Decision-making under future uncertainty: developing adaptive urban water strategies

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Abstract:

This paper describes a decision-making framework created to develop long term adaptive water supply and demand strategies to respond to future contextual uncertainties, such as climate change and urbanisation. Whilst there are various theoretical methods for decision making under uncertainty, they generally have not been applied to the water sector. Nor have they been brought together in an integrated, practically-grounded process to guide strategic planning and project level decisions, such as the approach proposed in this paper. This approach avoids predictions of the future or modelling intensive analysis, rather it integrates the fundamental characteristics of uncertain system influences (trends and shocks) with two additional thinking tools: the use of scenarios based on a number of uncertainties to describe potential futures, and the focus on investment approaches to guide the packaging of potential response measures.

Subject headings:

Adaptive systems; Decision making; Urban water; Uncertainty; Scenarios; Planning; Utilities

Biographical notes:

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Professor Cynthia Mitchell is a Research Director at the Institute for Sustainable Futures. Her research consulting experience spans people-centred (cultural change and learning for sustainability) and techno-centred approaches (life cycle analysis, water cycle management in industrial and urban settings, and a broad suite of water treatment technologies), with implementation strategies incorporating critical thinking, context evaluation, and sustainability criteria development, application, and evaluation.

Decision-Making Under Future Uncertainty: Developing Adaptive Urban Water Strategies

1 Introduction

Water service providers (WSPs) are currently faced with the need to balance water demands with available supplies under variable settings. Projected climate change impacts together with the uncertainty in other future system influences and drivers, such as economic growth, urbanisation, demand patters, etc., present an additional significant planning challenge for most WSPs. In combination, they present a challenging mix of uncertain impacts that manifest over varying spatial and temporal scales. Decision makers and planners often find such complexity overwhelming and may even avoid consideration of the many system influences in the planning process (Scott et al., 2012).

Reserve supplies through large scale infrastructure such as dams and desalination plants, together with water restrictions, have in the past be the default response to climate variations (Fane et al., 2010). However, more recently water services businesses have sought diversified portfolios and flexible strategies as a means towards improving security of supply (Erlanger and Neal, 2005; Wong and Brown, 2009; Wright and Goodwin, 2009; Maheepala et al., 2010). This new way of approaching resource planning decisions, represents a challenge to existing conceptual and analytical models. It requires a shift from traditional deterministic approaches, such as 'build it bigger', and measuring security in storage volume per capita, to ones which seek to prepare for uncertainty and respond to changes in the future by building adaptive capacity. This includes characteristics such as flexibility and robustness – *flexibility* for the phasing and sequencing of responses based on new information relating to trends, and *robustness* to withstand sudden shocks to the system (Scott et al., 2012).

Adaptive planning has its roots in social-ecological systems thinking, where the capacity to adapt and transform determine the system's resilience to periods of abrupt and gradual changes (Folke et al., 2010). Resilience is a measure of a system's capacity to cope with shocks and undergo change in response to trends, while retaining essentially the same structure and function (Walker et al., 2009).

There are many uncertainties about the timing, direction and extent of these shocks and trends that have not been a consideration historically. As these uncertainties become more apparent due to climatic impacts and fast changing socio-economic boundary conditions, rational water resource planning becomes more complicated (Pahl-Wostl, 2007). The predominant focus of water planners and managers has been to meet growing demands for water by augmenting the supply through large scale technical solutions based on medium term (30 years) demand projections. As these large infrastructure solutions have become less attractive, the development of new ideas such as integrated water management and the revival of traditional ideas such as rainwater harvesting have come to the fore (Gleick, 2003). Furthermore, Pahl-Wostl et al (2007) have observed that large-scale infrastructure with decade long life-spans offer few learning opportunities and often lead to "lock-in" situations, where adaptive management is limited to operational planning and is absent from strategic planning.

Adaptive water planning and management has therefore been put forward as the timely extension of IWRM to cope with these challenges, since it is aimed at increasing the adaptive capacity of water management based on the good understanding of key factors that determine its vulnerability and associated risks. This would also take into consideration the environmental, technological, economic, institutional and cultural characteristics of catchment and supply systems (Mukheibir, 2010). An adaptive management approach aims to have a flexible response to a range of future scenarios and should enable new learning over time of what was previously uncertain to inform and improve the future planning responses (Fane and Turner 2010).

However, this requires a paradigm shift in water planning and management from a ‘prediction and control’ to a ‘management as learning approach’, where water planning is flexible enough to adapt to changing socio-economic and environmental conditions (Pahl-Wostl, 2007). The main objective of adaptive water planning as defined by Pahl-Wostl et al (2005), is to enhance the adaptive capacity of a water system based on a good understanding of what determines resilience and vulnerability in that system.

Adaptive planning strategies represent an obvious method in principle, but are often difficult to develop and implement in practice. Rayner et al (2005) found, for example, that the principal factors affecting the use of new weather and climate information were conservatism and complexity. Water resource managers rely on traditional planning methods so as to avoid exposure if improved outcomes are not met. Probabilistic forecast information is complex and not well understood by water resource managers and viewed as unreliable (Rayner et al., 2005). Recently an increase in the interest in new tools and methods has been observed for helping decision makers identify and evaluate resilient decisions, as opposed to only financially optimal ones. A number of methodologies have been developed which are either at a national level in scale, or are project focused (Biggs et al., 2011; Polasky et al., 2011).

The finance and decision theory literature suggest a number of advanced decision making methods to deal with uncertainty and multiple objectives, but these methods are often too complex for practical implementation (Polasky et al., 2011), requiring more information than is probably avaiblable to the analysists, which makes it difficult to define the conditional probabilities required for the analysis.

However, these methodologies generally do not institutionalise and integrate the approach at a local level or sectoral level such as water provision. They generally start with an existing strategy in mind and then proceed to test it for robustness against climate impacts and then develop adaptation strategies to alleviate the identified vulnerabilities. Further, if climate variability is to increase it is important to understand how climate change will impact on the urban water sector and what the resultant vulnerabilities are likely to be. This process should therefore focus attention on where priority interventions might reduce the impacts of climate change and help WSPs to be pre-emptive, rather than reactive (Fane et al., 2010).

In light of this, a more systemic approach is needed which starts with identifying the problem and associated uncertainties. A flexible and robust strategy should then be devised in response to future uncertainties which may include climate change, population growth, economic activity and unexpected shocks, such as bushfires in the local catchment. In addition, the multiple values of water, such as the way in which water contributes to a sustainable, liveable, prosperous and healthy city as well as values attached to individual supply options, should ideally be incorporated into the decision making approach.

In response to this methodological challenge, the decision-making framework described here was designed to provide urban water planners with a transparent tool to understand and plan for future uncertainty in such a way that decision makers would be able to follow the logic behind final investment strategy. The process was specifically designed to stay close to current practice and knowledge, whilst also providing an opportunity to understand locally important uncertainties and their potential impacts on the system. As will be explained in the next section, by simplifying the problem into manageable steps, planners and decision makers were able to develop robust and flexible responses to a range of projected futures, thereby ensuring that the set objectives are always met. The adaptive planning approach was designed to assist in the strategic planning process for the Melbourne water businesses' fifty year water supply and demand strategy, as required by the Department of Sustainability and Environment, Victoria (DSE 2011; Mukheibir and Mitchell 2011).

This paper firstly provides an overview of the key concepts introduced by the decision-making framework viz. the characterisation and analysis of uncertain system influences as trends or shocks, the use of scenarios to describe potential futures, and the focus on investment approaches to guide the packaging of potential response measures to address the shortfall in the set objectives. *Measures* consist of the range of possible options, which could include measures such as large scale supply options, demand-side management options, large scale centralised non-potable supply options, and local small scale non-potable supply options. The shortfall in the set objectives are not limited to water supply only, but could include shortfalls in meeting minimum greenhouse gas (GHG) or nitrogen targets. The methodological steps required to undertake the options assessment process are discussed further, together with the outcomes obtained for an exercise undertaken with some water businesses located in Victoria, Australia (Mukheibir et al., 2012).

2 A decision-making framework

The framework presented here draws on resilience thinking (Blackmore and Plant, 2008; Folke et al., 2010), which focuses on the critical thresholds for system performance, the capacity for the system to adapt to changing conditions and/or transform to a completely different method of operation to accommodate the change in the social, environmental, technical and/or economic situation if the old method becomes unsustainable. This framework uses the scenarios to determine the potential thresholds of the system to meet the set objectives. The adaptability of the system to future uncertainty can be determined by firstly testing the system for *flexibility*, i.e. a characteristic of a portfolio of measures that can be altered to suit changing trend conditions at minimal additional community cost, e.g. avoiding large centralized supply systems with long lead times. And secondly, by testing the system for *robustness*, a characteristic of a portfolio of diverse measures that are not all dependent on the same influences and hence the impact of the variability in the influences is mitigated i.e. to not have all one's eggs in one basket, e.g. conjunctive supply sources.

The decision-making framework in this paper uses a variety of terms and concepts that may be new to some or may mean different things to different people and within different sectors or organisations, therefore this section sets out to provide definitions of the terms used.

Uncertainty in this paper is defined as the lack of information as to how system influences will play out in the future. *System influences* in this paper refers to the possible pressures and drivers, such as climate, population growth, consumption behaviour or energy pricing, that would have an impact on the social, environmental, technical and/or economic situation, as well as the outcome of a range of response measures (or options). The way that influences occur is significant, since it determines the nature and scale of the impact on system performance. System influences can manifest in one of three ways: as *trends* that change over the longer term (such as reduced run-off or demand growth), as *shocks* that lead to new norms (such as unexpected step changes in the trends), or as *extreme variability* in the short term. The latter is not discussed in this paper because it is addressed through other tactical planning and management mechanisms such as drought response processes. Longer term trends and shocks shift operations into a different paradigm, and so they are the specific focus of this framework.

In this framework, the idea of *scenarios* is used to describe a future contextual situation based on combinations of a number of specific influences (or drivers). The water sector has to contend with multiple trends in various combinations which have the potential to influence the supply-demand balance i.e. whether or not a shortfall exists. The scenarios approach draws on and extends the richness of traditional scenario planning methods (Schwartz, 1996). Such methods are processes for thinking creatively and systematically about complex futures and for analysing possible future events through the consideration of alternative, plausible, though not equally likely, future states of the world (Mahmoud et al., 2009). They are typically used in the context of either planning over long time horizons or making short-term decisions that have long-term consequences (Maack, 2001). The approach of using scenarios is intended to address both the shortcomings of traditional scenario approaches (which is usually limited to considering just two sets of influences at a time) and probabilistic approaches, which are limited by the quality of available models and inputs. Increasing the number and combinations of potential trends has an exponential effect on the number of scenarios and analyses required, which generally leads to numerical optimisation, such as probabilistic approaches. These methods are not well established in practice, so both of these are questionable for the water sector at this time. In scenario planning, it is not necessary to assign probabilities to the possible future scenarios (Polasky et al., 2011; Scott et al., 2012), and in such instances, each of the scenarios is equally possible. This is sometimes viewed as a potential weakness of scenario planning (Polasky et al., 2011), however the relative likelihood of future influences can be determined qualitatively, as is illustrated in the next section.

The final concept in this framework is the focus on *investment approaches*. Investment approaches set the hierarchy and rules for packaging up and sequencing the different types of measures. This approach avoids favoured options being proposed for expedient purposes. For example, an approach may nominate that large scale potable supply options are selected first. Whereas, another approach may first consider incremental small scale non-potable options before introducing the large scale potable supply options. In order to set the sequence in which the types of measures are chosen, an investment approach nominates thresholds and triggers for new measures; predecessors and constraints where necessary; and lead times before the benefit of a measure can be realized. By applying a specific investment approach, a group or portfolio of measures that satisfy the requirements of the investment approach, will be assembled to respond the influences described in a scenario, in order to avoid a shortfall in the set objectives, such as water supply targets and/or minimum greenhouse gas (GHG) or nitrogen targets.

Based on the purpose and innovative thinking described above, the decision-making framework for adaptive water systems presented in this paper consists of a number of distinct steps, discussed below. As can be seen from Figure 1, the process is step-wise and consists of a number of actions within each step, which set up complex logical information flows to subsequent steps. In summary, significant trends are identified, their impacts analysed and response measures to ameliorate the impacts developed. Then those responses are tested against the significant shocks and the responses modified accordingly.

2.1 Setting the key objectives of the system

This process begins by setting the objectives and boundaries of the water services system consistent with both statutory obligations and the aspirational pull of industry and stakeholder visions. Whilst the example used in this paper is that the objectives are focused on balancing supply and demand, the assessment framework is a generic process that could equally be applied to other objectives within the water sector, such as managing nitrogen or greenhouse gas (GHG) emissions, interception of stormwater and meeting open space demands (Mukheibir et al., 2012), or objectives from other sectors, such as energy or urban planning.

2.2 Identifying the system influences

In order to plan for and manage an adaptive water system it is necessary to identify what system influences may change in the future. These include influences which impact on the context in which a water business operates (for example, changes in population) and also influences which impact on specific measures (for example, a shift in energy price).

By characterising these long term influences as either trends or shocks, the impacts of the influences can be differentiated, and therefore more clearly assessed. The disaggregation of trends and shocks allows for the systematic analysis of differential responses of existing and new investments to qualitatively different uncertainties. For example, some measures may be able to cope with gradual changes, but may be unable to respond quickly enough to a sudden shock. This approach therefore allows more appropriate response measures can be identified to manage the different impacts (see Table 1). Adaptive planning through flexible responses deals well with changing trends (Fane et al., 2010). Together with flexible responses, robust responses deal well with shocks.

Since it is not practical to assess the impact of all the possible trends and shocks in combination, the most significant trends and shocks need to be identified. In this paper, the method is only interested in system influences that have a material impact on ensuring water security – that is, those that have high levels of uncertainty and high significance for whether or not the set objectives in section 2.1 can be achieved. Using a risk matrix (Figure 2), the trends and shocks can be ranked according to their relative uncertainty and the sensitivity of the existing system to that trend. The ranking process is designed to be subjective and consensus based, with the system influences being ranked relative to one another (Scott et al., 2012). Trends and shocks that are ranked both as highly uncertain and having the greatest system sensitivity should be considered as significant. Practitioners are warned not to fall into the trap of overestimating our ability to control the future, which can reduce the perceived magnitude of the uncertainty associated with the influence being considered (Peterson et al., 2003).

Firstly the significant trends are used to describe the future scenarios and test the possible portfolios of measures. Thereafter, the shocks are used to test the robustness of the investment strategy. Table 2 provides some examples of trend influences that were considered by the a water business located in Victoria (Australia) when undertaking this process.

2.3 Describing the future scenarios

There are more complex ways of analysing trends and shocks in combination, potentially involving probabilities. However, these approaches are ‘black-box’ in nature and often require data that is not readily available (Polasky et al., 2011). The process advocated here draws on and extends scenario planning approaches and is preferable because it provides transparency in the analysis, which is key for helping decision-makers and stakeholders to follow and understand the logic of the process. Peterson et al (2003) warn that since scenarios often deal with poorly understood issues outside the expertise of most people, the predictions of experts should not always be privileged over those of non-experts. Scenario planning should be an open process that includes a variety of world views, and one where participants are encouraged to recognise their own inherent assumptions.

The scenarios are created by describing a number of futures based on various combinations of the significant trend influences identified previously. By assessing the current system's capacity to respond to the compound effects of these trends under particular future scenarios, the gap between the set objectives and what is achievable under the different scenarios can be determined. Where the objectives relate to supply demand balances, this gap is the potential shortfall in water supply.

Applying the scenarios produces an envelope for future supply and demand, as illustrated in Figure 3.

2.4 Developing response measures

Once a shortfall has been identified, new response measures are needed to bridge the gap and meet the set objectives. For water planning, a wide range of measures can be identified that span supply and demand side options, small and large scale supplies, potable and non-potable supplies, and alternative supply options. These can be drawn from existing plans or could also be initial concepts and ideas.

The timing of a measure and the lag between planning, investment and delivery is a significant factor that needs to be included in the analysis. Measures which can be mobilised at relatively short notice provide the capacity to respond to shortfalls in the objective at the time when they are required, and are usually deployed when specific trigger points are reached (Fane and Turner, 2010). Other measures on the other hand, such as decentralised recycling distribution networks, may need to be installed on an incremental basis, as new developments are rolled out.

These measures are then assessed using economic, social, and environmental criteria that embody the objectives. Tools such as multi-criteria decision analysis (MCDA) and cost benefit analysis maybe appropriate. Only those measures that meet the selection criteria and that have the potential to contribute to reducing the projected shortfall in the objective within the necessary timeframe should be considered further.

The interaction and relationship between each trend influence and each proposed measure is further assessed in terms of how this will affect the projected shortfall. Those measures with high individual vulnerability to the influences and which will therefore fail to reduce the projected shortfall in the future should be discarded from the analysis. In some instances, some measures may be complementary and are best tested as a portfolio. The set of measures is now be carried through to the next step.

2.5 Setting the investment approaches

As discussed previously, investment approaches provide the rationale for packaging up types of measures into portfolios, to respond to the shortfalls identified under various scenarios above. By grouping the measures into their types, the focus is shifted away from identifying the specific measures, but to rather rely on an agreed investment approach for deploying specific types of measures to address future shortfalls.

For example, the following two investment approaches were used by a water business in Victoria, Australia, and applied to the trend scenarios (Mukheibir et al., 2012), viz.:

Approach A: An approach which draws on the large scale potable supply options as a first choice;

Approach B: An approach that first considered the introduction of demand side reduction programs as priority, together with the incremental installation of small scale non-potable options as the opportunities arise, before introducing the large scale potable supply options.

Once an investment approach has demonstrated its robustness and flexibility to cope with the future scenarios and deliver the set objectives, the details of the specific measures that make up the investment portfolio can be addressed.

2.6 Packaging up the portfolios of measures

According to the rules of a particular investment approach, portfolios of measures are then packaged up to meet the projected shortfalls in the set objective. The performance of these portfolios is then assessed against the objective of least community cost in the broadest sense - the aim here is to identify the economically, socially, and environmentally preferred portfolios. The use of MCDA is a useful tool in this instance, provided the criteria have been set up at the objective stage to avoid gaming of the process.

2.7 Testing the system against shock influences

Shock influences (sudden step changes in the trends) identified and assessed earlier in the process are now brought into consideration, in the form of a sensitivity analysis. The performance of the investment approaches (with preferred portfolios) is assessed against significant shock influences, following a process similar to that for the trend influences: shortfalls are again calculated, and portfolios are modified where necessary, and re-assessed against the broad performance criteria. The shock influences could include sudden energy price increases, sudden increases in demand or sudden drops in supply.

3 An adaptive outcome

In testing this new approach with an urban water utility in Victoria, it was found that an investment approach which first considered the small scale non-potable options before introducing the large scale potable supply options, was better placed to respond to the more extreme circumstances and respond to changing objectives than one that drew on the large scale potable supply options as a first choice. However, this adaptability came at the price of potential overinvestment under the more mild scenarios, characterised by low population growth and a wetter climate (Mukheibir et al. 2012). This is analogous to insurance where there is a need to invest a little bit more upfront to have flexibility and robustness later.

In dealing with shocks, Approach B was found to be more robust since it built in flexibility through progressively investing in diversity and readiness over time (Mukheibir et al. 2012). The risk due to the uncertainty in the significant influences can be reduced through investing in a range of independent options. Significantly, when tested against a range of shock influences, the cost variability over time for Approach B was considerably less than those for Approach A. This is because options were not triggered by a supply/demand imbalance but rather by urban growth. It deferred potable augmentation and therefore also deferred the adverse environmental and social impacts of the large scale potable supply options.

4 Conclusion

The outcome of this series of steps is an adaptive strategy since uncertainties in both trend and shock influences have been identified, assessed and addressed through portfolios of measures to ensure that the set objective is met under any situation. The process outlined above ensures a systematic integration of future uncertainty with the assessment of effective measures to address projected shortfalls, without the use of probability analysis. This method moves away from traditional deterministic approaches and provides the opportunity for non-traditional responses to be investigated and in some cases to be winners, whilst maintaining transparency in the analysis.

What distinguishes this approach from others, is the combination of the three concepts in thinking and planning, viz. the characterisation and analysis of uncertainty as trend or shock influences, the use of scenarios to group the influences, and the focus on investment approaches to package up the portfolio of measures.

By periodically reviewing the response of selected investment strategy to the influences, and based on new information, the portfolio of measures can be adjusted to ensure an adaptive decision-making process to meet the set (or changing) objectives. This allows the system to be flexible and adaptively planned and managed. In addition, building the capacity to respond to emerging changes before they occur, educating decision makers to recognise the signals and having the systems in place to adequately respond in timely manner, are key requisites for dealing with uncertainty in complex water systems.

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Table 1: Types of influences and their related responses

Influence Types	Description	Responses
Trends	Gradual changes over time (the rate or direction is unknown) Eg. run-off, water demand	Flexibility in decision making
Shocks	Sudden step changes in the trends (the scale or timing is unknown) Eg. Bush fires, energy pricing	Flexibility and robustness
Extreme variability	Extreme variations within the current trends that return to normal after the event e.g. droughts, floods, heat waves	Tactical responses that rely on redundancy and emergency measures

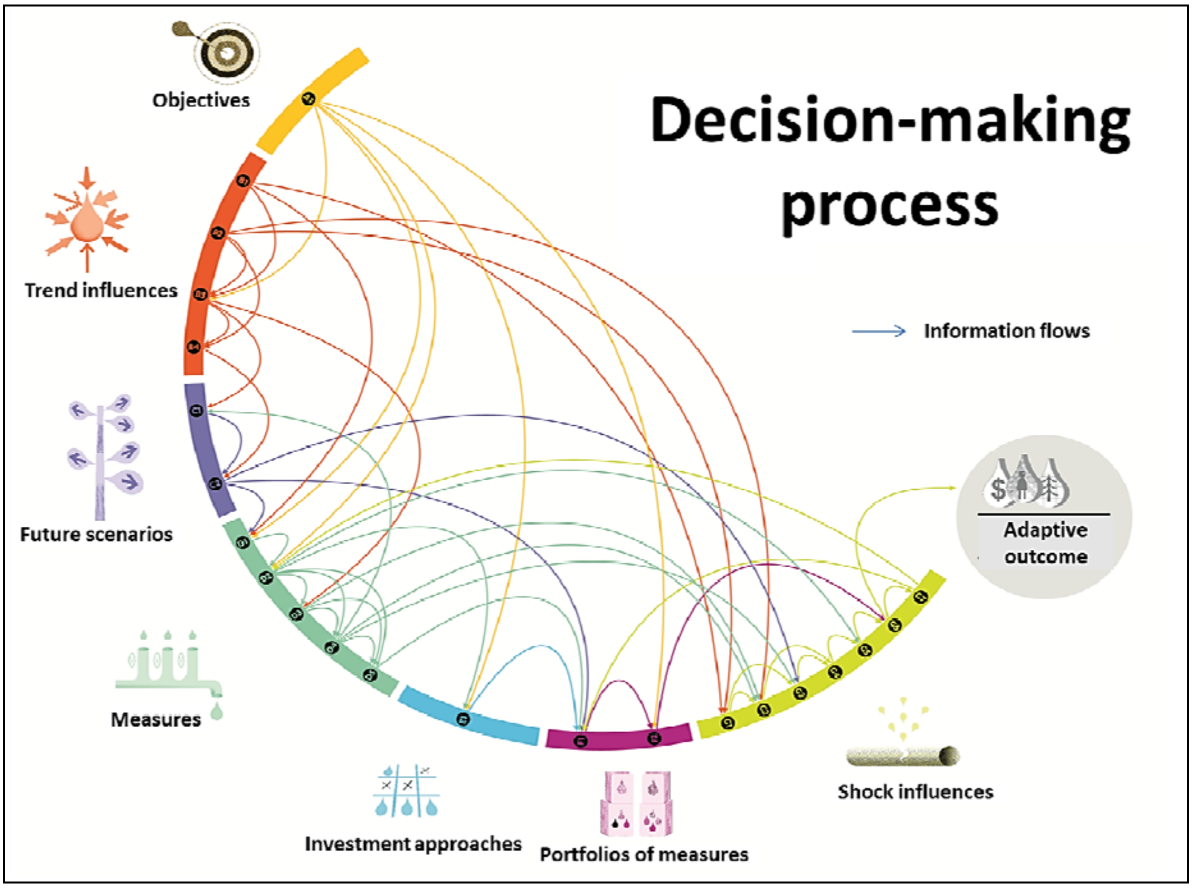
Table 2: Examples of trend influences (CSIRO 2007; DSE 2011; Mukheibir et al. 2012)

Trend	Key driver for	Trajectory
Climate change	supply	Wet (very little drying) climate scenario Medium climate scenario Dry climate scenario
Bushfires	supply	Long term stream-flow trends associated with natural forest aging following the 2009 bushfires. Gradual decline in average annual yield accruing 5-25 years after the bushfire Future change in the frequency, severity and extent of bushfires
Population growth	demand	Population growth rate projections follows historic trends Declining household size forecasts
Water consumption	demand	Initial declining per capita usage due to changes in water use behaviour, then stabilising per capita usage High adoption rate of water efficient appliances Changes in climatic conditions including temperature and rainfall (focus on garden irrigation)
Energy pricing	cost	Increase in energy costs based on the long term trends
Public perception on water source	supply	Positive changes in demand for fit-for-purpose water Positive changes in demand for alternative and recycled potable water

Figure 1: Decision-making process for adaptive urban water strategies

Figure 2: Uncertainty risk matrix

Figure 3: Typical supply and demand envelopes under various scenarios illustrating potential shortfalls in supply



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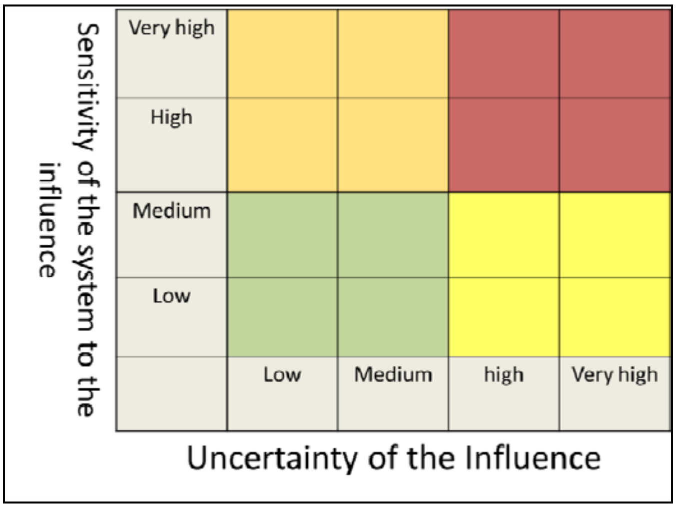

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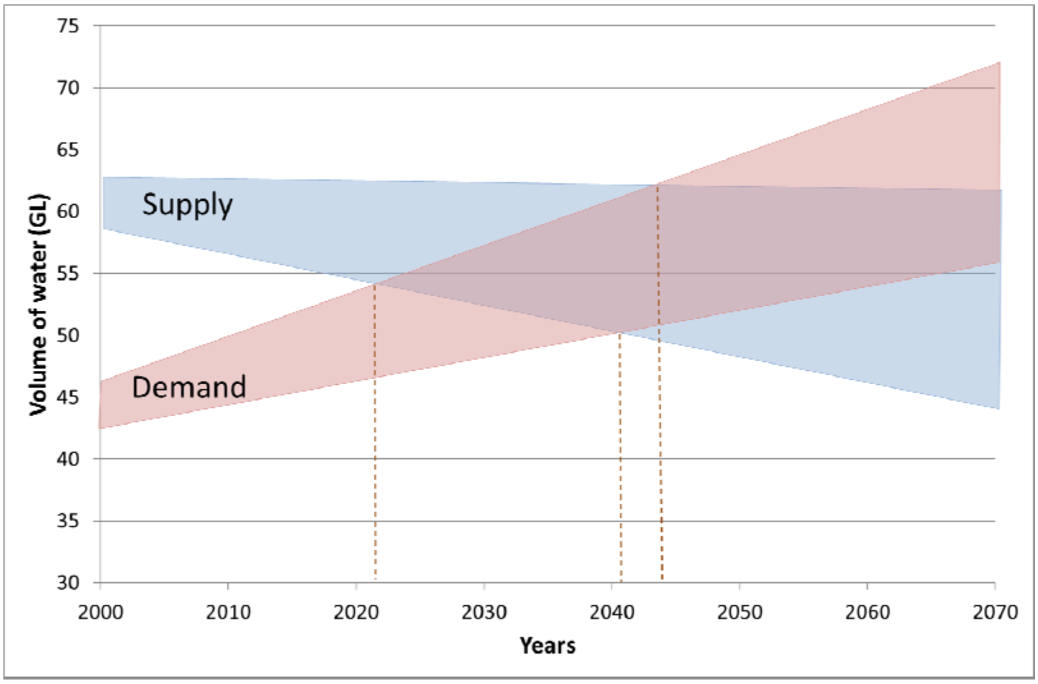

Figure 3. Typical supply and demand envelopes under various scenarios illustrating potential shortfalls in supply