lower mean water yields by scaling up the role of rain-independent desalination in the total. The probability distribution of supply outcomes is shifted to the right by adding the riskless supply. Reliability objectives can be met with even lower mean water yields if new sources of supply have low variability but are negatively correlated with pre-existing supplies.

The case for rain-independent desalination technologies can thus be justified on the basis of a portfolio approach. However, there are risks with this technology that arise from issues that go beyond rainfall dependence.

“Desalination is an option to be considered, on balance with other alternatives, when planning for future water supply shortages. The addition of desalinated seawater to a water supply portfolio provides a source of ‘new’ water, whose reliability is not linked to hydrologic variability (i.e., droughts). Of course, a water supply portfolio that is unbalanced in any direction can carry unexpected risks. Although the addition of desalination facilities can improve reliability under some circumstances, excessive reliance on desalination may have important energy implications in regions with constrained or unreliable energy supplies. Centralized desalination facilities may also carry security or seismic risks that require special attention.” (National Academy of Sciences, 2008, p.45).

## 2.6 Accounting for uncertainty

In economics a distinction is often drawn between situations of risk and uncertainty. Risk arises where all the possible outcomes or states of the world can be enumerated and probabilities attached to these outcomes. For example we might believe that with certain climate policies the chance of moderate water shortages is 0.7, the prospect of extreme water shortages is 0.25 and the probability of no water shortages at all is 0.05. Uncertainty arises when all possible states of the world can be enumerated but probabilities cannot be assigned to these states. Still more complicated situations arise where we neither know the states of the world that might arise — these are ‘unknown unknowns’, to use the expression made famous by Donald Rumsfeld. Henry and Henry (2002) refer to such situations as ‘gross ignorance’. In this setting, ‘surprises’ can occur. These are events that were not anticipated to be possible in the ex ante outcome set. For example, most people would not see global cooling and a resulting increase in water supplies as a possible outcome. In the main, only situations of uncertainty are considered here so that, with respect to climate change, the definite outcomes that are envisaged to occur are the only possible outcomes.

To simplify, suppose that the only possible states of the world that can eventuate with respect to investment in water augmentation technologies are:

1.  $S_1$  represents the state where severe climate change occurs, causing extreme water supply shortages that can be met by constructing a large desalination plant at cost  $C$
2.  $S_2$  represents the state where moderate climate change occurs, creating moderate water supply shortages that could be offset by a low-cost dam project or, at greater cost, by a desalination plant; the cost of the dam is  $CD$
3.  $S_3$  represents the state where severe climate change occurs and where desalination technologies fail to deliver a satisfactory water delivery. For example, the desalination plant may become uneconomic because energy costs associated with its operation are excessive. Whether or not  $S_3$  occurs — so the rainfall-independent supply option fails — has important implications for the analysis.

Suppose that both the dam and desalination technologies achieve desired water supply targets under moderate climate change but the dam partially fails with severe climate change.

The situation of uncertainty is considered so probabilities of various states of the world are unknown. The costs of pursuing the various options are set out in Table 2.1.

Table 2.1. Costs of water supply outcomes

	S1	S2	S3
Build desalination plant	C	C	C + L
Build dam	CD + Med	CD	CD + Med
Do nothing	L	M	L

*Costs of not meeting water demands at all with extreme climate change are L, not meeting moderate climate change are M, and providing only a dam when climate change induces severe water shortages are Med.*

Suppose here that  $L > C > CD$  and  $L > CD + Med > M$ . The losses incurred when severe climate change occurs but no desalination technology is employed exceed the costs of the desalination plant, which in turn exceed dam costs. Also suppose these losses exceed the total costs incurred when a dam is built that partially addresses these shortages. Thus, there is some net gain in building a dam when severe climate change occurs. More contentiously, suppose costs of partially addressing severe climate change with a dam exceed the costs of the shortages that arise when moderate climate change occurs but no dam is built.

An approach to choosing among the supply options is to use the ‘minimax decision criterion’. This involves choosing a supply option that minimises the worst that can happen given the uncertainty. This is sometimes viewed as a form of the ‘precautionary principle’ of environmental economics. The worst outcome that can happen in Table 2.1 is that a desalination technology is used but it fails, giving costs  $C + L$  so it will never be employed. Since  $CD + Med < L$ , the best policy in this situation is to do nothing. As a general principle, minimax will not favour selection of a costly policy that addresses a catastrophic risk that can ever fail. The worst that can happen is that the policy cost occurs, the policy fails and the catastrophe occurs.

If state of the world S3 is ruled out — so desalination policies always have their desired consequence — then only states of the world S1 and S2 are relevant. The maximum cost of building a desalination plant is then  $C$ , the maximum cost of building a dam is  $CD + M$  and the maximum cost of doing nothing is  $L > C$ . The policy of doing nothing will not be used and the decision rule will be to build the desalination plant if  $CD + Med > C$ , or build the dam otherwise.

An unattractive feature of this solution is that it might turn out that taking no action to address water shortages makes sense whenever a costly policy might fail. Another decision rule sometimes considered to avoid this impasse is to compute the regret that would be experienced in various states of the world given various policies, and to act to minimise the maximum regret. This is the ‘minimax regret decision rule’. Regret measures are set out in Table 2.2.

Table 2.2. Policy regret experienced

	S1	S2	S3
Build desalination plant	0	$C - CD$	$C$
Build dam	$L - Med + CD - C$	0	0
Do nothing	$L - C$	$M - CD$	0

For example, if a desalination plant is constructed and severe climate change occurs, there is no regret. Similarly, with moderate climate change and a dam there is no regret. If a desalination plant is built but is ineffective in dealing with climate change the regret is the wasted resource cost  $C$ . If only moderate climate change occurs and a desalination plant is built rather than a dam, the regret is the unnecessary extra costs incurred,  $C - CD$ . If nothing is done when climate change occurs then the regret is the respective cost, which is the cost of the policy avoided. If a dam is built and severe climate change occurs, with outcomes that would not have been avoided by a desalination plant, there is no regret. Finally, if a dam is built when a desalination plant would have better dealt with severe climate change, the loss is the extra water costs saved less the saving in capital costs.

The maximum regret from building a desalination plant occurs with S3 and is  $C$ . The maximum regret from building the dam is  $L - Med + CD - C$ , which can plausibly be supposed positive. The maximum regret from doing nothing,  $L - C$ , is presumably in S1 if, as is plausible,  $L - C > M - CD$ . One policy rule then is to select the option with minimum maximum regret — this is the option that makes the policy-maker regret least. If  $L - C > C$  so  $L > 2C$ , then building a desalination plant involves less regret than doing nothing. It remains to judge whether building a desalination plant involves less maximum regret than building a dam. It does if  $L > 2C + Med + M - CD$ , which puts a lower bound on the losses that occur with desalination.

This is only an example of the types of computations and decision-making procedures that can be used when probability information is unavailable. Other scenarios can be explored. The approach is set out more fully in Clarke (2010).

## 2.7 Catastrophic risks

Climate change scenarios offer the possibility that certain states of the world will eventuate with non-negligible probabilities that are associated with extremely large social costs. Such situations involve ‘catastrophic risks’. In the past the main catastrophic events envisaged with respect to water supply were the extreme and occasionally protracted water supply events of flood or drought as well as supply disturbances associated with dam failure perhaps due to earthquake. We are more interested in events whereby water supply is so affected by climate change that potable water becomes in extremely short supply for a significant segment of the population for an extended period. Then the policy problem of addressing climate change becomes straightforward in a cost–benefit sense because policy actions, if available, will be taken to offset the large social costs incurred whenever such extreme risks are non-negligible. The optimal extent of risk mitigation will depend on the costs of mitigation compared with the benefits in terms of risk reduction.

These problems resemble many pre-existing water infrastructure investment issues. The secular effects of climate change are likely to be gradual and will plausibly operate over a time scale that leaves the construction of feasible alternative rain-independent sources of supply such as desalination options possible. Severe extended droughts have been repeatedly experienced in Australia and the appropriate response has been and will continue to be a mix of temporary demand-management and supply-side options. There is a serious potential option pricing issue associated with the timing of a lumpy irreversible investment problem. However, this again involves issues of valuation at the margin — between postponing an irreversible investment when it might prove of low value and acting to realise it. There is not really a longer term sudden issue of avoiding potential catastrophic costs by making significant anticipatory investment actions. More plausibly there will be a conjunction of short-term emergency measures such as demand restrictions and a reactive investment response.

## 2.8 Concluding remarks

The problems imposed by climate change raise option pricing and, more generally, stochastic dynamic programming issues. Investments in water supply augmentation can take the form of rain-independent technologies such as desalination or the augmentation of rain-dependent technologies such as dams. The location of uncertainty in these investment problems determines where *QOV* arises and where incentives to ‘wait to’ invest arise. Mostly we have relied on simplified analytical models that give exact analytical results rather than larger scale models that, to this point, seem to rely on simulated data.

There are many important issues that have not been addressed. One is the determination of investments in wastewater treatment where significant economies of scale might be expected. There are relatively low costs in installing additional drainage capacity to deal with extreme runoff events. It makes economic sense to include generous safety margins in making these types of capacity decisions.

Water quality issues have not been addressed. This is important since desalination technologies potentially have the ability to provide better quality water than alternative sources can provide.

The issue of technological advances in delivering water supply options such as desalination has not been considered. The prospect of continuing trends toward cheaper desalination would compound option value arguments for delaying use of such technology. This case is complex. Past cost reductions have been associated with decreasing real energy prices and with technological improvements, neither of which may continue (Cooley et al. 2006, p.44–45).

Finally, at a conceptual level, an issue left unexplored is the integration of option pricing approaches with portfolio theories of water supply. Option pricing arguments suggest a case for delaying risky irreversible investments while portfolio arguments suggest diversifying them. Integrating these views is difficult because of the lumpy character of water supply investments.

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## 3. Infrastructure provision with an uncertain climate, urban water risk aversion and urban water decisions

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*John Freebairn*

### 3.1 Synopsis

Application of the product characteristics model and the finance portfolio choice model are used to illustrate the important effects of risk aversion held by decision-makers for the urban water markets. Decision-makers face uncertainty about water demand, water inflows and supply costs, and about government policy. Relative to risk neutrality assumed in many models, risk aversion changes decisions about the management of available water supply infrastructure, and about the form and timing of supply augmentation options. Recognising heterogeneity of buyer preferences with respect to risk suggests efficiency gains from offering a variety of cost-security of supply characteristic packages to water buyers.

This chapter is based on Freebairn (2012).

### 3.2 Introduction

Imperfect knowledge is an important characteristic of the urban water market. There is imperfect knowledge about demand, supply and government policy. Imperfect knowledge about the demand function can arise from imperfect forecasts of future levels of key shift variables such as population growth. Also, different available estimates of parameters such as price elasticity, which are often provided only as sample estimates with error bands, have error terms often more than one-third of the variation in the quantity.

Imperfect knowledge about the mathematical function for supply of urban water includes the variability of inflows to dams and now the likelihood of climate change-induced changes in the inflow distribution. Also, the capital and operating costs for new supply augmentation options are affected by changes in technology and relative input costs.

Extensive government intervention in the urban water market brings further imperfect knowledge about such things as future regulated prices, quantitative regulations on demand, and restrictions on and approval processes for different supply augmentation options. A focus of this chapter is imperfect knowledge, about risk or uncertainty, about the security of urban water supply.

Recent economic studies of decision-making about prices, regulations and water supply augmentation for urban water in Australia have explicitly recognised stochastic variability of inflows to dams; the importance of intemporal links of water demand, water inflow and the storage level; storage costs and capacity limits; and the lumpy and sunk cost characteristics of supply augments. Hughes et al. (2008, 2009) and Grafton and Ward (2010) use stochastic dynamic programming models, and the Productivity Commission (PC 2011) uses a very large

linear programming model. These studies maximised expected welfare, and implicitly assumed decision-makers are risk-neutral. This chapter asks whether risk aversion would result in different decisions about prices and storage levels, and on the forms and timing of supply augmentation investments. Further, it asks whether risk aversion would affect the magnitude of estimates of the efficiency costs found in these studies of regulations. It compares such estimates against adaptive prices to influence demand in response to variable inflows, and the timing and scale of investment in the desalination plant supply augment option.

This chapter uses an interpretation of Lancaster's (1971) product characteristic model. For illustration, we assume water has the two characteristics of average quantity supplied (or average cost) and security of supply (or probability of strong restrictions, very high prices, or both, in response to quantity demanded approaching available supply). In principle the model can be extended for a larger number of characteristics. These might include minimum health risks, water taste and other quality attributes, and perceptions of quality associated with recycling and stormwater.

The model is used to assess the effects of different degrees of risk aversion, from the extremes of risk neutrality to highly risk averse (or drought proofing), on urban water market decisions. These decisions affect the management and pricing of water and the form and timing of investment in supply augmentation. A variant of the finance portfolio choice model, where the water portfolio options have average cost and security of supply characteristics, provides similar results. Alternatively, the stochastic dynamic programming and linear programming models noted above could be improved to include risk aversion in the objective functions. However this means considerable additional computational challenges. The state contingent model of Chambers and Quiggin (2000) likely offers another framework.

The rest of the chapter is as follows. Section 3.3 considers the different players and decisions in the urban water market. Particular attention is given to evidence for risk aversion in key decision-making, and to options for decision-makers to measure risk. These options relate back to the fundamental sources of risks associated with imperfect knowledge about buyer demand for water and about inflows into dams.

Section 3.4 describes the Lancaster model for urban water with the two characteristics of average cost of water and security of supply to households. Illustrative applications of the model are provided for different types of decisions:

- choice of storage rules for a given supply infrastructure capital stock
- comparison of adaptive prices vs selective regulations in constraining quantity demanded
- heterogeneous household preferences in terms of different relative marginal rates of substitution for the average cost and security of supply product characteristics the benefits of different water packages for households
- choice of investment to augment supply across options with different product mix characteristics, in particular desalination with relatively high average cost and high security.

For each illustration, the effect of risk aversion relative to risk neutrality is explored. The reality is there are significant differences across different urban areas, and over time for each area, in both buyer preferences and in supply opportunities. Thus, there is no one-size-fits-all set of welfare-maximising decisions. Section 3.5 briefly discusses a version of the finance portfolio model as an alternative.

### **3.3 Decision players and risk aversion**

Decision-makers (or players) for urban water include final consumers of water such as households, businesses, local governments and environmental water managers, as well as water utilities that supply and treat water. In most instances government departments and agencies are also key decision-makers affecting water demand, storage, price and investment decisions.

In addition to describing the decisions of each group, this section focuses on evidence of the role and importance of attitudes to risk in the objective functions of different players with imperfect information about water inflows, technology, input costs and the reactions of other players. The focus is on the variability of future inflows of water to dams, aversion to the risks of demand exceeding available future water supplies, and how the risks might be allocated.

#### **Households**

Households consume about 60 per cent of the water supplied by water utilities. Less than one-half of this represents 'essential to life' indoor use (Australian Bureau of Statistics (ABS) 2011, p. 4610). Given markets or governments set prices and regulations, household decisions are primarily about the quantity of water to purchase.

Studies have estimated the social cost of water restrictions on the use of water for some household uses, reporting large social costs. Some studies indicate significant heterogeneity of household preferences. Gordon et al. (2001), Hensher et al. (2006) and Grafton and Ward (2008) used choice modelling survey techniques to estimate the willingness to pay to avoid water restrictions. Brennan et al. (2007) used a household production function model to estimate the additional costs to households of foregone leisure and poorer lawn products imposed by water restrictions. In each study, average social costs of water restrictions per household were found to increase with the severity of the restriction, and the high levels of restrictions of recent years were estimated to have social costs as high as one-half of the annual water bill. Brennan et al. (2007) and Cooper et al. (2012) also report significant differences among households about the costs of water restrictions, providing evidence of the heterogeneity of preferences regarding the security of urban water supply.

Other studies have considered the relative costs of allocating a limited quantity of water for urban use through a general price increase rather than the arbitrary 'one size fits all' restrictions on outdoor water use. In principle, the common method of increasing water price costs less because it equates the marginal social value of water used in different ways by each household. It equates the marginal social cost across different households (Edwards 2006; Sibly 2006; Grafton & Kompas 2007; PC 2008). These studies also question the equity

advantages of the price method relative to regulations. These studies point to the efficiency costs of multi-step tariffs by creating differences in marginal social costs across different users. Even a two-step tariff with a first step for 'minimum essential water use' to meet an equity objective involves an efficiency loss; but with a low demand elasticity, it is a small loss. However, more direct and explicit social security payments, including family allowances, better target families of different sizes or with low incomes.

Formally, we can express an individual household utility function with a focus on water as:

$$U = f(Q, S, O) \quad (3.1)$$

where  $Q$  is the quantity of water,  $S$  is the security of supply and  $O$  represents other goods and services. The first partial derivatives of  $Q$  and  $S$  are positive with negative second derivatives. In practice,  $S$  might be represented by the inverse of different combinations of the frequency of regulations on outdoor use and the severity of the restrictions (e.g. days and times of watering and limitations on using sprinklers and washing cars and pavements), or by the inverse of the frequency and level of relatively high prices to ration limited aggregate available water. Special cases of equation 3.1 include that of risk neutrality with the first derivative of  $S = 0$ , and an insistence for drought proofing with the first derivative of  $S \rightarrow \infty$ . Household heterogeneity with reference to differences in risk aversion can be represented by differences in the marginal rate of substitution, or relative marginal utilities, for  $Q$  and  $S$ .

## Businesses

Hensher et al. (2006) used a choice modelling study to find that businesses in the Australian Capital Territory (ACT) have a similar willingness as households to pay to avoid water restrictions.

## Environmental flows

Allocating available water for environmental flows has become a more explicit and important competing source of demand for water over time. In part this reflects a combination of higher incomes and environmental amenity as a normal, if not a superior, good. It also reflects the outwards shifts of demand for water by households and businesses with the growth of population and income. Further, there is a better understanding of the public good property of water for the environment, and the need for government intervention to correct the market failure. There is an important complementarity between environmental needs and security of supply of water for consumption because many environmental needs are for variable supplies, which mimic natural water flows. On the other hand, previous relegation of the environment as a residual consumer is being challenged.

## Water utilities

In most Australian urban areas, government-owned water utilities provide most of the services for treating and delivering water to final consumers. Given the natural monopoly status of supply of most of these services, the water utilities are regulated by independent price-setting bodies appointed by governments. They are constrained in other ways by government legislation regarding equity of access and water quality, for example. In general,

operations are easier and public support better for the utilities if supply is more than enough for the quantity demanded. Then, by implication, the managers of water utilities also are risk averse to low stocks of water and for demand to exceed supply.

Governments in Australia have maintained high direct and indirect involvement in urban water. Indirect involvement includes ownership of most water utilities, the establishment of a regulatory system on water prices and qualitative regulations on the time and form of use of water by households, businesses and local governments. Governments are directly involved in water supply through lumpy and infrequent investments in supply augmentation. These include investing in new dams, interconnecting pipelines, desalination and recycling plants, stormwater capture and underground water, wastewater treatment. Anecdotal evidence shows that security of supply is one factor considered. Certainly governments prefer not to have to impose regulations or other measures to ration what the public perceives as threats to security of supply. On the other hand, there is no publicly provided information on the weight attached to security of supply relative to other characteristics, in particular, the average cost.

We turn next to possible formal models that explicitly include security of supply as a valued characteristic, but also a characteristic with costs of supply. The models help make decisions on managing the current supply capital stock, and identify potential gains in differentiated product characteristic packages to meet heterogeneous buyer preferences, and the form and time of new investments to augment supply.

### 3.4 Multiple product characteristics model

Figure 3.1 recasts the Lancaster (1971) product characteristics model for urban water to analyse the implications of risk aversion for several decisions regarding urban water. The two product characteristics are average quantity of water, or the inverse of long-run average price per unit supplied, and security of supply. Security of supply might be measured as the inverse of the probability of water restrictions and/or the severity of water restrictions, the stability of prices that equate supply and demand, or the ratio of the opening stock in storage relative to quantity demanded.

Water buyers benefit from these two product characteristics, with equation 3.1 providing a formal view. From equation 3.1 a set of indifference curves concave to the origin with the marginal rate of substitution (MRS), which equals the ratio of marginal utilities of the two characteristics, are drawn. One of the family of indifference curves,  $I$ , is shown in Figure 3.1. Preferences for greater security of supply or risk aversion steepen the indifference curves. Different buyers can have different preferences. As shown, initially it is assumed that there is homogeneity across all buyers, or that it provides an appropriate aggregation of heterogeneous preferences, and that there is some risk aversion.

A production possibility frontier (PPF) is a general framework for expressing the opportunity costs of providing the two water characteristics with different decision choice options. Figure 3.1 shows the example of three different water storage management strategies given the existing investments in infrastructure. By way of illustration, strategy 1,  $S_1$ , involves very

little inter-year carryover storage; as a result it provides a relatively insecure supply, but with very small storage losses to evaporation and seepage and a low risk of a spill. Collectively these mean there is a relatively low average cost per unit of supply. Strategy 2, S2, is roughly the opposite with a high inter-year carry-over storage; as a result there is a relatively high security of supply, but at a higher cost per unit due to greater storage losses associated with evaporation and seepage and a higher probability of spills. An in-between strategy 3, S3, completes the available options. The PPF combines the offerings of the three strategies is shown as the curve A–S1–S3–S2–B in Figure 3.1. It has a quasi-concave shape, and approaches a continuous smooth function with more strategies.

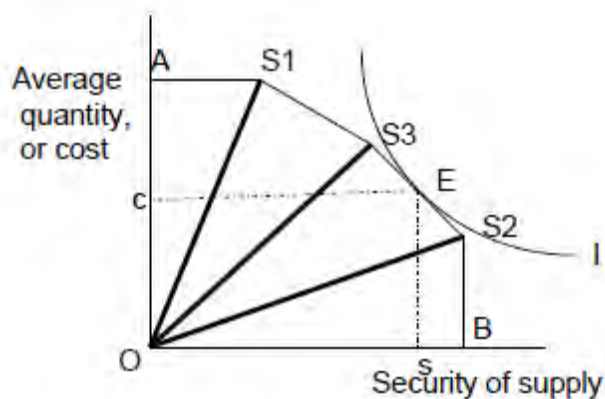


Figure 3.1. Evaluating water storage strategy options

Given the aggregate preferences represented by the indifference curve I and the production PPF represented by A–S1–S3–S2–B in Figure 3.1, the welfare maximising strategy for storage rules to provide the urban water attributes of average cost of water and security of supply is given at point E. This involves a linear combination of the two water storage management strategies of S2 and S3, yielding an average cost  $c$  and a security of supply of  $s$ . In practice, this suggests further investment in a strategy between S2 and S3, and in particular one that extends the PPF beyond the S3–S2 approximation.

### Effect of risk aversion

The special case decision problem is shown in Figure 3.1 for choosing the water storage strategy given the current infrastructure capital stock to maximise buyer utility. This can be used to illustrate the effect of risk aversion on decisions. Greater risk aversion to demand exceeding available supply means a steeper indifference curve and larger MRS and willingness to pay for water security, leading to a more conservative chosen water storage strategy. In the extreme, S2 would be chosen.

By contrast, a risk-neutral model solution, with an implicit horizontal indifference curve in Figure 3.1, would choose S1. If preferences are represented by I with some risk aversion, a choice of S1 would place buyers on a lower indifference curve and loss of welfare. The magnitude of this loss could be measured in the usual ways as a compensating or equivalent variation.

Choice of a very conservative storage strategy with the objective of drought-proofing implies the indifference curve in Figure 3.1 is close to vertical.

Figure 3.1 also illustrates that different urban areas and the same area over time will likely choose different storage management strategies (and mixes of the water characteristics). Almost certainly the position and shape of the PPF will vary with topography, climate and other factors from one city to another. For any urban area with population growth, it is most unlikely that the sequence of PPF will be a homothetic. Preferences driving the relative marginal utilities of the different water characteristics are likely to vary across different urban areas, and they will vary over time with changes in income, urban density and lifestyles.

### Heterogeneous preferences

Consider next the implications of heterogeneous preferences, and in particular where some buyers are more risk averse or willing to pay a higher premium to ensure supply exceeds demand more often than not. Figure 3.2, as for Figure 3.1, shows the case of urban water with the two characteristics of average quantity supplied (or the inverse of average cost) and security of supply (or lower probability of water restrictions and/or high scarcity prices to balance supply and demand in times of low opening storage and inflow). A smooth convex to the origin PPF shows the feasible options associated with, for example, more conservative storage rules and higher proportions of more stable manufactured to rain-fed water supplies. The indifference curves across the average cost and security of supply water product characteristics for buyers with different preferences are shown as I1 for the relatively risk-neutral buyer and I2 for the relatively risk-averse buyer. Relative to a one-size-fits-all treatment that all consumers have homogeneous preferences, say product characteristic input mix *E* of Figure 3.1, offering buyers the choice of retail packages with different mixes of the characteristics,  $c_1s_1$  and  $c_2s_2$ , would raise the welfare of both sets of buyers. This is a point made by the PC (2008) and others.

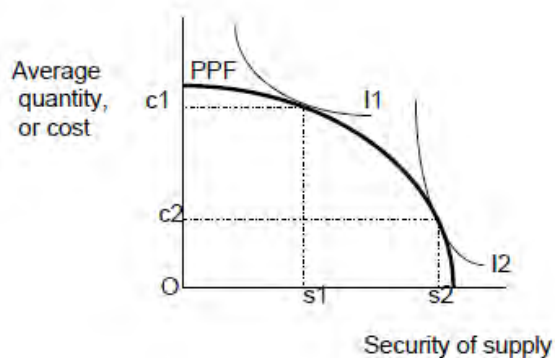


Figure 3.2. Heterogeneous buyer preferences

### Mixes of water product characteristics

A potentially important application of the product characteristics model is to assist the choice of supply augmentation investment options with different mixes of water product characteristics. Of current relevance around Australia is the choice between the higher cost and secure supply desalination plant and the lower cost but variable rain-fed dams. Other

potential supply augmentation investment options include interconnections to link dams with imperfect correlations of inflows, storm water capture and treatment, more- and less-aggressive storage carryover strategies and underground water. Suppose \$X bn is available to invest, with a choice of supply augmentation options to meet projected increases in demand with population growth and/or lower supply from existing investments with climate change. Several investment options provide different mixes of the consumer-desired water product characteristics of average cost and security of supply.

Figure 3.3 shows the preliminary offerings of the different investment options in terms of their mix of the average quantity and security of supply characteristics. Option A might be a new dam with relatively low average cost and relatively low security of supply. Option C is a desalination plant, which has the opposite characteristic mix. Option B might be a smaller dam with interconnection pipelines. Together, these options would provide a PPF A–B–C.

Consider other supply augmentation options. Suppose option M involves the new dam of A, but with a more proactive interseasonal storage strategy (resulting in greater security but at a loss of water to evaporation, seepage and spills). As shown, this option falls within the PPF; it is dominated by a combination of A and B (unless economies of scale are very important) and can be ignored from further analysis. Option N, for example stormwater collection and storage underground, provides a ray of water product characteristics outside the A–B–C PPF. It becomes a worthy addition to the choice set, and, while not illustrated in Figure 3.3, it could dominate one or more of the A, B and C investment options.

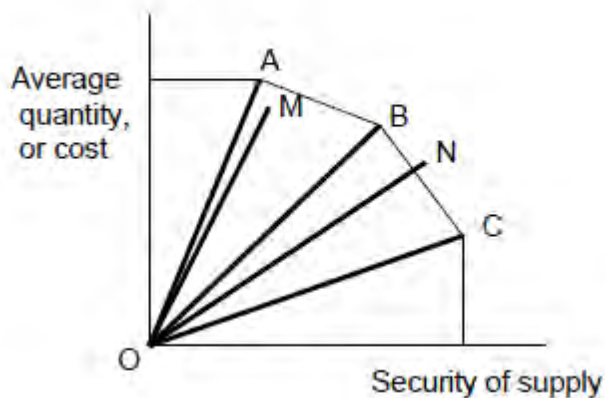


Figure 3.3. Evaluating new investment options to provide water

### Aggregate indifference

Following this early ranking of investment options, and retaining only those on the PPF, the choice of investment option, or combination of options, requires bringing into Figure 3.3 a measure of the aggregate indifference curve for decision-makers. The analysis finds the combination for the highest feasible indifference curve. The efficient choice for society equates the marginal willingness to pay for additional supply security with the marginal cost of its supply. The more risk averse the decision-makers, which ultimately should refer back to



urban water users, the higher the proportion of the available funds allocated to the higher security of supply investment options.

Analyses assuming risk neutrality as an approximation when risk aversion is important will dismiss desalination more often and relegate the option to a smaller share of investment in supply augmentation than is consistent with society optimisation. Also Hughes et al. (2009) show that desalination can have a higher option value than a rain-fed dam, because desalination guarantees supply when completed but a dam depends on uncertain rainfall.

Conflicting logical arguments exist on whether greater risk aversion brings forward the time of supply augmentation investments. It is likely the answer will require empirical assessment. A preference for greater security of supply with risk aversion would, *ceteris paribus*, bring forward a supply increase investment, reducing the probability of demand exceeding supply. Working in the opposite direction, the more conservative management strategy with existing supply infrastructure results in less demand per year, but also higher average carry-over storage and more losses to evaporation and spills. Also, to the extent risk aversion favours desalination and perhaps later investment compared with the lower average cost but more risky new dam option, the supply augmenting investment might be delayed. Potentially important empirical factors driving the net outcome include the elasticity of demand to higher prices, the magnitude of losses associated with more aggressive carryover storage, and relative costs and reliability characteristics of the different supply augmentation options.

Again, it is important to note that the position and shape of the investment PPF will vary among urban areas, and for each urban area over time. Thus, the socially efficient mix of investment choice options and resulting mixes of water product characteristics will vary with urban area and time.

### 3.5 Portfolio model

A variant of the expected value-variance model of portfolio choice of the finance literature provides another option for assessing the effect of risk aversion on urban water decisions (Fig. 3.4). Here the vertical axis represents the average cost per unit of water supplied and the horizontal axis represents the security of supply (or inverse of the variance or standard deviation of supply each year). The PPF slopes upward and is convex, indicating that security of supply of urban water can be achieved, but at a rising marginal cost. Examples are more aggressive storage carry-over management and a higher proportion of supply augmentation in desalination plants. A set of concave indifference curves represents a decline in marginal utility for additional security and rising marginal utility for a smaller average quantity (purchased at a higher average price).  $I$  is shown as the highest attainable indifference curve resulting in a welfare maximising portfolio choice with urban water product characteristics  $c$  and  $s$ .

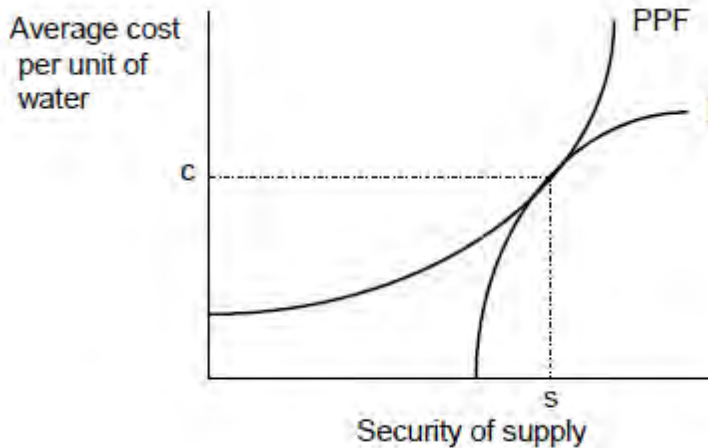


Figure 3.4. Portfolio choice model

Different levels of risk aversion have important effects on choice decisions for the urban water market. In Figure 3.4, more risk-averse water decision-making produces a steeper indifference curve, and the choice shifts to a higher average cost and higher security of water supply option. This result is similar to that reported with the product attributes model.

### 3.6 Concluding remarks

This chapter argues that risk aversion to demand running ahead of supply is important to the objective of decision-makers in urban markets. This chapter also argues that risk aversion relative to risk neutrality leads to different decisions if: (1) society is to choose welfare-maximising decisions about the management of existing water supply infrastructure; and (2) decision-makers choose to augment supply according to population growth and the likelihood of climate change. Choice modelling studies of willingness to pay to avoid water restrictions and the costs of water restrictions in a household production model indicate high risk aversion by households, and also heterogeneity of preferences.

A product characteristics model is used to assess the effects of risk aversion on some key decisions in urban water markets; a portfolio model would generate similar results. Relative to a risk neutral model, risk aversion would involve a more aggressive storage carryover management strategy; it would increase the share of augmented supply provided by more costly but also more reliable supply augments such as desalination and recycled water plants. The heterogeneity of attitudes to risk warrants investigation of the benefits of offering buyers different security of supply and average cost water packages. These decisions will vary across different urban water markets with differences in choice options and preferences, and over time.

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## 4. Institutional reforms to enhance urban water infrastructure with climate change uncertainty

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*Ananda Jayanath*

### 4.1 Synopsis

Climate change adds another layer of uncertainty to the complex issue of urban water infrastructure provision. This section evaluates the regulatory and planning frameworks surrounding the urban water infrastructure provision in Victoria and examines the constraints water businesses face adopting adaptive infrastructure decisions. This paper contends that future reforms need to focus on clarifying roles and objectives of water agencies, removing barriers to supply augmentation options including inter-sectoral transfers and creating a regulatory model that embeds flexibility in infrastructure decision processes.

This chapter is based on Jayanath (2012).

### 4.2 Introduction

Climate-related supply security concerns have recently instigated a renewed focus on urban water infrastructure investment. The water supply–demand imbalance has triggered numerous supply augmentation projects across Australia. In Victoria, these investments included the \$3.5 bn Victorian Desalination Plant (VDP) at Wonthaggi and the \$750 M North–South Pipeline that connects the Melbourne water system to the Goulburn River. In addition, \$2.5 bn has been allocated to new supply pipelines, sewerage schemes and wastewater treatment over 2008–2013 (Essential Services Commission (ESC) 2008). Most investment proposals have opted for large scale infrastructure projects rather than combining multiple smaller projects, which may provide greater flexibility in implementation, if and when they are needed. It is contended by the author that inefficient urban water supply augmentation has resulted in billions of dollars of expenditure to the Australian community recently.

Water businesses operate in a complex regulatory and planning environment (‘water business’ and ‘water utility’ are used interchangeably in this chapter). Climate uncertainty has added complexity to urban water infrastructure provision. Water businesses, as natural monopolies, are subject to various government regulations. Often, they are obliged to meet all demand and a prescribed service quality standard at regulated prices. The structure of the sector is complex and is subject to many different contractual relationships and hence different investment regimes. A core concern is the treatment (or lack thereof) of uncertainty in infrastructure evaluations in the water sector. To address this type of uncertainty, flexible approaches such as real options analysis (ROA) have been proposed in evaluating urban infrastructure investments (PC 2008, 2011). However, the most effective way to embed the dynamic nature of infrastructure decisions into regulatory and planning frameworks is less clear and less researched.

This research examines the existing institutional configurations surrounding urban water management with a particular focus on the infrastructure provision under uncertainty. This paper aims to address the questions:

- Do the current institutional settings for urban water infrastructure provision resonate with the climate uncertainty issues?
- What specific institutional arrangements constrain the implementation of flexible and adaptive decision-making frameworks?

This chapter specifically analyses the Victorian urban water planning and regulatory frameworks and their effect on long-term capital investment. The findings will have implications for the Australian urban water institutional reform agenda.

The chapter is organised as follows. Section 4.3 'Infrastructure investment and regulation' provides some theoretical perspectives. Current planning and regulatory frameworks for the Victorian urban water sector are briefly discussed in section 4.4. Section 4.5 relates to the infrastructure provision under uncertainty. Section 4.6 'Policy implications' also comments on possible reform paths. Section 4.7 provides concluding comments.

### **4.3 Infrastructure investment and regulation**

Infrastructure investments in the urban water sector often tend to be lumpy, cyclical and location-specific. Essentially they are irreversible because once committed they become sunk costs. The institutional environment, in which the water businesses operate, frames the motivations, choices and actions of water managers. Particularly, regulatory and planning institutions affect the infrastructure investment behaviour. The literature on how specific regulatory rules invoke different investment behaviour patterns is voluminous and a comprehensive review is beyond the scope of this chapter. Guthrie (2006) provides a comprehensive analysis.

The discussion of the effects of regulation on infrastructure investment dates back to the classical debate about the over-investment in a rate-of-return regulated natural monopoly (Averch & Johnson 1962) and theories of underinvestment (Baumol & Klevorick 1970). Regulation in the urban water sector typically represents a classical utility regulation of vertically integrated monopoly. Other forms are 'the regulated and integrated monopoly' with access regulation and the vertically disintegrated monopoly. In classical utility regulation, the choice of regulatory instrument (rate of return, cost-plus, price cap, etc.) heavily influences the level of investment (Hirschhausen et al. 2004).

Overall, price caps have become the most widespread form of incentive regulation. Price caps are defined by an index of the regulated services that is adjusted annually for inflation, an X-factor that reflects efficiency improvements of the company and a Y-factor that allows for pass-through of specific cost items outside the utility's control (Vogelsang 2002).

A close substitute to price caps is revenue caps, where the regulator puts a cap on the utility's average revenue. Outcomes achieved in a total revenue cap are different from outcomes of

average revenue cap. The rate of return regulation, despite its name, does not allow the regulated utility to set prices, and hence provides the least flexibility in setting prices (Guthrie 2006).

Highly prescriptive and unnecessarily complex regulation can hinder flexibility and innovation. Global evidence suggests that most classical utility regulation regimes are moving from price regulation to price monitoring and outcome-based regulation (PC 2011). So far, there has not been an overarching consensus reached on the matter. However, it is generally contended that the mix of incentives and the institutional framework that make up the overall regulatory package can lead to a variety of outcomes (Burns & Riechmann 2004).

The timing of regulatory reviews is crucial for any regulatory regime. Regulatory approvals are needed before commencing infrastructure projects and the time lags associated with approvals can restrict the utility's investment flexibility. In the USA, under rate-of-return regulation, the public utilities commission often sets a hearing date. However, customers can pressure the commission to initiate a hearing. In contrast, price cap regulation typically orders periodic reviews, usually 5 years apart (Guthrie 2006).

Traditional regulation that focuses on competitive prices may neglect significant sunk costs. Empirical work of Dixit and Pindyck (1994) suggests that regulators can underestimate the real cost of capital if the dynamic nature of investment is not accounted for (Hirschhausen 2008). The cost measures and 'regulatory asset base' and its valuation are also important when considering regulatory settings. Changes to these parameters can have a significant influence in the investment evaluation.

## 4.4 Planning and regulatory framework

The Victorian water businesses operate in a complex institutional environment. The sector comprises 19 water businesses, which are structurally and functionally dissimilar: there are four metropolitan water utilities, 13 regional urban water utilities and two rural water utilities. The metropolitan water businesses come under the *Corporations Act 2001 (Cth)*, which requires paying dividends to the Victorian Government as the sole shareholder while all the others are state-owned water authorities. Nine separate Acts and five regulators oversee various functions of the Victorian water businesses (Table 4.1).

**Table 4.1. Regulatory governance of the Victorian water industry**

<b>Regulator</b>	<b>Area of regulation</b>
Department of Treasury & Finance	Financial management
Secretary to the Department of Health	Safe drinking water
Essential Services Commission	Pricing and performance
Environmental Protection Agency	Environmental protection
Energy and Water Ombudsman	Dispute resolution

Source: The State of Victoria (2011)

The *Water Act 1989 (Victoria)* provides the basis for Victoria's water allocation and entitlement framework. The overarching policy plan, *Securing our water future together* (DSE

2004), sets out the planning framework for resource security in Victoria. Sustainable water strategies legislated under the *Water Act 1989* address the ongoing security of water and balance the competing demands over the 50 years between 2006 and 2055. Accordingly, each water business must prepare a 'Water supply demand strategy' (WSDS), outlining its long-term perspective (50 years) in balancing water supply and demand as the basis for its investment strategies. The WSDS is subject to five-yearly updates to accommodate new information.

Each water business is bestowed with a set of water entitlements. Water entitlements are governed by risk assignment principles laid down by the National Water Initiative (NWI). They intend to provide certainty over who should bear the risks of future water quantity reductions or reliability of allocations. According to the provisions, the above risks will be carried by: (1) entitlement holders, if the reduction is caused by seasonal or long-term changes in climate or natural events such as bushfires; (2) the government, if the reduction is a result of government policy; and (3) both water entitlement holders and governments based on a specified formula (Commonwealth of Australia 2010).

The Victorian adaptation of NWI risk-sharing principles involves coordinated interactions among regional sustainable water strategies (SWS), bulk entitlements, WSDS, regional river health strategies and management plans for water supply protection areas. These various planning tools apply to different geographical scales.

The Essential Services Commission (ESC) has been the independent economic regulator (pricing and performance) of the water industry in Victoria since 2004. Water businesses must submit a water plan to the ESC before the start of each five-year pricing regulatory period, detailing the proposed revenue requirements, investment plans and tariffs and pricing structures. Both the water businesses and the ESC engage customer groups in the water plan development process. ESC then sets the individual water utility's price limits for the impending regulatory period.

## **4.5 Institutional constraints to flexibility**

Institutional configurations surrounding urban water governance can distort efficient infrastructure decisions and prevent achieving a desirable water supply security cost-effectively. This section discusses some of the broad institutional constraints and how they might affect infrastructure decisions in the urban water sector in Victoria.

### **Clarity in roles and objectives**

Institutional clarity is pivotal if any organisation is to carry out its tasks effectively. This is critical for the water industry as it features a complex institutional environment. There is a lack of clarity in water businesses as they are urged to pursue conflicting objectives such as the commercial objective of selling more water and the conservation objective of selling less water. Governmental target setting can also be in conflict with efficiency objectives and acts as an impediment to flexibility. For instance, there was a target of a 20 per cent increase in use of recycled wastewater by 2030 in Victoria. These anomalies can affect the investment behaviour of water businesses.



Water businesses are regulated by several government agencies (Table 4.1). Lack of clarity in regulatory objectives also creates uncertainty for both the regulator and those entities being regulated. Different regulators may interpret the same legislation differently (PC 2011). For instance, the economic regulator may be prepared to offer the water business a price cap that is conducive to a particular infrastructure project but the Environment Protection Agency (EPA) may not approve the project on environmental grounds. Water businesses are also required to collaborate with agencies such as Catchment Management Authorities (CMAs) and the Department of Sustainability and Environment (DSE) to oversee water catchments and river health.

Clarity in property rights or water entitlements also enables the metropolitan water utilities, in particular, to manage supply security effectively. Currently, Melbourne metropolitan retailers have pooled water entitlements to Melbourne reservoirs. Specifying these entitlements by the individual retailer may open up opportunities to water trading among metropolitan retailers.

A clear assignment of roles, responsibilities and accountabilities in water supply augmentation policy is crucial for efficient investment decisions. Water supply augmentation decisions made outside the jurisdiction of the water business could be perceived as lacking transparency if they do not form a part of a rigorous infrastructure evaluation process.

Water supply augmentation concerns not only the nature of options but also the timing of supply augmentation options. Both desalination and wastewater recycling offer climate-independent augmentation options compared to reservoirs or dams, which are subject to rainfall variability and climate change. However, these options involve substantial capital and operating costs, with the risk that if the expected adverse climate did not materialise, then the desalination and wastewater recycling options would not be utilised to a level that justifies the large capital outlays in plant and distribution networks. The VDP provides a classic illustration of this point. Since the inception of the plant, the weather has become relatively wetter and water from the desalination plant is not required in the foreseeable future. However, the fixed service fee payable to the operator of the plant, Aqua-Sure Consortium, would be \$654 M per year (Millar & Schneiders 2012). Melbourne Water claims that this 'security payment' alone would constitute about 60 per cent of Melbourne Water's total annual operating expenditure in the 2013 Water Plan period (Melbourne Water 2012). Ultimately, these capital costs would be passed on to the water customer and rough calculations indicate that it would be about \$170 per household per year (Edwards 2012).

### **Rural–urban transfers**

Removing impediments to rural–urban water transfers improves the choice of supply augmentation options and economic efficiency as water is transferred to a higher marginal value (Cruse & Dollery 2006; Quiggin 2006). Water grids and interconnecting pipelines can contribute to effective intersectoral water transfers. This is imperative to most regional water businesses where a small diversion of rural water to urban use is physically and economically feasible either through voluntary trade or mandated allocations (Byron et al. 2008).

Although the rural–urban transfer policy lever may not be available to all water utilities because of geographical location or hydrology, when feasible this option provides cost efficiency in water supply security for regional water utilities. However, there is currently an artificial policy barrier to drawing water from rural use. For example, in Victoria there is a 4 per cent annual volumetric limit on trade from irrigation districts and not more than 10 per cent of water entitlements can be held by non-landowners (PWC 2010). Given that the bulk of the water is allocated for rural use (>70 per cent in some regions), there is enormous potential to remove inefficiencies in costly supply augmentation options. This option would be more cost–effective than the recycling option. The rural–urban transfer option has been tried and tested by several water utilities in northern Victoria with great success. There is even opportunity to link bulk water price to the volumetric component of urban water to reflect scarcity.

### **Evaluation of risky infrastructure projects**

A guiding principle in water management, ‘stationarity’, assumes that natural systems are subject to fluctuations but these fluctuations remain within the bounds of a defined range of variability. Human-induced climate change and its predicted impacts have rendered the stationarity assumption obsolete (Milly et al. 2008). Therefore, stationarity as a basis of decision-making is no longer valid. This makes infrastructure planning difficult because short-term capacity buffers are unlikely to withstand the rapid changes that exceed the planned buffer capacity.

Although the decision to go ahead with a particular infrastructure investment depends on both the water utility and regulator, primarily it is the water utility’s responsibility to evaluate the investment in terms of its economic viability. Water plans, water supply and demand forecasts are all subject to considerable uncertainty in addition to climate uncertainty. Uncertainty can make a significant difference in the valuation of infrastructure projects. In principle, all investment projects should undergo a cost–benefit analysis. In practice, however, there are no universal standards or clear guidelines on option evaluation for water supply augmentation. More importantly, the conventional cost–benefit analysis fails to accommodate the climate uncertainty effectively. This is an area where current policies have limitations.

Sophisticated techniques such as ROA can be used to estimate the value of flexibility — when to invest in what type of supply option. ROA embodies adaptive management principles as it explicitly recognises uncertainty, places a value on deferring options in the event that the ‘worst case’ scenario eventuates and is capable of capitalising on new climate information as it unfolds. For example, when a water utility has the option to delay an investment, it will only invest once the present value of the cash flows generated by the investment exceeds the sum of the required investment and the value of the delay option destroyed by investment. This value-maximising investment policy can provide a transparent basis for the water utility’s supply augmentation strategy. In some cases, inaction or delaying action can be a sound policy choice.

A related challenge to implement ROA and the like is the adaptive capacity of water sector decision-makers. Adaptive capacity is often referred to as the ability of a system to respond successfully to climate variability. Change includes adjustments in behaviour, resources and technologies. Both the portfolio approach and ROA to water supply augmentation require sophisticated models and a much larger gamut of information fed into these models. The institutional capacity in terms of financial and technical capabilities is essential for the successful implementation of such an approach (PC 2011).

Evaluating potential options using methodologies such as ROA requires specialised skills, which need to be hired if not available in-house. Also needed are procedures to articulate knowledge and codify practices that are internally defined or which may be imposed by external regulators to suit new decision-making frameworks. Access to this kind of sophisticated option evaluation practice enables decision-makers in the urban water sector to identify economically efficient supply augmentation options.

ROA is not a panacea to the problems involving water infrastructure decisions. Other flexible and robust decision-making strategies should complement the ROA evaluations. To that end, introducing decision-making strategies such as no-regret strategies, reversible strategies, safety margin strategies (Clarke 2008) and strategies to reduce time horizons in decision-making are worthwhile. 'No regret' strategies yield benefits even in the absence of climate change. For example, reducing pipe leakages is considered a good form of investment even in the absence of climate change. These strategies are reversible and keep costs as low as possible in the event of being wrong about future climate change. Retrofitting is a good example of a reversible strategy. An annual adjustment to insurance and early warning systems in response to new climate change information is another good example. Safety-first strategies exercise precaution by lowering the probability that welfare in the future will be less than some constant level. This type of strategy is widely applied in calibrating water and drainage infrastructure decisions.

### **Risk preferences and information asymmetries**

Many decision-makers accept that there is a need for account for climate uncertainty in water supply investment, but operationalising this within the current institutional framework has been problematic. The dispersed and opaque responsibility for water supply security is a major problem in infrastructure decisions. (There is no universal definition of urban water supply security. Often it is described in terms of the frequency of water restrictions or sprinkler bans.) Currently, water utilities, government departments and regulators all have a role in influencing the level of supply security, which makes the process ambiguous and less accountable (PWC 2010). Currently, water businesses carry a substantial level of risk in supply security. This is consistent with the NWI risk-sharing principles mentioned in section 4.4.

Water businesses or regulators may not have a clear understanding of the level of supply security desired by their customers. If a water business is overly risk averse, it can over-invest in supply augmentation options and vice versa. Clarifying the 'acceptable level' of water supply security needs to be the first step in new infrastructure evaluation, because different supply augmentation options offer different supply security levels. As highlighted by

Freebairn (2011), evaluating new investment options to provide water requires information about customer preferences, because different groups have different risk preferences of supply reliability. It is important to understand the nature of risk assessments required and how they can be built into existing planning frameworks.

The existing modalities for customer consultations are not designed to harness risk preference information. Nevertheless, this is not an insurmountable task. Utilities around the world use customer representatives to reveal risk preferences and willingness to pay for various supply augmentation options (PC 2011). The customer base serviced by a typical water business is not homogenous. Certain customer segments such as business groups might put a high value on the security of supply compared to residential water customers. In such cases, it may be worthwhile to consider differentiating between high-security and general-security urban water and charge a premium for high-security water.

### **Regulatory constraints**

The five-year regulatory period for the price determination acts as a constraint to adapting flexible approaches to infrastructure investment. The engineering estimations of capital projects included in the water plan depend on climate data, among other factors. However, climate data and forecasts are uncertain and subject to change. The projected speed of the expected changes in climate as outlined by the available modelling has implications for infrastructure design and the choice of investment.

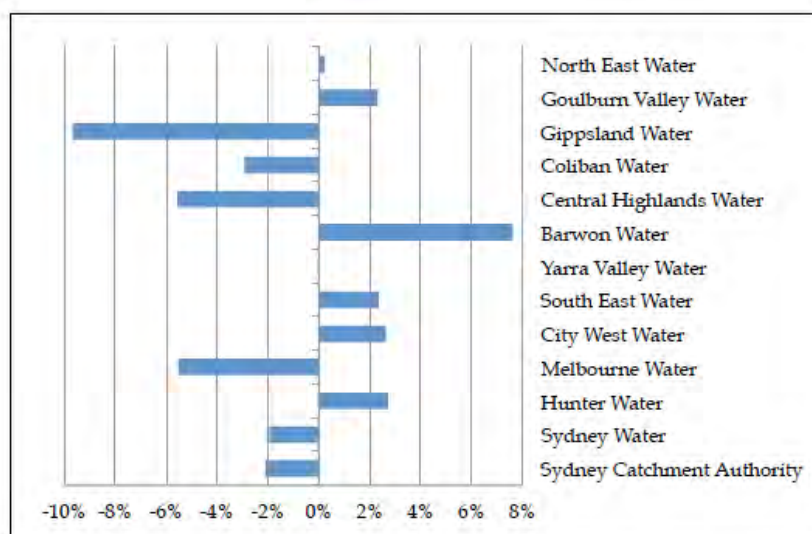
This type of a rigid arrangement creates a regulatory lag, which on one hand offers a strong incentive to control costs, but on the other, can potentially hinder the flexibility in investment. (Although interim price determinations are allowed, they are rare.) Regulatory lags can also affect the valuation of a water business's investment, which in turn can have an adverse impact on consumer welfare. In particular, these regulatory constraints can delay, prevent, start-and-stop or altogether prevent implementing any or all water supply augmentation options. This has an economic and social cost.

There are already changes to the regulatory period to counter disadvantages with the current arrangement. For example, in Victoria, water businesses may apply for a change in the regulatory period given sufficient justification (ESC 2011). The ESC also allows mid-period price adjustments to reflect any significant uncertain or unforeseen events, although this is only a short-term tool for price adjustments. This mechanism cannot be regarded as a vehicle for managing climate uncertainty in capital investment. Under this provision, water businesses can apply for a price adjustment in the event of significant and uncontrollable changes in the timing or costs associated with a major capital project, discrepancies in forecasted and actual water demand, legislative changes and catastrophic events such as fire or earthquake (ESC 2011).

The aim of the current price regulation in urban water services focuses on ensuring sufficient revenue to cover costs and a return on the asset base. There are no provisions for water scarcity or the opportunity cost of negative externalities. Currently, no jurisdiction uses administered seasonal pricing to reflect short-term variability of water supply (PWC 2010).

Regulation can be viewed as a repeated game between the utility and the regulator and an emphasis needs to be placed on institutional aspects of regulation. The outcome of this repeated game is determined by the commitment and credibility of the parties involved (Spiller 1993). Under current institutional arrangements, water 'security buffers' are often set by water businesses, which have a commercial interest to withhold that information from regulators and other parties when putting forward bulk water supply options. This contributes to the 'gaming' aspect of utility regulation.

Figure 4.1 shows the discrepancy between the proposed and approved revenues for New South Wales (NSW) and Victorian urban water utilities. Although some form of regulatory gaming is unavoidable and may go undetected, there is no concrete evidence to indicate that this to be a widespread problem in Victoria and NSW.



Notes: 1. Positive values reflect additional expenditure that utilities put forward to deliver programs not initially included in water plans; 2. New South Wales figures are for 2005-06 to 2008-09 and Victoria for 2005-06 to 2007-08

Source: NWC, 2011 and PC, 2011

**Figure 4.1. Difference in proposed and approved revenues for Victorian and NSW water utilities. Positive values reflect additional expenditure that utilities put forward to deliver programs initially included in water plans. Figures for NSW are for 2005–2006 to 2008–2009, and for Victoria are for 2005–2006 to 2007–2008. Sources: NWC (2001) and PC (2011).**

## Socio-political barriers

Attitudes and preferences of water stakeholders are critical when implementing large infrastructure projects. Chief among them are customer perceptions towards demand management tools and supply augmentation options. Anecdotal evidence suggests that certain communities prefer water restrictions over new supply segmentation options in order to tackle the water supply demand imbalance. This can be an impediment to choosing the most suitable and economically efficient option.

Currently, recycled wastewater is not a part of drinking water supply in Victoria; this is a major social barrier. The attitudinal factors are reflected in some existing water policies relating to recycled water in Victoria. Restrictions on indirect potable water reuse can be an

impediment to efficiency gains in water supply augmentation. However, public policies and attitude towards recycled water is changing, as evidenced in Western Australia. Water Corporation's Beenyup groundwater replenishment trial treated approximately 1.5 GL of secondary treated wastewater using an advanced technique and recharged it back into groundwater aquifers. Substantial community engagement about this new water supply option appears to have altered the public perception about the trial (Water Corporation 2012).

### **Competency trap**

An important constraint to institutionalising flexibility in infrastructure management relates to the specialisation in one particular approach to achieve water supply security. Institutional competencies and preferences mean that certain options are not identified or considered. The Norwegian energy sector provides a classic example of a competency trap where sector agents, predominantly hydropower engineers, resisted demand-side management and diversification of supply options and instead relied on costly expansion of hydropower development (Inderberg & Eikeland 2009). The urban water sector typically has strong technological leniencies, which may hinder institutional learning by favouring technological trajectories to uncertainty problems.

## **4.6 Policy implications**

Climate uncertainty calls for flexibility in dealing with infrastructure investments and a re-examination of the current planning and regulatory settings. The proposed Governance Charter (PC 2011) to some extent addresses the lack of clarity in the objectives, roles and accountabilities of the water stakeholders and establishing service quality standards in a transparent manner. Further reforms such as a greater corporatisation of urban water utilities including merit-based appointment of directors, incorporation of public utilities (except those under local governments) under the *Corporations Act 2001 (Cth)* and transparency in ministerial directions have been proposed. However, the reforms suggested would not provide the radical changes needed to improve utility regulation in general and infrastructure decisions in particular.

Some commentators argue for a complete redefinition of monopoly water utility regulation (Cave 2009; Walker 2009; Littlechild 2011). For example, the customer engagement model and negotiated settlement model have been tried in gas, electricity and aviation industries in the USA and UK (Littlechild 2011). These approaches strengthen the link between the service provider and the utility by providing opportunity to negotiate service quality and tariffs while the regulator acts as an arbiter in the process. In this context, it appears beneficial to move towards a revenue cap or price-monitoring regime. The customer engagement model offers flexibility to water businesses and may also be beneficial from a transaction costs point of view, because the current process is lengthy and onerous. However, significant limitations exist in adopting such an approach. They include the degree of customer group sophistication, issues relating to representation, and the technical capacity to effectively negotiate service reliability issues and associated tariff changes. Nevertheless, there are important implications for customer engagement in the urban water sector. Current customer engagement modalities can be further improved along the principles proposed by the approach.

The optimal bulk water procurement arrangement has been regarded as an essential ingredient for balancing water supply and demand (PC 2010). A centralised approach to bulk water procurement has been proposed (PC 2011). In this approach, a portfolio manager runs a competitive procurement process for water supply augmentation. Note that this type of arrangement is more relevant to interconnected water supply systems than water utilities dispersed far apart geographically. Interconnections, water grid managers, intersectoral trade and option trades can potentially enhance the capacity to adapt to climate change uncertainty. With option trades, buyers and sellers agree to a transfer before they know how much water will be available for the coming year. Incremental payments are made to the seller until the buyer's final decision deadline (Hollinshead & Lund 2007).

Centralised water procurement, if feasible, can potentially bring considerable efficiency gains while managing security of supply strategically across a jurisdiction. However, anecdotal evidence suggests that the centralised determination of supply augmentation may discourage the option development by the private sector, thus creating a barrier to entry. Moreover, incorporating future investments into the regulatory process is a difficult task especially in the presence of third-party access regimes. Under such regimes, the property rights associated with infrastructure are diluted. Untangling the ramifications of diverse property rights can be a challenging exercise for the regulator.

Alternative supply augmentation options may typically characterise the risk profile of the individual water utility and combinations of small-scale projects and demand management options. A risk profile of a large, centralised entity may not match the smaller water utility's risk preferences. From a climate adaptation point of view, centralisation of the bulk water procurement function can be viewed as moving away from a polycentric or decentralised structure that already exists in Victoria. Obviously, there is a trade-off between the efficiency gains from a centralised approach and the flexibility offered by a decentralised approach. Adaptive management literature tends to favour polycentric structures to deal with uncertainty better than centralised or monocentric structures (Huitema et al. 2009). These proposals can significantly alter incentives and risk alignment patterns in the water sector.

Forecasting of demand and supply requirements while incorporating climate change projections and making them publicly available is another aspect that has not received adequate attention, especially in urban water planning in regional areas. The application of the best available scientific modelling in water planning underpins efficient infrastructure investment. For instance, an application of ROA to bulk water procurement decisions must be aided by gathering and processing information. This process must ensure up-to-date information on current stream flows, demand forecasts and other water supply–demand variables. More importantly, the supply augmentation decision-making process must allow new information on demand and supply conditions, including trigger levels for water restrictions, storage capacity and dam inflows to be fed into the system.

## 4.7 Concluding remarks

Traditional regulatory and planning regimes have been challenged by new decision-making approaches such as ROA. Such adaptive decision-making approaches purport that, under uncertainty, delaying investments may be beneficial even though a project may cover its capital costs. Several institutional constraints act as barriers to flexibility in urban water supply augmentation. The current settings in the urban water sector are ill-equipped to tackle climate uncertainty. In this environment, it is important to reconfigure the institutional settings — regulatory and planning frameworks — to embed flexibility and support efficient infrastructure provision in the urban water sector.

Clarity in organisational purpose in both regulators and those being regulated is of paramount importance to water supply augmentation. Allowing the water utility to retain some price flexibility can improve infrastructure investment efficiency. Hence, current price regulatory models need to be reviewed. Flexible and adaptive decision-making strategies such as no-regret theory, reversible strategies and safety-margin strategies can complement more rigorous infrastructure evaluations.

Reform agendas should also consider reforms to the water-planning framework. In particular, customer engagement modalities need more attention because they can be potentially harnessed to provide valuable information on customer willingness to pay for various water products and service quality standards. Building institutional learning capacity to address information asymmetries that underpin infrastructure investment decisions is also imperative.

It is also important that reforms be shaped by adaptive institutional principles that enhance efficiency by factoring in risk and uncertainty considerations. Guiding the reform agenda through a set of adaptive principles is important so that the reform process, as Marshall (2003) pointed out, will not resemble a random walk but a systematic process that will reap dividends in terms of better urban water outcomes.



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## 5. Optimal portfolio of urban water supply assets under climate change

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*Anke D Leroux (with Vance L Martin)*

### 5.1 Synopsis

Urban population growth coupled with reduced water supply from conventional surface and groundwater sources is generating mismatches of water supply and demand in many urban centres around the world. Projected climate change impacts, including greater variation in rainfall, higher temperatures and reduced inflows, are likely to exacerbate the problem. These factors have resulted in a surge in actual and planned investments to augment urban water supply and ensure future supply security. In such an environment we may think of a portfolio of investment options, of which upgrading traditional water supply assets is but one option. Investments in large capital-intensive desalination and recycling plants that are capable of producing water at any time may be seen as insurance against declining supply from conventional sources.

By contrast, decentralised stormwater harvesting represents a means to capitalise on the greater variation in precipitation patterns by harvesting and treating surface runoff from heavy rainfall events. Whether the latter represents a viable alternative to other investment options depends on technological constraints and local precipitation patterns.

The optimal portfolio of water supply assets is derived for safe and risky assets. Here, supply risks from reservoirs as a result of inflow variability, and for stormwater harvesting systems as a result of rainfall variability, are modelled as gamma distributions. The theoretical model yields closed-form solutions to determine optimal consumption and optimal contributions to total water stock by asset. The theoretical framework is calibrated to Melbourne for known parameter values. Maximum likelihood estimation is applied to time-series data from 1915 and 2010 on Melbourne precipitation and reservoir inflows in order to estimate the moments of the gamma distributions for monthly rainfall and monthly reservoir inflows. It is shown that the nature of investments made to augment water supply depends on prevailing and expected rainfall patterns and inflows.

### 5.2 Introduction

Most cities around the world have been experiencing some form of water shortage, where urban water demand exceeds supply now, or in the near or medium terms. Climate change is likely to exacerbate the problem. This has also been recognised by water managers, as a recent surge in investments to secure future water supply shows. However, the type of water supply infrastructure investment is far from obvious, because the optimal portfolio of assets is determined by current and projected precipitation and inflow patterns, and other economic and natural factors.

## Climate change

The effects of climate change on future water supply are complex and not yet well understood. There is considerable uncertainty about the localised effects of global warming and their combined outcome for water availability. First indications suggest that shifts in precipitation patterns are inconsistent across countries and regions (Bates et al. 2008). Since 1979, regional drying has been evident in parts of the world including south-west North America, Southern Europe and Chile. Other areas, such as Northern Europe, experienced increases in mean rainfall. Over the same period, a widespread increase in heavy precipitation events has been observed, even in places where mean rainfall has been declining. These trends are predicted to become more significant by the late 21st century, with increases in precipitation levels at high latitudes and in parts of the tropics, and decreasing rainfall in sub-tropical and lower and mid-latitude regions. Drying in decreasing rainfall zones will most likely be accompanied by longer periods of no rain and an increased risk of drought. Simultaneously, it is highly probable that heavy precipitation events will become more frequent across most of the globe and more intense in those regions that will experience higher mean precipitation. Importantly, the implications of shifts in rainfall patterns for water availability are not straightforward, because altered evaporation and runoff conditions may lead to reduced water supply even for some regions with greater mean rainfall.

Recently, urban water supply and demand have become mismatched in some parts of the world because of declining water availability and greater urbanisation. A surge in investments to augment water supply and water security has followed in Denmark, Sweden, Namibia, Japan, Australia and the USA (Rygaard et al. 2011). With continuing climate change, water shortages are expected to worsen globally in the near future. For example, by 2013, 36 states in the USA are anticipating local or state-wide water shortages. In its report on *Climate Change and Water*, the Intergovernmental Panel on Climate Change advocates “an improved incorporation of current climate variability into water-related management” to facilitate adaptation to future climate change (Bates et al. 2008, p.74).

A large proportion of cities rely on surface water or underground aquifers, which depend on rainfall for replenishment. In the past, building dams was often seen as the most cost-efficient investment in water supply. However, suitable sites for the construction of new dams have become increasingly scarce. Moreover, in a climate that is characterised by reduced inflows and more frequent heavy precipitation events, we may think of a portfolio of investment options to augment and secure future water supply. Large capital-intensive infrastructure projects, capable of producing water at any time, may be seen as insurance against the declining trend in dam and underground storage levels. Water can be desalinated and recycled at some positive marginal cost that is independent of prevailing climate conditions and therefore not subject to the same volatility as water supplied from other, rain-dependent sources.

## Decentralised water infrastructure

Another class of water supply investments comprises decentralised infrastructures that capitalise on the greater future variation in precipitation patterns. Urban centres are

characterised by a large proportion of impermeable surfaces, resulting in large volumes of runoff during medium and heavy precipitation events. The objective of decentralised stormwater harvesting systems is to capture surplus water from storm and flood events when and where they occur. Stormwater, harvested in city water reservoirs, tanks, raingardens and various streetscape infrastructures, may be treated to augment a city's water supply. While such investments are unlikely to ensure fully against future water shortages, especially during an extended drought, they go some way to reducing the demand on stored water throughout the year, therefore enabling higher reservoir storages that can be drawn on during dry spells.

The amount of harvested stormwater is dependent on rainfall. Specifically, stormwater harvesting systems are designed to capitalise on extreme rainfall events. Because of their decentralised nature they are capable of capturing rain when and where it falls as opposed to centralised dams that may miss out on highly localised downpours. Hence decentralised stormwater systems are less susceptible to rainfall variation than other surface water sources. However, the capital costs involved in building these systems are comparatively higher.

### **Infrastructure management literature**

The management of urban water supply infrastructure has been studied extensively in the literature. Oezelkan et al. (1997) solve the problem of optimal investment in and management of a water reservoir under supply uncertainty, where the random variable is assumed to be normally distributed. Feiring et al. (1998) optimise water reservoir management for the dual purposes of supplying water and energy. The economic efficiency of alternative water supply assets has been studied and compared to conventional sources by Pickering et al. (2007) for rainwater tanks and Fletcher et al. (2007) and Salibya et al. (2009) for desalination technology.

However, none of these water supply assets are mutually exclusive. Indeed a combination of different types of water supply assets may be necessary to generate the desired amount of water. This has been recognised by Kasprzyk et al. (2009) and Kirsch et al. (2009), who investigated the role tradeable water products may play in securing urban water supply in the short and medium terms. However, investing in water products to secure urban water supply may not be a realistic option where urban water markets are either non-existent or insufficiently developed. If investment in a physical water supply asset were to be chosen to secure future supply, important questions arise concerning the optimal timing of such an investment. Borison et al. (2008) and policy advisors (Productivity Commission (PC) 2011) have advocated using real option theory to determine the optimal timing of investing in water supply augmenting technologies such as desalination plants.

### **Current research**

This research is more concerned with optimal mix of assets than the optimal timing of water supply augmentation. The crucial questions answered in this chapter are about the proportion of the total water stock that should be produced from which type of asset, and how these contributions depend on prevailing precipitation and inflow patterns. This chapter develops a theoretical model of optimal consumption and contributions from three distinct

water supply assets, two of which are rainfall dependent and therefore subject to supply uncertainty. The theoretical framework is based on Merton's (1969, 1971) optimal portfolio allocation problem with the important distinction that the underlying random variable, rain, follows a gamma rather than a normal Gaussian distribution. This divergence is directly motivated from the climate literature (Wilks 1990; Groisman et al. 1999) and is confirmed by the empirical analysis conducted in this chapter. To our knowledge, only a few studies have attempted to solve Merton's model for distributions other than geometric Brownian motion. These studies include Merton (1971) for a combined Brownian–Poisson process and Benth et al. (2001) who derived a numerical solution for the optimal portfolio allocations assuming normal inverse Gaussian–Levy processes.

While the construction of optimal energy portfolios forms an important body of literature (Locatelli & Mancini 2011 present a comprehensive review), we are not aware of similar studies for the water sector. The chapter is organised as follows. Section 5.3 derives closed-form solutions for a three-asset model of water supply investments, where the flow returns from two assets are subject to risk as modelled by correlated but not identical gamma processes. In section 5.4, the moments of a gamma distributions for rain and inflows are estimated for each month of the year from 1915 to 2010 using aggregated daily precipitation data for Melbourne and monthly data on inflows into Melbourne's reservoirs between 1915 and 2010. Section 5.5 explains the model calibration. Results of the simulation exercises are discussed in section 5.6, before concluding remarks in section 5.7.

### 5.3 Method

Merton's (1969) portfolio model of optimal consumption and investment in one risky and one safe financial asset for a given stock of wealth is adapted to analyse optimal urban water supply and consumption. In particular, the stochastic, continuous-time model is extended to determine the optimal contributions to total urban water supply for three types of water supply assets: (1) desalination or water recycling plants; (2) water reservoirs; and (3) stormwater harvesting systems.

The flows per investment dollar from each type of asset differ in their means and variances. Desalination and water recycling plants have a comparatively low mean flow due to technological constraints and high production costs. However, water supply from these assets is guaranteed in as much as it is independent of rainfall. As a result, investment in such assets may be considered risk-free. By contrast, the amount of water harvested in large reservoirs (dams) and decentralised stormwater harvesting systems depends on technological and natural factors. The water stock in reservoirs depends on rainfall and river inflows, which combine into a mean inflow and inflow volatility. However, the amount of stormwater that is harvested depends on mean rainfall and rainfall volatility. Importantly, the decentralised nature of stormwater harvesting compared to a centralised dam structure may imply that its inflows are less susceptible to rainfall volatility because rain may be captured when and where it falls while dams are subject to locality constraints. Furthermore, the high degree of impermeability of urban centres means that a much larger proportion of rainwater may be harvested even after long periods of no rain. By contrast, most of the water falling in a reservoir catchment area after a lengthy period of high temperatures and no rain may

evaporate or be absorbed by the vegetation and in the soil. Hence, dams may be seen as a riskier investment option than stormwater harvesting systems; desalination plants bear zero supply risk.

The standard Merton model assumes that the state variable, share price, follows a log-normal distribution. This assumption is inappropriate for the water sector, as empirical analysis on precipitation data shows that a gamma distribution is preferable when describing rainfall (Wilks 1990; Groisman et al. 1999).

### Water stock dynamics

The change in total water stock  $dW(t)$  is derived first in discrete form, before limits are taken to move towards the continuous case. As in the original model (Merton 1969), portfolio adjustment costs are not considered. This assumption implies, for urban water supply assets, that optimal contributions to total water supply should be used to guide supply augmenting investment decisions, instead of being interpreted as a justification for the decommissioning of existing water supply assets.

Let  $S_i(t)$  be the water supply to investment ratio for asset  $i$  at time  $t$ .

Assuming constant returns to scale from rain-independent asset  $i$  this ratio is constant. On the other hand, for rain-dependent water supply assets, the water stock to investment ratio varies stochastically with rainfall or inflows. The change in the stock of water of asset  $i$  is described by the stochastic differential equation:

$$dS_i(t) = (\alpha_{0i} + \alpha_{1i}S_i(t)) dt + \sigma_i S_i(t)^{1/2} dz_i \quad (5.1)$$

where the term  $(\alpha_{0i} + \alpha_{1i}S_i(t))$  is mean change in the stock to investment ratio and  $\sigma^2 S_i(t)$  is its variance. This choice of specification can be shown to yield a gamma distribution as a stationary distribution (Malliaris & Brock 1982).

Let  $K_i(t)$  be the capital held in asset  $i$  at time  $t$ , specifically between  $t$  and  $t + h$ . In this context,  $h > 0$  could be thought of as one year and let  $x(t)$  be the amount of water consumed per unit time; for example, this is a city's water consumption over one year. It is assumed that a city comes into period  $t$  with capital invested in a portfolio of water assets such that the total stock of water at this time is:

$$W(t) = \sum_i^3 K_i(t-h) S_i(t) \quad (5.2)$$

Going forward, consumption and capital investment decisions are made simultaneously such that:

$$-x(t)h = \sum_i^3 [K_i(t) - K_i(t-h)] S_i(t) \quad (5.3)$$

holds. Equation 5.3 states that water consumption during period  $t$  must balance with changes in water stock during this period adjusted for portfolio allocation decisions made during period  $t$ . Incrementing equations 5.2 and 5.3 by  $h$  to eliminate backward differences yields:

$$W(t+h) = \sum_i^3 K_i(t) S_i(t+h) \quad (5.4)$$

and, after some manipulation of equation 5.3 the expression for incremental changes is obtained:

$$-x(t+h)h = \sum_i^3 [K_i(t+h) - K_i(t)] [S_i(t+h) - S_i(t)] \quad (5.5)$$

$$-x(t+h)h = \sum_i^3 [K_i(t+h) - K_i(t)] [S_i(t+h) - S_i(t)] \quad (5.6)$$

Moving to continuous time by taking the limits  $h \rightarrow 0$  yields equation 5.7 for equation 5.2:

$$W(t) = \sum_i^3 K_i(t) S_i(t) \quad (5.7)$$



and equation 5.8 for equation (??):

$$-x(t) dt = \sum_i^3 dK_i(t) dS_i(t) + \sum_i^3 dK_i(t) S_i(t) \quad (5.8)$$

An expression for  $dW(t)$  is obtained by applying Ito's lemma:

$$dW = \sum_i^3 K_i(t) dS_i(t) + \sum_i^3 dK_i(t) S_i(t) + \sum_i^3 dK_i(t) dS_i(t) \quad (5.9)$$

Substitution of equation 5.8 for the last two terms in equation 5.9 yields:

$$dW = \sum_i^3 K_i(t) dS_i(t) - x(t) dt \quad (5.10)$$

which states that the change in total water stock equals the change in water stocks held in an individual water supply asset net of consumption. Substitution of equation 5.1 for  $dS_i(t)$  and

defining the contribution to total water stock by water supply asset  $i$ ,  $\theta_i = \frac{K_i(t)S_i(t)}{W(t)}$ , yields:

- Defining  $\phi_i = \frac{W(t)}{S_i(t)}$ , which as the interpretation of the capital expenditure on asset  $i$  that

$$dW = \sum_i^3 \alpha_{i0} \theta_i \frac{W(t)}{S_i(t)} dt + \sum_i^3 \alpha_{i1} \theta_i W(t) dt + \sum_i^3 \sigma_i \theta_i W(t) [S_i(t)]^{-1/2} dz_i - x(t) dt$$

$$dW = \sum_i^3 \alpha_{i0} \theta_i \phi_i dt + \sum_i^3 \alpha_{i1} \theta_i W(t) dt + \sum_i^3 \theta_i \sigma_i \phi_i^{1/2} W(t)^{1/2} dz_i - x(t) dt$$

would be necessary if we were to generate the total water stock using only supply asset  $i$ , preserves the gamma structure of the expression for  $dW$ :

(5.11)

### Three-asset portfolio model

An isoelastic utility function with constant average risk aversion and zero transaction costs is assumed. Let water consumption yield utility be:

$$U(x) = x^\gamma / \gamma$$

where  $x$  is current water consumption and  $\gamma < 1$ . In this form, the elasticity of intertemporal substitution is  $1/\gamma$ , and  $(1 - \gamma)$  is the Arrow–Pratt measure of relative risk aversion. The total water stock per investment dollar at time  $t$  is  $W(t)$  with its dynamics described by equation 5.11. Making use of the assumption that investment in desalination technology is risk-free as the inflow of desalinated water per dollar invested is independent of rainfall volatility, set  $\alpha_{d1} = \sigma_d^2 = 0$ . The riskless inflow of desalinated water is denoted  $\alpha_{d1} = \alpha_d$ . Hence, from equation 5.11:

$$\begin{aligned} dW = & [\alpha_{r0}\theta_r\phi_r + \alpha_{s0}\theta_s\phi_s + \alpha_d\theta_d\phi_d + \alpha_{r1}\theta_r W(t) + \alpha_{s1}\theta_s W(t) - x(t)] dt \\ & + \theta_r\sigma_r\phi_r^{1/2} W(t)^{1/2} dz_r + \theta_s\sigma_s\phi_s^{1/2} W(t)^{1/2} dz_s. \end{aligned} \quad (12)$$

(5.12)

The objective is to maximise  $V$ , the present value of the utility stream from water consumption by a population growing at rate  $\xi$  and having a discount rate of  $\delta$  over an infinite horizon:

$$\max E \int_0^\infty \left( e^{(\xi-\delta)t} x^\gamma / \gamma \right) dt$$

(5.13)

subject to equation 5.12 and  $W(0) = W_0$  (5.14)

Dynamic programming yields equation 5.15:

$$\begin{aligned} (\delta - \xi) V = & \max_{x, \theta_r, \theta_s, \theta_d} \left[ (x^\gamma / \gamma) \right. \\ & + [\alpha_{r0}\theta_r\phi_r + \alpha_{s0}\theta_s\phi_s + \alpha_d\theta_d\phi_d + \alpha_{r1}\theta_r W + \alpha_{s1}\theta_s W - x] V_W \\ & \left. + \frac{1}{2} \left( \theta_r^2 \sigma_r^2 \phi_r + \theta_s^2 \sigma_s^2 \phi_s + 2\theta_r \theta_s \sigma_{r,s} (\phi_r \phi_s)^{1/2} \right) W V_{WW} \right], \end{aligned} \quad (15)$$

(5.15)

where  $\sigma_{r,s}$  is the covariance of the stochastic processes. Maximising with respect to  $x$  gives:

$$x = [V_W]^{\frac{1}{\gamma-1}} \tag{5.16}$$

Imposing the restriction:

$$\theta_s + \theta_r + \theta_d = 1 \tag{5.17}$$

and maximising with respect to  $\theta_r$  and  $\theta_s$  yields the linear system of equations:

$$\begin{aligned} [\alpha_{r0}\phi_r - \alpha_d\phi_d + \alpha_{r1}W] V_W + \left( \theta_r\sigma_r^2\phi_r + \theta_s\sigma_{r,s}(\phi_r\phi_s)^{1/2} \right) W V_{WW} &= 0 \\ [\alpha_{s0}\phi_s - \alpha_d\phi_d + \alpha_{s1}W] V_W + \left( \theta_s\sigma_s^2\phi_s + \theta_r\sigma_{r,s}(\phi_r\phi_s)^{1/2} \right) W V_{WW} &= 0 \end{aligned}$$

with solutions

$$\theta_r = -[k_{0r} + k_{1r}W] \frac{V_W}{W V_{WW}} \tag{5.18}$$

and

$$\theta_s = -[k_{0s} + k_{1s}W] \frac{V_W}{W V_{WW}} \tag{5.19}$$

where

$$\begin{aligned} k_{0r} &= \frac{(\alpha_{r0}\phi_r - \alpha_d\phi_d)\sigma_s^2\phi_r^{-1} - (\alpha_{s0}\phi_s - \alpha_d\phi_d)\sigma_{r,s}(\phi_r\phi_s)^{-1/2}}{\sigma_r^2\sigma_s^2 - \sigma_{r,s}^2} \\ k_{1r} &= \frac{\alpha_{r1}\sigma_s^2\phi_r^{-1} - \alpha_{s1}\sigma_{r,s}(\phi_r\phi_s)^{-1/2}}{\sigma_r^2\sigma_s^2 - \sigma_{r,s}^2}, \end{aligned} \tag{5.20}$$

(5.21)

and

$$k_{0s} = \frac{(\alpha_{s0}\phi_s - \alpha_d\phi_d)\sigma_r^2\phi_s^{-1} - (\alpha_{r0}\phi_r - \alpha_d\phi_d)\sigma_{r,s}(\phi_r\phi_s)^{-1/2}}{\sigma_r^2\sigma_s^2 - \sigma_{r,s}^2},$$

$$k_{1s} = \frac{\alpha_{s1}\sigma_r^2\phi_s^{-1} - \alpha_{r1}\sigma_{r,s}(\phi_r\phi_s)^{-1/2}}{\sigma_r^2\sigma_s^2 - \sigma_{r,s}^2}.$$

(5.22)

(5.23)

Substituting equations 5.16, 5.18 and 5.19 for  $x$ ,  $\theta_r$  and  $\theta_s$  in equation 5.15 yields the ordinary

$$(\delta - \xi)V = \frac{1 - \gamma}{\gamma} [V_W]^{\frac{\gamma}{\gamma-1}} + \alpha_d\phi_d V_W - k \frac{V_W^2}{W V_{WW}}$$

differential equation:

(5.24)

$$k = \left[ \left( \alpha_{r0}\phi_r - \alpha_d\phi_d + \alpha_{r1}W - \frac{1}{2}\sigma_r^2\phi_r(k_{0r} + k_{1r}W) \right) (k_{0r} + k_{1r}W) \right. \\ \left. + \left( \alpha_{s0}\phi_s - \alpha_d\phi_d + \alpha_{s1}W - \frac{1}{2}\sigma_s^2\phi_s(k_{0s} + k_{1s}W) \right) (k_{0s} + k_{1s}W) \right. \\ \left. - \sigma_{r,s}(\phi_r\phi_s)^{1/2}(k_{0r} + k_{1r}W)(k_{0s} + k_{1s}W) \right].$$

where

(5.25)

$$V(W) = AW^\gamma$$

Equation 5.24 yields a closed-form solution for

(5.26)

such that:

$$\gamma A = \left[ \frac{\delta - \xi}{1 - \gamma} - \frac{\gamma}{1 - \gamma} \frac{\alpha_d \phi_d}{W} - \frac{\gamma}{(1 - \gamma)^2} \frac{k}{W} \right]^{\gamma - 1}$$

(5.27)

Using equations 5.26 and 5.27 in equation 5.16 yields the optimal control function for water consumption:

$$x = \frac{\delta - \xi}{1 - \gamma} W - \frac{\gamma}{1 - \gamma} \alpha_d \phi_d - \frac{\gamma}{(1 - \gamma)^2} k,$$

(5.28)

where  $k$  is given by equation 5.25. Similarly, using equations 5.26 and 5.27 in equations 5.18 and 5.19 yields:

$$\theta_r = (k_{0r} + k_{1r}W) \frac{1}{(1 - \gamma)}$$

and

$$\theta_s = (k_{0s} + k_{1s}W) \frac{1}{(1 - \gamma)}$$

(5.29)

(5.30)

as the optimal contributions of reservoirs,  $\theta_r$ , and stormwater harvesting systems,  $\theta_s$ , to total water supply. The constants  $k_{0r}$ ,  $k_{1r}$ ,  $k_{0s}$  and  $k_{1s}$  are given by equations 5.20, 5.21, 5.22 and 5.23, respectively. The optimal solution for  $\theta_d$  is obtained from the normalisation condition equation 5.17.

### Economic interpretation of the theoretical model

The properties of the theoretical model are best explored under the assumption of independence of the stochastic processes governing reservoir inflows and rainfall. This special case implies  $\sigma_{r,s} = 0$ , which yields for the simplified expressions for equations 5.29 and 5.30:

$$\theta_r = \frac{\alpha_{r0}\phi_r - \alpha_d\phi_d + \alpha_{r1}W}{(1 - \gamma)\sigma_r^2\phi_r}$$

$$\theta_s = \frac{\alpha_{s0}\phi_s - \alpha_d\phi_d + \alpha_{s1}W}{(1 - \gamma)\sigma_s^2\phi_s}$$

(5.31)

(5.32)

Viewed independently, equations 5.31 and 5.32 are equivalent to the optimal solution in the two-asset case with one risk-free asset and one risky asset (either reservoir or stormwater) described by a gamma distribution. The solution to this special case retains features of the standard Merton model, which assumes a log-normal distribution. Contributions to total water stock from both rain-dependent assets vary inversely with the constant of relative risk

aversion,  $\frac{\partial \theta_i}{\partial (1-\gamma)} < 0$  and inflow or rainfall variance,  $\frac{\partial \theta_i}{\partial \sigma_i^2} < 0$ . An increase in mean excess returns over the rain-independent alternative,  $\alpha_{i0}\phi_i - \alpha_d\phi_d + \alpha_{i1}W$ , increases the optimal share of that asset in the portfolio. The implications of assuming a gamma distribution may similarly be explored using equations 5.31 and 5.32. While the standard Merton result involves optimal share allocations that are independent of  $W$ , the current model allows for dynamic contributions over time that vary directly with total water supply,  $\frac{\partial \theta_i}{\partial W} > 0$ . The intuition is that the greater is total water supply the greater is the proportion that can be sourced from riskier assets.

$$x = \frac{\delta - \xi}{1 - \gamma} W - \frac{\gamma}{1 - \gamma} \alpha_d \phi_d - \frac{\gamma}{(1 - \gamma)^2} k$$

Setting  $\sigma_{r,s} = 0$  in equation 5.28 yields the optimal solution of water consumption:

(5.33)

where:

$$k = \frac{(\alpha_{r0}\phi_r - \alpha_d\phi_d + \alpha_{r1}W)^2}{2\sigma_r^2\phi_r} + \frac{(\alpha_{s0}\phi_s - \alpha_d\phi_d + \alpha_{s1}W)^2}{2\sigma_s^2\phi_s}$$

(5.34)

Note that  $-1 < \gamma < 0$  ensures  $x > 0$  for  $\delta > \xi$  and  $k > W$ , which is confirmed by the numerical results in the section on model calibration, below. This requirement must also hold for consumption to be positive in the standard Merton model (Merton 1969). Furthermore,

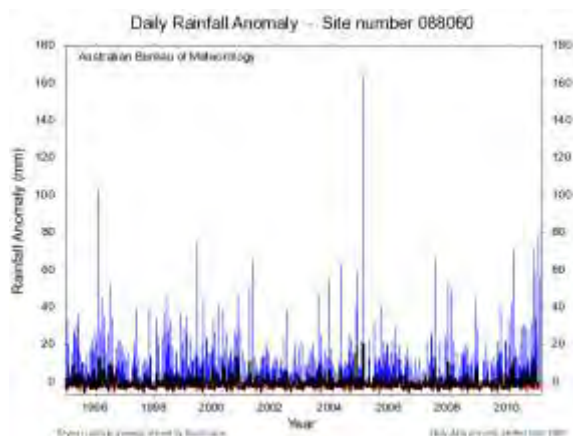
optimal consumption increases with the level of risk aversion,  $\frac{\partial x}{\partial \gamma} < 0$ , when  $\delta > \xi$  and  $k > W$  and  $-1 < \gamma < 1$ . These properties imply that a sensible range for is moderate risk aversion, i.e.  $-1 < \gamma < 0$ .

Optimal current consumption varies directly with the discount rate,  $\frac{\partial x}{\partial \delta} > 0$ , indirectly with the population growth rate,  $\frac{\partial x}{\partial \xi} < 0$ , and increases with the variances of water inflows from rain-dependent assets  $\frac{\partial x}{\partial \sigma_i^2} > 0$  for  $\gamma < 0$ . The last term in equation 5.33 is also a function of  $\theta_r^2$  and  $\theta_s^2$ , with  $\frac{\partial x}{\partial \theta_r} > 0$  and  $\frac{\partial x}{\partial \theta_s} > 0$ . Hence, optimal consumption depends positively on the contributions to total water stock from the risky supply assets. This result mirrors that of the standard Merton (1969) model.

## 5.4 Empirical estimation of gamma distributions

Projections for Australia reveal increased variability in future precipitation patterns, with storms and droughts likely to become more frequent. Figure 5.1 shows daily rainfall anomalies for Wallaby Creek Weir, a weather station within the Melbourne catchment. In contrast, projections for changes in average annual rainfall for Victoria by 2030 encompass the broad range between  $-8.3$  and  $0.9$  per cent (Garnaut 2008). While average annual rainfall may or may not increase, rates of runoff and stream inflow are predicted to decrease because of higher temperatures and evaporation (CSIRO 2007). As a result, dam inflows are likely to decrease. For example, the largest reservoir for Melbourne, the Thomson Dam, may see a reduction in inflows of up to 25% by 2030 (Jones & Durack 2005). The reduced future supply from existing dams is particularly problematic for large and growing urban centres. Population growth increases the demand for water, necessitating accelerated investment in additional water supply infrastructures (PC 2011).

Figure 5.1. Daily rainfall anomaly for the Wallaby Creek Weir, Victoria (site number 008680); source: BoM



An important component of the theoretical model developed in section 5.3 is that precipitation as well as inflows into reservoirs are based on a gamma distribution. This choice of distribution is adopted by Wilks (1990) and Groisman et al. (1999) among others to model rainfall by country. The density function of the gamma distribution is:

$$g(r; \alpha, \beta) = \left(\frac{r}{\beta}\right)^{\alpha-1} \exp\left[-\frac{r}{\beta}\right] \frac{1}{\beta\Gamma[\alpha]}, \quad r \geq 0, \quad \alpha, \beta > 0$$

(5.35)

where  $r$  represents either rainfall or inflows and  $\alpha$  and  $\beta$  represent the shape and shift parameters, respectively. To estimate the parameters of the gamma distribution of monthly rainfall or reservoir inflows, a maximum likelihood approach is adopted. The log-likelihood for a sample of  $T$  observations is:

$$\begin{aligned} \ln L &= \ln g(r_t; \alpha, \beta) \\ &= (\alpha - 1) \ln\left(\frac{r_t}{\beta}\right) - \frac{r_t}{\beta} - \ln \beta - \ln \Gamma[\alpha] \end{aligned}$$

(5.36)

The log-likelihood function in equation 5.36 is nonlinear in the parameters  $\alpha$  and  $\beta$ , which is maximised using a gradient algorithm with derivatives computed numerically. All computations are performed using GAUSS version 10, with the optimiser based on the software MAXLIK.

Two separate gamma distributions are estimated to describe the distributions for rainfall and dam inflows. Daily precipitation data between 1 January 1915 and 31 December 2010 for six weather stations across Melbourne was converted into monthly rainfall and averaged across the stations. The stations are Lovely Banks, Meredith, Portarlinton, Toorourrong, Yan Yean and Wallaby Creek. They were chosen for being ‘high quality climate sites’ that are used for climate projections by the Bureau of Meteorology (BoM 2011). Monthly dam inflow data from 1 January 1915 and 31 December 2010 for the four major water reservoirs (Maroondah, O’Shannassy, Upper Yarra and Thomson) servicing Melbourne were obtained from Melbourne Water. The individual inflows were summed by month to generate a dataset of total inflows into Melbourne’s reservoirs by month over the period.

The parameter estimates of  $\alpha$  and  $\beta$  for the gamma distributions for rainfall and dam inflows for each month are given in the last two columns of Tables 5.1 and 5.2, respectively. The estimates of the shape parameter for both distributions for all months are  $\hat{\alpha} > 1$ , implying a



hump-shaped distribution. The scale parameters show some variations over the months to reflect the change in the spread of the distributions in precipitation and inflows over the year.

### Mapping into the stochastic differential equation

The first two moments of stochastic differential equation (SDE) describing the stock of water per investment in asset  $i$  (1) are:

$$E[dS] = (\alpha_0 + \alpha_1 S)dt$$

$$E([dS] - E[dS])^2 = \sigma^2 S dt$$

Equating these moments with the moments from the stationary distribution yields:

$$\sigma^2 = \frac{\alpha\beta^2}{K^2 S dt}$$

(5.37)

$$\alpha_0 = \frac{\alpha\beta}{K dt} - \alpha_1^* S$$

and

(5.38)

where  $\alpha^2$  and  $\alpha$  are expressed in units of ML/\$ and  $\alpha_1^*$  is the unit-free and \normalised value of  $\alpha_1$ . This model is calibrated for yearly consumption and water stocks and monthly time units,  $1/dt = 12$ .

While the estimates of  $\alpha$  and  $\beta$  from Table 5.2 can be mapped directly into (1) according to equations 5.37 and 5.38, unit conversion from millimetres (mm) into megalitres (ML) is required for the estimates describing the rainfall distribution. This is achieved by multiplying the rainfall with the effective catchment area for the four stormwater harvesting projects and converting into ML.

**Table 5.1. Descriptive statistics of stormwater harvesting (average of 6 sites, in mm of rainfall per month), January 1915 to December 2010**

Month	Mean	SD	Min	Max	$\alpha$	$\beta$
Jan.	43.997	26.249	1.333	127.400	2.177	20.208
Feb.	48.046	43.231	2.367	228.050	1.378	34.861
March	45.687	33.668	4.350	157.283	1.968	23.220
April	59.005	37.546	0.250	205.833	2.337	25.246
May	62.212	31.752	5.217	154.600	3.542	17.566
June	60.681	24.985	8.700	146.683	5.717	10.614
July	63.758	23.705	20.967	123.900	6.956	9.165
Aug.	70.725	27.893	15.967	159.950	5.605	12.618
Sept.	68.811	30.099	18.617	218.533	5.807	11.850
Oct.	72.985	34.455	12.100	173.483	3.884	18.794
Nov.	65.996	37.326	13.300	182.233	3.281	20.112
Dec.	57.170	34.255	2.467	166.533	2.528	22.616
Annualised	59.923	37.820	0.250	228.050	2.509	23.878

$\alpha$  and  $\beta$  are the shape and shift parameters, respectively, that define the stationary gamma distribution of the total water stock

**Table 5.2. Descriptive statistics of reservoirs (sum of 4 reservoirs, in ML per month), January 1915 to December 2010**

Month	Mean	SD	Min	Max	$\alpha$	$\beta$
Jan.	23213.421	9744.093	5443.000	53615.343	5.673	4091.755
Feb.	16912.036	9194.138	3684.262	64859.060	4.277	3954.134
March	16356.291	8313.488	4472.000	50754.072	4.648	3518.987
April	19927.671	12686.039	5548.000	80483.481	3.442	5789.801
May	29256.242	17946.342	9484.000	99452.790	3.558	8223.219
June	43058.990	20772.678	11202.829	97958.685	4.429	9722.082
July	55467.028	20521.512	14902.106	97074.053	6.606	8396.565
Aug.	65509.361	19502.929	21994.000	98428.000	9.820	6671.093
Sept.	69736.933	19267.831	19267.000	99097.286	10.930	6380.506
Oct.	63322.184	22390.410	10956.000	97675.610	6.306	10041.363
Nov.	49807.112	20693.482	10411.000	98170.529	5.189	9598.715
Dec.	36720.605	16171.074	5806.000	90018.000	4.933	7443.229
Annualised	48654.150	16150.960	3684.262	99452.790	9.021	5393.473

$\alpha$  and  $\beta$  are the shape and shift parameters, respectively, that define the stationary gamma distribution of the total water stock.

## 5.5 Model calibration

This section reports the preliminary calibration and simulation results for the purpose of demonstrating the properties of the model derived in section 5.3, and for deriving first insights. For this reason  $\rho = 0.0$  is initially assumed. The model is calibrated using the annualised values for the estimated  $\alpha$  and  $\beta$  parameters. In terms of reservoir parameter values, the average annual inflow into the four reservoirs from 1915 to 2010 was calculated as  $W_r = 584,000$  ML. The annualised total life cycle cost for Melbourne reservoirs,  $K_r = \$18M$ , is available from Melbourne Water.

The parameter values for desalination are taken from reported values for the Wonthaggi desalination plant. that is currently under construction and scheduled to begin operations in 2012. The plant has a capacity of supplying  $W_d = 160,000$  ML/year at an estimated annualised life cycle cost of  $K_d = \$98M$ .

The corresponding values for stormwater harvesting systems and effective catchment size were taken from a report on sustainable water supply technologies, prepared for the centre for water sensitive cities. To date, stormwater is not harvested at nearly the same scale as the other two supply assets. Hence the parameter values used are based on four small stormwater harvesting projects with a combined catchment area of 628 ha and annual harvesting volume of  $W_s = 210$  ML. This implies, for average annual precipitation, an effective harvesting rate of 5 per cent. The total annualised life cycle cost across the four projects is  $K_s = \$580,000$ .

The population growth rate for Melbourne,  $\xi$ , is approximately 0.02. This leaves only two parameter values,  $\gamma$  and  $\sigma$ , to be determined. Substitution of equation 5.29 for  $\theta_r$  and equation 5.30 for  $\theta_s$  in equation 5.17 yields:

$$\gamma = 1 - \frac{k_{0r} + k_{0s} + (k_{1r} + k_{1s}) W^*}{1 - \theta_d^*} \quad (5.39)$$

as the value of the risk aversion parameter that is implied from observed values of the total annual water supply  $W^o = W_r + W_s + W_d$  and the observed share from desalination  $\theta_d^2 = W_d/W^o$ . Substitution of equation 5.39 into equation 5.28 yields an expression for the implied discount rate:

$$\delta = \left[ \frac{(x^o - \alpha_d \phi_d)}{1 - \theta_d^o} [k_{0r} + k_{0s} + (k_{1r} + k_{1s}) W^o] + \alpha_d \phi_d \right. \\ \left. + \left( \frac{1 - \theta_d^o}{k_{0r} + k_{0s} + (k_{1r} + k_{1s}) W^o} - 1 \right) k \right] \frac{1}{W^o} + \xi,$$

(5.40)

(5.41)

where  $x^0 = 500,000$  ML was total water consumption in Melbourne during 2001. Having thus derived the remaining two unknown parameter values, the model can now be simulated using all parameter values discussed above and summarised in Table 5.3.

## 5.6 Analysis

The results of the preliminary calibration using the estimated gamma distributions over the past 100 or so years for reservoir inflows and rainfall, and parameter values from Table 5.3, are summarised in Table 5.4. Compared with the observed annual consumption  $x^0 = 500,000$  ML and observed contributions to total water stock of  $\theta_r^0 = 0.80$  from reservoirs,  $\theta_s^0 = 0.00$  from stormwater harvesting and  $\theta_d^0 = 0.20$  from desalination, the optimal values averaged across the year are shown in the last row of Table 5.4. While optimal consumption for available water stock is only slightly below the observed level, it can be seen clearly that future investment in water supply augmentation should target stormwater harvesting projects, with the annualised optimal contribution to total water stock of around 20 per cent. Investments in desalination should occur such that the annual contribution of desalinated water to total water stock remains at 20 per cent. Any further investments in reservoirs for Melbourne do not seem wise based on historic rainfall and inflow data.

**Table 5.3. Model parameter values for Melbourne**

Parameter	Value	Unit	Description
$W_r$	584,000	ML/year	Total reservoir stock
$W_d$	160,000	ML/year	Total desalination capacity
$W_s$	210	ML/year	Total stock of harvested stormwater
$A_s$	314,000	m <sup>2</sup>	Effective stormwater catchment area
$K_r$	18	\$/M/year	Total annualised reservoir life cycle costs
$K_d$	98	\$/M/year	Total annualised desalination life cycle costs
$K_s$	0.58	\$/M/year	Total annualised stormwater harvesting life cycle costs

$\xi$	0.02	-	Population growth rate for Melbourne
$\delta$	0.12	-	Implied discount rate
$\gamma$	-0.11	-	Implied level of risk aversion
$\rho$	0.0	-	Correlation coefficient
$\alpha_{1i}$	-10	-	Normalised value of $\alpha_{1i}$

- = not applicable.

There is significant variation of optimal consumption and asset contributions to total water supply from month to month. Understanding such variation is particularly important to cities, which do not have storages that hold several months' supply. Besides managing demand, water planners in this situation must be able to optimise their water supply portfolio to ensure sufficient water supply in critical months when demand and supply mismatches are most likely to occur. Table 5.4 shows that aggressive demand management that results in significant water savings during the drier summer months should be part of an urban water strategy. Investments to boost water supply in the most critical months may be targeted to either desalination or stormwater harvesting technologies, or both. Supply augmentation investments for Melbourne are likely to concern the drier summer months, roughly December to April. Table 5.4 reveals fairly constant optimal stormwater contribution of 10–20 per cent. Optimal contributions to total water stock from desalination, on the other hand, vary significantly from 40 per cent and 35 per cent in December and April, respectively, which would imply the construction of a second desalination plant, to only 10 per cent to 5 per cent in January and March, which suggests Melbourne has currently over-invested in desalination technology.

The reason for these significant differences in targeted technologies lies in the volatility in rain-dependent supply. While mean rainfall and inflows are comparatively low across all four months, there is much higher volatility of rainfall and reservoir inflows in December in April. This suggests that while investment in stormwater harvesting is still optimal to capture stormwater where and when it falls, the risk of water supply shortages from unreliable dam inflows are best mitigated using a risk-free supply technology, such as desalination or water recycling. In contrast, January and March are characterised by relatively low rainfall and inflow volatility, suggesting that rain-dependent assets, if optimised in terms of scale and location, can reliably ensure the supply of water over critical months.

**Table 5.4. Optimal annual water consumption and proportional contributions to total water stock from reservoirs, stormwater harvesting and desalination technologies for prevailing precipitation patterns and probabilities of value at risk (*VaR*)**

Month	$x$	$\theta_r$	$\theta_s$	$\theta_d$	$p(VaR = 300)$
Jan.	335	0.70	0.20	0.10	0.002
Feb.	265	0.70	0.10	0.20	0.001
March	285	0.80	0.15	0.05	0.001
April	285	0.50	0.15	0.35	0.002
May	335	0.40	0.20	0.40	0.003
June	430	0.35	0.35	0.30	0.004
July	540	0.40	0.45	0.15	0.004
Aug.	605	0.50	0.35	0.15	0.004
Sept.	645	0.55	0.35	0.10	0.004
Oct.	790	0.35	0.20	0.45	0.003
Nov.	390	0.35	0.20	0.45	0.003
Dec.	350	0.45	0.15	0.40	0.003
Annual	475	0.60	0.20	0.20	0.010

$x$  = optimal annual water consumption (in '000 ML)

$\theta_r$  =

$\theta_s$  =

$\theta_d$  =

$p(VaR)$  = probabilities of falling below a given value at risk, expressed in '000 ML

All values rounded except for  $p(VaR)$  to the nearest 5 or 0.05,  $p(VaR = 300)$

To put the simulation results into perspective, the probabilities of falling below a given value at risk (*VaR*) are reported next to the optimal supply shares in Table 5.4. The computational and calibration aspects of the *VaR* analysis are detailed in Appendix 5.1. The *VaR* is an annual supply of 300,000 ML, which is achieved with 99 per cent probability under the observed contributions of water supply assets to total water stock. This *VaR* also makes sense from a consumption point of view as it is slightly below the consumption level of 365,000 ML achieved under high water restrictions in 2007. As such, 300,000 ML could be interpreted as the minimum sustainable urban water supply in a year. The lower probabilities of falling below this critical level under the various optimal portfolio contributions reveal that the suggested optimal portfolios reduce downside risk by up to a factor of 10. Thus, they may be considered a safer management target than the current water supply portfolio.

In order to assess optimal water management strategies in anticipation of climate change, some high-level assumptions that are consistent with current projections are needed. Greater variation in precipitation patterns with longer and more frequent droughts and more frequent extreme rainfall events are projected to increase rainfall in Melbourne by 10 per cent on average. However, this greater variation in rainfall together with higher temperatures is likely to decrease average inflows into Melbourne's dams by an estimated 7 per cent (Howe et al. 2005). To arrive at these mean estimates while respecting forecasts of increased variation in weather patterns required the following adjustments to the estimated  $\alpha$  and  $\beta$  parameters. To model an average increase in rainfall totals by 10 per cent, the  $\alpha$  estimate from the rainfall distributions is multiplied by a factor of 1:1, which yields an increase of exactly 10 per cent of the mean ( $\alpha\beta$ ) of the gamma distribution and translates into a 5 per cent increase in the standard deviation ( $\sqrt{\alpha\beta^2}$ ) of rainfall. To model the impacts of climate change in terms of reduced dam inflows while allowing for greater inflow variation, the  $\alpha$  estimate of the inflow distribution is multiplied by 0.5, but the  $\beta$  estimate is multiplied by 1.86. The expectation is again for a mean reduction in inflows of 7 per cent, while the standard deviation of inflows increases by 30 per cent. This calibration is necessarily arbitrary given the lack of more precise predictions regarding the impacts of climate change on the standard deviations of the random variables. As a result, the simulation results shown in Table 5.5 are at best indicative of the general trend.

From Table 5.5, three insights become immediately obvious. First, even moderate climate change impacts as those assumed here will lead to insufficient water supply from current supply assets. This is obvious from the severe reductions in consumption that would become necessary if no additional investments were made to augment the future water supply. In addition, the VaR analysis reveals probabilities likely to be in excess of those acceptable to an urban water manager. That is, the probability of supply falling below the critical 300,000 ML mark for all optimal portfolios is more than 1 per cent and for some portfolios as great as 15 per cent. As a result, further augmentation to the existing water supply will become necessary as the climate continues to change.

Second, the optimal contribution of desalination technology to total water supply has increased across all months, while optimal stormwater harvesting contributions do not change significantly (Table 5.4). Hence it seems that investment in stormwater harvesting is an optimal strategy with and without climate change. However, further desalination upgrades may be planned but their realisation should be postponed until the impacts from climate change start to become apparent.

**Table 5.5. Optimal annual water consumption and proportional contributions to total water stock from reservoirs, stormwater harvesting and desalination technologies for prevailing precipitation patterns and probabilities of value at risk (*VaR*) under medium climate change impacts**

Month	$x$	$\theta_r$	$\theta_s$	$\theta_d$	$p(VaR = 300)$
Jan.	275	0.40	0.20	0.40	0.021
Feb.	225	0.35	0.10	0.50	0.014
March	245	0.40	0.15	0.40	0.009
April	255	0.25	0.15	0.60	0.045
May	300	0.20	0.25	0.60	0.107
June	390	0.20	0.40	0.45	0.149
July	425	0.20	0.45	0.35	0.125
Aug.	475	0.25	0.30	0.40	0.086
Sept.	500	0.30	0.35	0.35	0.079
Oct.	365	0.20	0.20	0.60	0.162
Nov.	325	0.20	0.20	0.60	0.150
Dec.	290	0.25	0.20	0.60	0.098
Annual	350	0.35	0.15	0.50	0.056

$x$  = optimal annual water consumption (in '000 ML)

$\theta_r$  =

$\theta_s$  =

$\theta_d$  =

$p(VaR)$  = probabilities of falling below a given value at risk, expressed in '000 ML

All values rounded except for  $p(VaR)$  to the nearest 5 or 0.05,  $p(VaR = 300)$

## 5.7 Concluding remarks

Worldwide, cities increasingly struggle to meet the demand for water from conventional sources as urban populations continue to grow. Water supply shortages are predicted to become worse in the future, with climate change likely to result in greater precipitation variation and possibly reductions in mean levels in the sub-tropical and lower to mid-latitudes. At the same time, the frequency of heavy rainfall events is likely to increase in these regions.

In this environment, we may think of a portfolio of alternative water assets to augment future water supply. Investment options include large centralised infrastructure projects capable of producing water at any time and decentralised infrastructures that capitalise on greater predicted future variation in rainfall. In this chapter, the optimal water consumption and contribution to total water supply from conventional and alternative sources was derived



using a continuous-time dynamic model of long-term optimal portfolio allocation. In doing so, it was assumed that one alternative source of water supply is independent of rainfall and therefore able to deliver water risk-free. However, water sourced from water reservoirs and harvested stormwater are subject to inflow and precipitation volatility. In the theoretical model, a stationary distribution of rainfall of the gamma form was assumed. A closed-form solution was shown to exist for optimal consumption and optimal individual contributions from the three types of water supply assets to total water stock.

Using the maximum likelihood approach, the shift and shape parameters of the gamma distributions of rainfall and reservoir inflows were estimated for each month of the year. The aggregated monthly precipitation data for Melbourne and monthly dam inflow data between 1915 and 2010 were used.

The preliminary calibration results confirm that the model can provide important insights about optimal water asset portfolio choices over time.

In addition, the results show that investment decisions to ensure water supply may not be uniform throughout the year. If infrastructure investments are made to augment urban water supply over the critical summer months, it is shown that those investments may optimally target desalination and recycling technologies if low mean values are coupled with high variation. Targeting rain-dependent infrastructure assets such as stormwater harvesting systems for future investment, on the other hand, is preferred for low-variance months even if mean rainfall and inflow are comparatively low. The model simulation further shows that upgrading or constructing new reservoirs may not optimally form part of Melbourne's water strategy in the near and medium terms.

In this chapter, considering medium-level impacts from climate change on optimal water supply management highlighted the issue of future water scarcity and the need to invest in additional water supply infrastructure. To this end, investments in stormwater harvesting systems can be considered a no-regrets option, because harvested stormwater contributions of around 20 per cent are optimal with and without considering climate change. Any upgrades to the existing desalination plant, on the other hand, should be planned but not executed until the impacts of climate change on water supply become more apparent.

## 5.8 References

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## Appendix 5.1 Value at risk analysis

The performance of the optimal portfolio is assessed against the risk of supply falling below a minimum subsistence level of consumption. The value at risk analysis is performed on the stationary distribution that corresponds to the stochastic differential equation 5.12, where  $\theta_r$  and  $\theta_s$  are now the optimal contributions to total water stock according to solutions in equations 5.29 and 5.30. Given the focus on securing a given level of supply, the consumption is disregarded in this analysis.

If the stochastic differential equation of total water stock is given by:

$$dW = [\alpha_{r0}\theta_r\phi_r + \alpha_{s0}\theta_s\phi_s + \alpha_d\theta_d\phi_d + \alpha_{r1}\theta_r W + \alpha_{s1}\theta_s W] dt + \theta_r\sigma_r\phi_r^{1/2}W^{1/2}dz_r + \theta_s\sigma_s\phi_s^{1/2}W^{1/2}dz_s. \quad (5.42)$$

the corresponding stationary distribution is of the form:

$$g(w) = \eta \exp \left[ \int_0^w \left( \frac{2\mu(s) - d\sigma^2(s)/ds}{\sigma^2(s)} \right) ds \right] \quad (5.43)$$

where  $\eta$  is the normalising constant to ensure that  $\int_0^\infty g(s) ds = 1$ , and from equation 5.42:

$$\begin{aligned} \mu(s) &= \alpha_{r0}\theta_r\phi_r + \alpha_{s0}\theta_s\phi_s + \alpha_d\theta_d\phi_d + \alpha_{r1}\theta_r w + \alpha_{s1}\theta_s w \\ \sigma^2(s) &= \theta_r^2\sigma_r^2\phi_r w + \theta_s^2\sigma_s^2\phi_s w + \theta_r\theta_s\sigma_{r,s}\phi_r^{1/2}\phi_s^{1/2}w \end{aligned}$$

Using these expressions for  $\mu(s)$  and  $\sigma^2(s)$  in equation 43 gives:

$$g(w) = \eta \exp \left[ \frac{2(\alpha_{r0}\theta_r\phi_r + \alpha_{s0}\theta_s\phi_s + \alpha_d\theta_d\phi_d) - \theta_r^2\sigma_r^2\phi_r - \theta_s^2\sigma_s^2\phi_s - \theta_r\theta_s\sigma_{r,s}\phi_r^{1/2}\phi_s^{1/2}}{\theta_r^2\sigma_r^2\phi_r + \theta_s^2\sigma_s^2\phi_s + \theta_r\theta_s\sigma_{r,s}\phi_r^{1/2}\phi_s^{1/2}} \ln s + \frac{2(\alpha_{r1}\theta_r + \alpha_{s1}\theta_s)}{\theta_r^2\sigma_r^2\phi_r + \theta_s^2\sigma_s^2\phi_s + \theta_r\theta_s\sigma_{r,s}\phi_r^{1/2}\phi_s^{1/2}} s \right], \quad (45)$$

(5.45)

which is a gamma distribution. The relationship between this expression and a more conventional form of the gamma distribution, for example the form given in equation 35, is found by rewriting the more conventional form of the gamma distribution as:

$$\begin{aligned} g(w; \alpha, \beta) &= \left(\frac{w}{\beta}\right)^{\alpha-1} \exp\left[-\frac{w}{\beta}\right] \frac{1}{\beta\Gamma[\alpha]}, \\ &= \exp\left[(\alpha-1)\ln w - \frac{w}{\beta}\right] \frac{1}{\beta^\alpha\Gamma[\alpha]} \end{aligned}$$

Comparing equations 5.44 and 5.46 shows that:

$$\begin{aligned} \alpha &= \frac{2(\alpha_{r0}\theta_r\phi_r + \alpha_{s0}\theta_s\phi_s + \alpha_d\theta_d\phi_d)}{\theta_r^2\sigma_r^2\phi_r + \theta_s^2\sigma_s^2\phi_s + \theta_r\theta_s\sigma_{r,s}\phi_r^{1/2}\phi_s^{1/2}} \\ \beta &= \frac{\theta_r^2\sigma_r^2\phi_r + \theta_s^2\sigma_s^2\phi_s + \theta_r\theta_s\sigma_{r,s}\phi_r^{1/2}\phi_s^{1/2}}{2(\alpha_{r1}\theta_r + \alpha_{s1}\theta_s)} \\ \eta &= \frac{1}{\beta^\alpha\Gamma[\alpha]}. \end{aligned}$$

where  $\alpha$  and  $\beta$  are the shape and shift parameters that define the stationary gamma distribution of the total water stock.

To perform the VaR analysis, the value at risk that corresponds to a 1 per cent probability is selected for the observed asset contributions to total water stock and for a normalisation value of  $\alpha_1 = -10$ . It was found that the normalisation matters for the value at risk analysis and therefore the normalisation was selected in a way to yield to most robust results for the VaR. Table 5.4 contrasts the probabilities for a given VaR.