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Water security through scarcity pricing and reverse osmosis: A system dynamics approach

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ABSTRACT

Water supply and demand planning is often conducted independently of social and economic strategies. There are presently no comprehensive life-cycle approaches to modelling urban water balances that incorporate economic feedbacks, such as tariff adjustment, which can in turn create a financing capacity for investment responses to low reservoir levels. This paper addresses this gap, and presents a system dynamics model that augments the usual water utility representation of the physical linkages of water grids, by adding inter-connected feedback loops in tariff structures, demand levels and financing capacity. The model, applied in the south-east Queensland region in Australia, enables simulation of alternatives and analysis of stocks and flows around a grid or portfolio of bulk supplies including an increasing proportion of rain-independent desalination plants. Such rain-independent water production plants complement the rain-dependent sources in the region and can potentially offer indefinite water security at a price. The study also shows how an alternative temporary drought pricing regime not only defers costly bulk supply infrastructure but actually generates greater price stability than traditional pricing approaches. The model has implications for water supply planners seeking to pro-actively plan, justify and finance portfolios of rain-dependent and rain-independent bulk water supply infrastructure. Interestingly, the modelling showed that a temporary drought pricing regime not only lowers the frequency and severity of water insecurity events but also reduces the long-run marginal cost of water supply for the region when compared to traditional reactive planning approaches that focus on restrictions to affect demand in scarcity periods.

ABSTRACT

Often, city or region water supply and demand planning is conducted independently of social and economic strategies. There are presently no comprehensive life-cycle approaches to modelling city water balances that incorporate economic feedbacks, such as tariff adjustment, which can in turn create a financing capacity for investment responses to low reservoir levels. This paper addresses this gap, and presents a system dynamics model that augments the usual water utility representation of the physical linkages of water grids, by adding inter-connected feedback loops in tariff structures, demand levels and financing capacity. The model is applied in the south-east Queensland region in Australia (3.2M population), incorporating the linked cities of the Gold Coast, Brisbane (State Capital), Sunshine Coast and Ipswich. The model enables simulation of alternatives and analysis of stocks and flows around a grid or portfolio of bulk supplies including an increasing proportion of rain-independent desalination plants. Such rain-independent water production plants complement the rain-dependent (i.e. dams) sources in the region and can potentially offer indefinite water security at a price. The study also shows how an alternative temporary drought pricing regime (i.e. scarcity pricing) not only defers costly bulk supply infrastructure but actually generates greater price stability than traditional pricing approaches. The developed model has implications for water supply infrastructure planners seeking to pro-actively plan, justify and finance portfolios of rain-dependent (e.g. dams) and rain-independent (e.g. desalination) bulk water supply infrastructure. Interestingly, the modelling showed that a temporary drought pricing regime not only lowers the frequency and severity of water insecurity events but also reduces the long-run marginal cost of water supply for the region when compared to traditional reactive planning approaches that focus on restrictions to affect demand in scarcity periods.

Keywords: Water security, desalination, scarcity pricing, temporary drought pricing, system dynamics modeling

1. BACKGROUND

The need for effective planning regarding potable water infrastructure is of growing concern in major cities, as population increases and development places stress on existing systems for augmenting our sources of supply. In policy terms the water supply “market” such as it is, calls for variations in pricing, trading, pipelines and now the use of desalinated seawater as mechanisms for balancing the aggregates of water supplied and demanded. While many of the water “shortages” reflect a shortage of sound governance and price incentives, the concern over changing rainfall patterns and reduced inflows makes increased water security through desalinated water highly attractive. While desalination options may have a higher capital cost than some rain-dependent schemes, they provide a greater degree of water security to a region, which in turn decreases planning risks for water-intensive industries as well as residential and commercial customers.

Australia is characterised by extreme climatic and annual rainfall variability, and therefore water supply and demand should be assessed in this context (ABS, 2012b). Not surprisingly, the large number and size of water storages is a function of both Australia's aridity and the variable rainfall, and yet many urban centres are reliant on rain-dependent supply sources such as dams and groundwater (ABS, 2010, 2012a). Consequently, Australia stores more water per capita than any other country in the world. The cities are often very dependent on normal rainfall patterns to replenish supply sources, making them highly exposed to extended drought conditions.

In this paper, the term water security refers to a water supply guarantee as defined in the South-east Queensland (SEQ) water strategy report (QWC, 2010). That is, there will be sufficient water to support a comfortable, sustainable and prosperous lifestyle while meeting the needs of urban, industrial and rural growth and the environment. In order to provide water security and prepare for future extreme conditions, the QWC considered potential droughts with a severity of between a one in 1,000 and one in 10,000 year occurrence, which is worse than what was experienced during the recent drought that ran nearly eight years from between 2001 and 2009. As the availability of water has influenced the pattern of economic development throughout history in Australia (Roberts et al., 2006), so water is a critical input to almost every industry. Expanded and secure water supplies are clearly vital for Australia's socio-economic wellbeing as the Australian population grows, perhaps more than tripling to 70 million by 2100 (ABS, 2013). Regardless of the exact numbers, secure and expandable water supply is integral to dynamic

industrial and commercial sectors, which can be can now for the first time be enhanced by secure water supply with desalination options (WSAA, 2010).

Water security is one of Australia's greatest issues of concern (Beal et al., 2013). Population and economic growth all add to the competition for water resources, with droughts exacerbating concerns at the level of security of existing water resources. During the recent "Millennium Drought" (from 2002 onwards) in most parts of Australia, water shortages have been dramatic, with inflows reduced by 70% or more in extreme years (Pittock and Connell, 2010). For example, according to Willis et al. (2013), during the recent drought, many water supply reservoirs in SEQ dropped below 20%. Consequently, the high variability in rainfall resulted in mandatory restrictions in response to drought as observed in many part of Australia since 2002. The problem of securing enough water for urban requirements in Australia is not really an issue of insufficient water resources, but rather an issue of local and regional water balance and costs of moving and treating water including salt water. More accurately stated, dealing with water imbalance (NCEDA, 2010) is all about sound water governance including pricing, financing and regulation.

Water utilities across the world are struggling to satisfy the increasing demand for both potable and non-potable water whilst also improving the environmental profile of the urban water system (Amores et al., 2013). Clearly, with increasing pressure on existing water infrastructure from population growth and climate change, there is a need for alternative water supply sources (Gurung and Sharma, 2014). To complement traditional rain-dependent supply sources and maintain a more reliable supply of potable water to consumers, governments and water authorities, there are now a range of alternative rain-independent options such as desalination plants, advanced wastewater plants and even storm water recycling schemes. However, these capital intensive infrastructures are often planned and built only in crisis or drought periods when there may be no adequate existing funding pool for such significant expenses. As experienced in most Australian state capital cities in the recent drought, extensive debts were taken on by government and water businesses to build bulk supply infrastructure, creating on-going servicing costs on the capital raised.

When drought hits, the standard experience has been a sequence of level 1 to 5 restrictions, with increasingly severe bans on watering gardens, washing cars, and even using drip irrigation systems. Studies have estimated the costs per person of the restrictions as in excess

of AUS\$100 per household for each dry summer (Grafton and Ward, 2008). This means that any reform such as new desalination supply that avoids restrictions, say for 10 million people, enables in principle the self-funding of new investments at a cost of \$1 billion per dry summer.

A sound and sustainable financing and economic approach to water supply and demand through a comprehensive tariff structure, as distinct from a restrictions approach, creates a capacity to fund required capital, and to optimise bulk water sources according to costs and risks. Rather than having politicians using water crises and pricing as a political platform through announcing new dams, subsidies, pipelines and desalination plants, the sound financing approach can consider the full portfolio of options, including rain-independent sources, and seek to achieve best value for money in achieving the required level of water security. Despite the potential welfare effects of household water restrictions there have been surprisingly few studies that have compared the use of volumetric prices versus water rationing (Grafton and Ward, 2008).

At the outset, it is imperative that most environmental systems are complex and highly dynamic with many feedbacks. These complex systems are characterised by feedbacks, interdependencies, and chaotic and discontinuous non-linear relations of their elements (Patten and Jørgensen, 1995). These systems have a large number of elements, which are in a series of dynamic interactions and driven by multi-causality. Effective environmental management requires an understanding of the interactions between policy choice and complex social, economic, technical and environmental processes and related aims (Kelly et al., 2013). Typically, water resources systems are highly dynamic and characterised by multiple interdependent components that together produce multiple economic, environmental, ecological and social impacts (Loucks and van Beek, 2005). Thus, as stated by Proust and Newell (2006), managing the water system optimally, and assessing its resilience and sustainability by considering possible changes in climate, population and patterns of consumption requires these systemic changes to be taken into account.

In the light of above discussion, the primary objective of this research was to develop a dynamic modelling framework for evaluating the water resource system for a number of bulk water supply source futures over a 100 year life cycle and addressing the following issues in SEQ, Australia:

- the impact of desalinated water supply in reducing the SEQ regions' vulnerability to urban water security;
- the role of desalination plants for providing water security to the SEQ region, particularly during times of drought; and
- the potential welfare gains from the use of desalination plants in combination with an alternative pricing regime (access, volume and seasonal or drought reflective tariffs) rather than restricting water use during periods of scarce supply.

To achieve the research objective, System Dynamics (SD) modelling is employed to investigate the water system in SEQ as well as conduct scenario analysis. SD modelling is a system approach and offers a suitable platform for exploring complex water systems. The following section provides more detail about the approach.

2. APPROACH

2.1 Provision of potable water in the study area: SEQ region, Australia

SEQ stretches from Noosa, south to the state border of New South Wales, and west to Toowoomba. In 2013, the SEQ region had an approximate population of 3.2 million people. Total urban water demand accounts for approximately 65% of SEQ's total water usage (QWC, 2010, 2012). The SEQ region, like many major cities in Australia, predominantly rely on surface water reservoirs (96%), with the exception of Perth, which relies on groundwater for 60% of its water needs (NCEDA, 2010). Such a high proportion of rain-dependent supply sources means that SEQ, like most Australian cities, requires a large storage buffer against low rainfall years (Marsden and Pickering, 2006). Dam inflow yields are particularly susceptible to the effects of global climate change as well as to natural climate variability (NWC, 2006; NCEDA, 2010). The accessible water storage capacity and volumes of reservoirs supplying the SEQ region was 2,220 ML in 2013 (BOM, 2013). Despite having such a large storage capacity, which represents over six years of supply at current demand levels, the accessible volume dropped below 40% accessible capacity in the 2002-2007 drought period, and in many instances as reported by Willis et al. (2013), many reservoirs dropped below 20%. Accordingly, QWC (2012) adopted a preparatory approach, introducing drought storage reserves and pre-defined trigger levels (40% combined capacity) to drive a prepared response should water storage levels become critical. At this point, the drought response plan, which includes a combination of applying medium level

restrictions, introducing the existing purified recycled water to the water grid and constructing new climate resilient supplies, would be triggered.

The urban water stakeholders in the densely populated regions of SEQ, Sydney, Adelaide and Melbourne, that experienced drought conditions in the late 2000's all followed a similar pattern of reactive debt-funded drought response actions. This similar pattern of response is partially a result of the industries highly regulated (i.e. prices reviewed by competition authorities), government controlled (i.e. restrictions set by government departments) and monopolised (e.g. state and local government owned entities prevalent) makeup and also the strong political influence over water planning and pricing across these cities (i.e. government often sets caps on price rises). This situational context perpetuates cycles of long-term under-investing and then catch-up over-investing in water supply infrastructure, combined with periods of weakened and then strengthened restrictions. Well considered long-term water supply and demand planning is often undertaken but rarely operationalised in such a restrictive planning context. Moreover, new paradigms of urban water planning such as those considered herein rarely gain the necessary groundswell support within the community in such a planning context.

2.2 Temporary drought pricing

Permanent Water Conservation Measures (PWCM) are low-level water restrictions that were introduced across SEQ on 1 December 2009 (QWC, 2010) and revised on 21 April 2012 (QWC, 2012). Under these measures, time-based restrictions (i.e. outdoor watering only at certain times) have been eased, but efficiency measures remain in place. There has been some consensus that, in order to maintain the integrity of and public confidence in Australia's water management, PWCM must be maintained. Consistent with this statement, NWC (2008) also reported that these ongoing urban water restrictions underline the need to ensure reliable urban water supplies and restore public confidence in the security of their supply. It should be noted that the PWCM strategy has not been communicated widely to the public post drought. While the efficient management of water supply and demand has an important part to play, this historical approach to water supply planning is inadequate in an era where desalination and other water recycling technologies has afforded developed countries the option to have a reliable supply of water at a cost. The National Water Commission regards long-term temporary (for several years in some cases) water restrictions as an inequitable and inefficient way of balancing supply and demand, and considers improved supply to be critical to

delivering secure, sustainable urban water into the future (Frontier Economics, 2008). Although the levels, types and trigger points are not consistent across jurisdictions in Australia, temporary restrictions are generally focused on restricting outdoor household usage (enforced measure) and using behaviour change measures (i.e. social marketing), and may last for several years in some cases.

Temporary Drought Pricing (TDP) is a name for scarcity-based pricing mechanisms where water charges are set inversely with available supply benchmarks. When a resource (such as water) is sufficiently abundant such that everyone who wants to use it can do so without affecting others' ability to consume it, then it is not scarce in any economic sense and has a lower value in the marketplace (Frontier Economics, 2008). Inflexible pricing, as Grafton and Ward (2010) argue, results in current demand that is too large when water storages are low; consequently this would encourage premature and/or over-investment in supply augmentation. Further, Mansur and Olmstead (2012) found that there would be substantial gains from adopting price-based approaches to regulate water demand rather than restrictions.

City water suppliers are often government controlled monopolies or heavily regulated private concerns, or contract suppliers, so it is unlikely that a true market economy for urban water will ever prevail universally as in grain or retail goods markets. Historically, in Queensland, the state government has provided funding programs to aid local governments in the provision of water, notably the Water and Sewerage Program. According to Engineers Australia (2010) report, the reduction in Queensland Government's water infrastructure subsidies in recent years has resulted in a number of local governments deferring planned upgrades of water infrastructure because costs would be beyond their constrained budgets. The application of a TDP structure would provide a means to communicate to the consumer that bulk water supplies are dwindling and that additional supply capacity along with demand efficiency are needed and must also be funded through higher water prices. A TDP achieves two key goals of a water provider in a water scarcity period. Firstly, it can take the place of restrictions to reduce water demand when supplies are diminished, although both, price and restriction can be used when time horizons are short and water storage levels are unexpectedly critical. The elevated price serves to promote consumers to reduce their demand through a range of physical and behavioural measures; the price elasticity of demand is discussed later. In the case of restrictions, where this reduction in demand also reduces revenues, a well-targeted TDP achieves the second goal to generate the necessary surplus revenues to provide the

capital funding for needed bulk supply infrastructure. Thus, there is a choice: (1) water agency actions to restrict supply through a number of punitive measures while scrambling to secure new source alternatives, often without additional immediate revenue funding; or (2) escalation in price at varying trigger point thresholds of drought (e.g. 50%, 40%, 30%, 20%) serves to both reduce consumer water demand while simultaneously providing the additional revenue to bring forward more water supply capacity (e.g. capital cost for a new desalination plant). For example, Denver Water has recently introduced a drought pricing regime as part of their response program. According to their TDP schedule, the amount consumers are charged for water varies depending on how much water has been used. The more they use, the more they pay. Additionally, drought price is added per 1,000 gallons (3,785 L) used increasing as water consumption increases (Denver Water, 2013).

In this research, a System Dynamics Model (SDM) uses these insights to provide a robust platform for demonstrating interactions, including the new elements encouraging reduced demand and generating associated revenue responses to pricing adjustments. Such an augmented SDM is a powerful tool for decision-makers seeking to understand the best pricing approach for managing demand while also providing the funds for new supply side investments such as dams, desalination plants, advanced recycling facilities, etc.

2.3 Systems Approach and participatory system dynamics

The systems approach integrates the analytic and the synthetic method, encompassing both holism and reductionism, which was first proposed by the biologist von Bertalanffy (1950).

The concept has been applied to a range of fields. For example: Ruth and Pieper (1994) coupled SD and GIS to simulate changes in the physical landscape of coastal zones; Sterman (2000) introduced a range of SD models for the analysis of policy and strategy, with a focus on business and public policy applications; Xu et al. (2002) used an object-oriented SD approach to develop a model for evaluating the sustainability of the water resource system in the Yellow River basin, China; Chan and Huang (2004) used the SD approach for planning a sustainable community and built a model of the development of the community of Ping-Ding, Taiwan; in the context of the climate-energy-water nexus, Newell et al. (2011) employed systems approach to examine the factors that can affect the resilience of the Australian National Electricity Market; and Sahin and Mohamed (2013) utilised SD to assess coastal vulnerability and the adaptation alternatives to sea level rise based upon a combination of SD

modelling, GIS and multi-criteria analyses of stakeholders' views. Evidently, most environmental systems are defined by feedbacks, interdependencies, and chaotic and discontinuous non-linear relations of their elements (Patten and Jørgensen, 1995). In the same way, water resources systems are also characterised by their multiple interdependent components that together produce multiple economic, environmental, ecological and social impacts (Loucks and van Beek, 2005).

Water authorities make decisions on when and how to invest in water infrastructure to increase the supply capacity and how to price access and usage of water. Faced with bounded rationality resulting from a limited knowledge about future conditions, inadequate capabilities to handle uncertainties, and short political timeframes, critical bulk water supply infrastructure decisions are usually made once a water security crisis is happening, and often to *not* deliver desired outcomes when needed. In order to make more optimal decision under uncertainty, critical factors and probabilities affecting the water supply system and its consumers must be taken into account. Generally, these factors are interlinked, forming a complex feedback relationships network. Therefore, decision makers should utilise a suitable method to solve this complex probabilistic, sequential and dynamic decision problem. To do so, incorporating price, supply and demand, as well as all other key factors into modelling requires a dynamic approach that would provide much needed knowledge (or understanding) of future behaviour of all key factors in the system.

Further, it is not easy to assess the effects of various urban water policy options using existing models (Barker et al., 2010). Much of the existing modelling has used rigid supply-side models, which are focussed on meeting set levels of demand given various engineering constraints (Hughes et al., 2009). Studies by Hughes (2008) and Grafton and Ward (2008) have incorporated endogenous demand curves so that demand is able to respond to prices. Thus, simulation is an effective method of evaluating assumptions about water supply and demand futures, based on differing behavioural assumptions, including responses to prices and restrictions. In addition to predicting the future state of the system, simulation models are useful for exploration, communication, and analysis. Therefore, simulation in this context would provide a powerful tool for analysing different options and understanding the long-term implications of management decisions.

Simulation, as defined by Borshchev and Filippov (2004), is the process of model execution that takes the model through discrete or continuous state changes, over time. Therefore, simulation modelling is a better answer for complex problems where time dynamics are important. Various simulation modelling concepts can be used for dynamic modelling, including System Dynamics (SD) and Agent-Based Modelling (ABM), two major non-linear modelling approaches. Underlying these approaches are control theory and the complexity theory (Scholl, 2001b, 2001a). According to Frenkiel and Goodall (1978), who identified the relationships between major simulation techniques, a discrete simulation is often appropriate for situations where the system being studied contains a number of separate items, and each item has its own characteristics and period of existence within the system, whereas, changes occur continuously and smoothly in the continuous simulation technique. Ossimitz and Mroczek (2008) argue that, although it is generally considered to be a methodology based on continuous time, SD is compatible both with the continuous and the discrete concept of time. Further, an SD model makes a useful distinction between the true and perceived system conditions, which is essential for modelling decision-making and social responses (Kelly et al., 2013).

For this reason, SD can be considered as a hybrid methodology. Hence, this “hybrid” potential makes SD a superior technique for modelling time, as it combines the advantages of continuous and discrete time concepts. As the water supply-demand system contains both discrete and continuous elements, the SD concept has been chosen as the research approach to be applied in the development of a dynamic model.

SD is a system approach based on servo-mechanism theory (Lane, 2000), and represents a set of conceptual and numerical methods that is used to understand the structure and behaviour of complex systems (Kelly et al., 2013). This powerful simulation modelling technique was initially rooted in the management and engineering sciences (Forrester, 1961). Gradually it spread into other fields, including social, economic, physical, chemical, biological, and ecological systems. SD related to the internal feedback loops and time delays that affect the behaviour of an entire system. Feedback loops are the basic structural elements of systems. Feedback loops are building blocks of dynamic systems that reflect a chain of causal relations among the interacting components of a system. More formally, a feedback loop is a closed sequence of causes and effects, or, a closed path of action and information (Kirkwood, 1998).

SD models consider simulation-based ‘what if’ type questions, and use differential and difference equations to represent the interconnections within a system.

SD has been used by number of researchers studying the water field, for example: Voinov and Gaddis (2008) developed watershed and water quality models to address water resource issues in Maryland, Vermont, Utah, and Virginia based on experience working with stakeholder groups; Zhang (2008) created a one dimensional river quality SD model for applying to water quality simulations for water pollution accidents; Winz et al. (2009) discussed the use of SD to address water resources management problems and best practices and common pitfalls in its applications; Dawadi and Ahmad (2013) investigated the effect of increasing population and changing climatic conditions on the water resources of a semi-arid region, the Las Vegas Valley in southern Nevada; Rehan et al. (2013) used SD to illustrate the unique characteristics and feedback loops for financially self-sustaining water distribution networks interactions among system variables over time. In addition to these works, Kelly et al. (2013) also provided some examples of how SD and some other well-known systems approaches have been utilised to investigate complex interactions between humans and ecosystems.

2.4 Systems model formulation, input parameters and scenarios

Following the guidance of Randers (1980); Sterman (2000), we started by identifying the questions to be investigated in Section 1, and determined the model boundary of the SEQ water system. System boundaries are important in identifying the key variables, deciding which process is endogenous (or exogenous), and specifying which variables are stocks and which are flows. Key variables required for the SDM were identified through a literature review and consultation with experts. SDM inputs included those related to population growth, changes in water demand patterns, changes in environmental patterns (e.g. rainfall and dam inflow), existing portfolio of rain dependent water resources, existing portfolio of rain independent water resources, construction of new desalination plants to meet bulk supply needs and pricing, to name a few. Table 1 shows the key exogenous and endogenous variables of the SDM. Spatial boundaries of the SDM comply with the boundaries of the SEQ water systems. The time horizon of the model is 100 years. To eliminate anomalies due to the seasonal variations in reservoir levels, the SDM uses monthly simulation steps and then aggregates to annual output.

Table 1 The model boundary details

Endogenous	Exogenous
<ul style="list-style-type: none"> • Population in the region • Rain independent water supply (Desalination and recycled water) • Changes in water price (Temporary drought pricing) • Water consumption • Water restriction • Desalination/recycled water plants construction • Dam construction • Accessible storage capacity 	<ul style="list-style-type: none"> • Population growth rate • Rain dependent water supply (Surface and ground water) • Climate change (Rainfall pattern and temperature change) • Price elasticity of demand

The SDM, using Vensim® DSS (Ventana Systems, 2012), was built by identifying key variables, estimating assumed relationships between these variables and finally parameterising these relationships. In building the SD model, a participatory modelling approach was employed following the approach outlined by (Van den Belt et al., 2004; Langsdale et al., 2009). Participatory model development can focus on portraying system structure, while model simulations reveal system behaviour, which is less intuitive and often the source of confusion. To build the model and raise the shared level of understanding, we have worked with assumptions re parameters and responses drawn from a range of experts from academia, private consulting firms and government water agencies, in order to produce a logical simulation model. Thus, the model development flowed through a multi stage process, including: 1) Desktop study 2) Problem scoping and model conceptualisation (first round of workshops with experts); 3) SD model development; and 4) Model testing and calibration (Second round of workshops with experts).

The SDM is composed of three main components or modules capturing demand, supply, and finance (i.e. pricing, revenue, investment etc.). There is a strong interdependency between these components of the SDM. Simulation involves modelling joint variations in key parameters, (e.g. estimating) the effect of decreasing one or more key factors and simultaneously increasing another. That is, the SDM enables a time-based exploration of various combined scenarios and alternatives (i.e. a new desalination plant, a new reservoir, climate change, new pricing structure, and population growth), and provides better visualization of how water supplies and demands vary in the system over time, thereby revealing any feedbacks that might cause unexpected changes in other parts of the system.

The testing of any model, in the sense of establishing robust results across variations of assumptions, is important to examine whether the proposed model is realistic and useful to the users; it should answer the question: “Was the model successful at addressing its intended purpose?” That is, the proposed model matches the real-world (Sojda, 2007) as seen by informed observers. Thus, this model was validated using two methods: 1) Parameter validation; and 2) overall model validation through a stakeholder engagement workshop (consisting of four researchers, two water engineering consultants and two government agency executives). The parameter validation method was used to validate randomly generated data by comparing with the historical data. Stakeholder consultation was used to assess the validity of the major components of the model through seeking agreement about the following aspects: input data validity; modelling logic (i.e. parameter relationships); and ensuring the model output adequately reflects the real situation.

The modelling framework presented in this paper provides insights into the complex SEQ water system. The systems model conceptualisation and its input data was aided by the SEQ Water Strategy Reports and other available information (QWC, 2010, 2012). Historical inflow data were then randomly generated for future time periods. This provides a consistent approximation of the historical inflows pattern to the existing portfolio of dam storages in the SEQ region. In addition to the existing extensive grid connected portfolio of rain dependent supply sources, the inclusion of a growing portfolio of desalination supply in the bulk water supply network was considered as they are necessary to satisfy the long term water supply needs of the SEQ region.

The rate of population growth and the magnitude of price change strongly influence both supply and demand over time. Therefore, in this research, to estimate the future population, two growth rates, namely the current 2% and the projected 1.5%, were used (Queensland Treasury, 2011). The primary water demand input we modelled is the present per capita demand which has been influenced by the step-wise sustained reduction in water demand due to long-term water restrictions that were in place in the late 2000’s drought period (i.e. 200 residential + 100 industrial/other = 300 L/p/d). To account for a potential rebound to historical demand levels we have also considered a scenario of historical pre-drought demand level (300 + 150 = 450 L/p/d). Finally, we have modelled the SEQ Level of Service (LOS) objectives demand levels (230 + 145 = 375 L/p/d). On balanced, our exploratory analysis showed that these average demand scenarios, especially the 300 L/p/d demand figure, likely represent the

three likely future scenarios of consumer demand in the SEQ region (QWC, 2012). Potentially, we may have long-term futures of lower water demand approaching 250 L/p/d (i.e. 160 residential + 90 industrial/other = 250 L/p/d) due to higher urban densities, appliance efficiency improvements, etc. but this would likely only occur in the context of sustained water restrictions, tightened building standards and sustained environmental behaviour change in the community, which we are not convinced will eventuate as the most likely case in the changeable democratic political context.

In this research, rather than limiting the users to predefined scenarios, a flexible scenario development approach has been employed, which enables users to modify key variables in the model. Although the SDM is capable of simulating a large number of scenarios by using a multivariate Monte Carlo simulation technique, due to paper space limitations, only 5 predefined scenarios (Table 2) were presented in this current paper to demonstrate the impacts of the key variables on the water supply-demand system.

Table 2 Predefined input values for examined simulation scenarios

Scenarios	Scenario Description			
	Population Growth (%)	Water Use (L/Person/Day)	New Desal (Yes/No)	TDP Pricing (Yes/No)
BAU-1 Business As Usual	1.5	300	No ¹	No ²
BAUD-1 Business As Usual with Desal	1.5	300	Yes	No ²
BAUP-1 Business As Usual with TDP	1.5	Varying	No ¹	Yes
BAUDP-1 Business As Usual with Desal and TDP	1.5	Varying	Yes	Yes
Restriction-1 Five level restriction	1.5	Varying	Yes	No ²

Notes: ¹This scenario still considers the utilisation of the existing 125 ML/d capacity desalination plant and the 100 ML/d indirect potable reuse recycled water plant into account but assumes that there will be no more rain-independent investments in the future. ²This scenario assumes that the real cost of water of water does not change and demand reductions not induced by pricing; only TDP will reduce a reduction in demand.

3. RESULTS

3.1 Water supply and demand projections: business as usual

The first step in forecasting the SEQ regions water demand is to estimate the current population and its likely rate of growth. Then, the SDM simulates the Annual Water Demand as a function of the Population, Per Capita Water Demand and Climate Impacts incorporating the variability and changes into the demand estimation (Figure 1). The model takes into account future variations in Annual Water Demand by simulating changes in important drivers such as temperature, TDP, and population growth rate over the planning timescale.

Figure 1. Demand sub-model and key drivers affecting the water demand system

Three variables, Annual Water Demand (ML/year), Population (Person) and Per Capita Water Demand (L/Person/day) were computed using the following equations:

$$AWD = P \times WD_{pc} \quad (1)$$

$$P = \int (P_{Ch}) dt + [P_i] \quad (2)$$

$$WD_{pc} = WU_{pc} \times (C_I) \quad (3)$$

Where:

AWD : Annual Water Demand

P : Population

- P_{Ch} : Population Change
 P_i : Initial Population
 WD_{pc} : Per Capita Water Demand
 WU_{pc} : Per Capita Water Use Projection
 C_I : Climate Impacts

The projection of future demand is calculated using current per capita water consumption and the future population projection. For the 2 per cent growth rate scenario, SEQ's population increases from about 3 million in 2011 to 4.56 million in 2031, 6.78 million in 2051, and 21.8 million in 2110. This finding is consistent with the Queensland Government projection. Using the reduced 1.5 per cent population growth rate scenario, the SEQ population is estimated to increase to 4.13 million by 2031, 5.57 by 2051, and 13.6 million by 2110. Based on the projections for population and per capita water consumption, the Annual Water Demand is simulated for five scenarios using this traditional approach, which does not consider alternative pricing strategies (i.e. TDP) for demand management. The result indicates that water demand is highly sensitive to population growth, per capita water use and climate change variability. The annual water demand at the end of the 100 year simulation period is ranging from about 1.86 million ML/year to 3.65 million ML/year. 30 years from today, the minimum expected water demand level is equal to 30 per cent of the current SEQ accessible storage capacity (2,220,150 ML), while max demand level would account for 45.2 per cent.

Annual water supply is simulated by considering the available water storage level. Presently in the SEQ grid system, changes in available supply are largely dependent on rainfall influenced dam inflow and groundwater reservoirs but also one rain independent desalination plant and one purified recycled water plant (QWC, 2010, 2012). The accessible volume of water at any given time is one of the most important factors affecting water security. Therefore, the construction of new supplies is triggered at certain accessible volume thresholds as part of a response to meet demand in order to ensure continuity of supply regardless of climatic variability. The existing desalination and recycled water plants, as highlighted in the SEQ Water Grid Annual Operations Plan, (SEQ Water Grid, 2011), are important supply sources that contribute to water security for SEQ. While critical to the long-term water security, these plants do not operate at capacity at all times. These plants are called upon if a water quality or asset related issue requires additional supply volume to meet demand or mitigate relevant water supply risks, or when key Water Grid storages are below

60% of combined capacity. Following this logic, the developed SDM is able to determine whether manufactured water is required in the grid system at any point in time. For instance, if the water storage capacity is 80% or more, rainfall independent supply sources (desalination plant and purified recycled water plant) go into the standby or mothballing stage to reduce the supply cost. However, when the storage level drops below an 80% level, then desalination plants become active gradually (i.e. 33% capacity) and supply water to the water grid. When below a 60% level, the plants run at full capacity. The reason to start partial producing water early, such as 80% rather than 60%, is to ensure a lower depletion rate of storages.

Two supply scenarios are tested by using randomly created inflow data mimicking historical trends, and are then compared using the three demand scenarios (Figure 2). The simulation results show that even when a 10 per cent increase in the current accessible water storage capacity is considered (i.e. 2,220 ML to 2,442 ML) the water supply will still not be sufficient to meet annual demand due to high inflow variability and a growing water demand in the SEQ region. Considering the high demand scenario (2% population growth and 450 L/p/d water use) and beyond 50 years from now, the present portfolio of water storages is shown to be inadequate as they will deplete too rapidly to critical levels, thereby making the region highly vulnerable. According to the SEQ water strategy, the combined SEQ Water Grid drought storage reserve underpins the drought response plan. The drought storage reserve is sized to provide, in conjunction with climate resilient sources, a minimum of 36 months' supply of water at a restricted demand. In this model, the drought storage level is calculated based on annual demand without restriction.

Figure 2. Combined storage level based on current accessible storage volume and 10% increase

3.2 Role of desalination plants and TDP for maintaining long-term water security

In previous section, the SDM focused on physical demand – supply interactions. Market forces, such as interactions between changes in the water price and the water demand of consumers were omitted.

Under the current pricing structure for residential water services in SEQ, retail suppliers charge a two-part tariff, with customers paying a fixed annual charge, in addition to a volumetric charge based on actual water consumption. For volumetric charges, two types of tariff structures are commonly adopted in the region: uniform volumetric tariff where all units (kL) are priced the same rate regardless of total consumption; and an Inclining Block Tariff (IBT) structure, where households are charged progressively higher prices for successive blocks of water in some cities in the region. The current water pricing approach encourages technical efficiency and protects against the exercise of market power; however, the widespread use of inclining block tariffs reduces price efficiency, by breaking the link between marginal costs and prices, and raises equity issues (Frontier Economics, 2008). As a result, the practice of setting prices with regard to long-run marginal cost would require water restrictions to balance supply and demand in times of shortage. Frequently, water authorities have maintained that consumers do not respond to price changes, so demand management has occurred mostly through restrictions on water uses and requirements for the adoption of specific technologies. However, water consumers are also likely to adjust their demand for water in response to changes in prices (Barker et al., 2010). In theory, raising prices to bring about water conservation is less costly than implementing a command-and-control approach, even if the prices in question are inefficient (Olmstead et al., 2007). Consistent with the aforementioned studies, NWC (2011) confirmed that, in most state and territory capital cities in Australia, there was a reduction in residential water consumption per property immediately after the introduction of two-part tariffs and the removal of free allowances during the 1990s.

The SDM considers existing and additional supply sources such as, desalination plants dams, purified recycled water, and ground water. However, for the purpose of this current study, the model mainly focuses on the role of desalination plants in addressing future water security (i.e. the predominant supply source in the future) and examines the impact of TDP on consumer demand and water provider revenue. Using SDM, the desalinated water supply

option was evaluated in terms of investment and operating costs, reliability of supply, time to build, and economic life.

The extent of the consumers' response to a price change was calculated using the following basic demand elasticity equation:

$$\text{Change in demand} = RD \times (P / RP)^{E_d} \quad (4)$$

Where:

- RD : Per capita water usage (all uses)
- P : Bulk water price
- RP : The current bulk water price (\$0.002/L)
- E_d : Demand elasticity (taken as -0.5 for analysis)

A study, based on earlier analyses of 124 estimates generated between 1963 and 1993, suggests that the mean price elasticity is -0.51, the short-run median is -0.38, and the long-run median is -0.64, with 90 per cent of all estimates between 0 and -0.75 (Olmstead et al., 2007). Further, demand is likely to be more price responsive over a period of time. Hoffmann et al. (2006) estimates a price elasticity of residential water demand equal to -0.507 for the Queensland state capital Brisbane. According to a study by ACIL Tasman (2007), the price elasticity of non-residential water demand are around -0.6 for smaller users and around -1.1 for larger users in Melbourne. Therefore, to incorporate a time varying elasticity into the model, the changes in demand were dynamically computed. The model is designed to simulate the impacts of different level of elasticity on demand by enabling the varying of the elasticity level between -0.3 to -0.8.

The SDM model simulates the impacts of the changing price level and TDP on demand, supply, revenue and the costs of construction of new desalination plants under a range of scenarios (Table 2). TDP is only enacted during drought periods when water availability is becoming increasingly scarce. The TDP escalation above the base price level is linked to the available storage or supply level (i.e. starts at 60%). As the storage level reduces below the threshold level for TDP initiation, it increases the normal water price between 10 and 300% at certain critical levels. Similarly, as the total storage levels restore due to above average

rainfall or newly constructed desalination supply, the TDP levy is withdrawn at the same trigger points.

The impacts of TDP and desalinated water supply were simulated over a hundred year period and the comparative results of two scenarios, BAUP-1 and BAUDP-1, are presented in Figure 3. This figure shows when the TDP occurs for both scenarios and the revenue it generates. These projections should not be mistaken for the total revenue for the water provider which is a function of total demand and base price plus the TDP levy component.

Figure 3. Required TDP implementation and its revenue created with/without desalination

Without including sufficient numbers of desalination plants into the bulk water supply portfolio, implementation of pricing (TDP) strategies alone (BAUP-1 scenario) could be an effective way to reduce the annual demand (dotted line). However, there are two clear disadvantages of this strategy, namely: 1) Reduction in water demand is the result of an increasingly frequent implementation of TDP (grey bars) due to the diminishing level of water security in SEQ, which puts government officials in a precarious position as this scenario indicates that they are regularly in a water security crisis, and forcing tariff increases;

and 2) Consequently, sustained reductions in demand without increasing water supply significantly reduces the overall revenue base of the water provider and thereby also limiting its ability to invest and so enhance water security for the region. On the other hand, for the BAUDP-1 scenario, which combines demand reduction through TDP and water scarcity triggered supply augmentation through new investment in desalinated supply, eliminates these disadvantages and offers better long-term water security. The simulation results reveal that the total revenue (including revenues from regular tariff charges and TDP) would be 1.4 billion dollars per year for BAUP-1 Scenario and 1.54 billion dollars per year for BAUDP-1 scenario. This equates approximately 9 percent decrease in total revenue due to reduced demand as a result of frequent implementation of TDP without supply augmentation. That is, the revenue generated from augmented supply would be sufficient to build 10 new desalination plants with a 125 ML/d capacity (equivalent to the current desalination plant capacity) without requiring additional funding.

As a final note to readers, the modelling shows that for the second 50 years (i.e. years 51-100) of the analysis period, the SEQ regions' population is sufficiently large that even the planning and construction of small 50,000 ML/year sized plants is insufficient to provide water security. Consequently, the region is persistently in crisis conditions and TDP is almost always in place, meaning relentless price increases. The scenario analysis reveals that in the latter 50 years, the population is such that a large new dam storage (e.g. >1,000,000 ML storage volume) or very large manufactured water plant (e.g. >500,000 ML/year) is required to meet demand.

3.3 Role of rain-independent factory water for improving water supply reliability

Water supply reliability, as defined in this paper, refers to ensuring a water supply during times of drought and other emergencies (i.e. contamination during flood events) without water use restrictions (ability to meet water demands). The water supply reliability for the SEQ system, with and without desalinated supply, was also simulated as a function of water shortages and the system storage level, and frequency of water use restrictions at varying degrees (Level 1 to 5) were estimated (Figure 4).

Figure 4 Frequency of water restrictions due to water shortages over a hundred year period, with/without new desalinated supply

The simulation results showed that water supply reliability significantly increased when the desalinated water supply was included in the portfolio. As a result, the severity and frequency of restrictions due to variations in the water storage level decrease when the scenario of a growing portfolio of desalination plants is considered indicating that a higher water supply reliability can be achieved with this strategy (Figure 4). Therefore, desalination (or recycled water) offers drought-resistant water supply reliability within the context of long-term water supply planning. While the BAU demand scenario (i.e. 300 L/p/d total consumption) considers the recent drop in demand from pre-2005 levels, the future may provide even more rapid diffusion of advanced water efficient technologies coupled with effective behaviour change strategies that could also serve to reduce the requirement for severe restrictions without the need to construct as many new bulk supply sources. Nonetheless, population growth is such that new bulk supply infrastructure, preferably of a rain-independent nature, will eventually be needed to satisfy demand in the SEQ region.

4. DISCUSSION

4.1 Water security benefits of a balanced water supply portfolio

According to the SEQ water strategy (QWC, 2010, 2012), the drought storage reserve is defined as the stock of water below 60% of the working volume. The combined SEQ Water

Grid drought storage reserve underpins the drought response plan. The drought storage reserve is sized to provide, in conjunction with running at capacity existing rain-independent resilient sources, a minimum of 36 months' supply of water at a restricted demand (i.e. considers medium level restrictions enforced resulting in a 15% reduction in demand). However, this reserve level reflected the current supplies, which are heavily dependent on rainfall. Considering that the supply portfolio would now include increasing proportions of rain independent supply resources over time, it can be assumed that the actual volume of the drought storage reserve would vary over time according to the mix of supplies and the demand for water. Therefore, in this model, the drought storage level is calculated based on the Proportion of Desalination supply in total supply. For example, while the current drought reserve level is equal to a 36 month supply (approximately 3% from Desalination plants and Purified Recycled Water plants), as the contribution of manufactured water increases over time, the 36 month drought reserve level can be decreased.

Using the above logic, the required drought storage level was simulated. The simulation results indicate that as the proportion of desalinated supply in the grid portfolio increases (i.e. from the initial 3% to 40%), so the required minimum storage reserve level decreases from 36 months to 22 months' supply of water (995,000 ML/Year). Given that desalination or other manufactured water provides an almost reliable supply, regardless of rainfall conditions, the results allow a large urban centre to have lower reserve requirements than if they were solely reliant on dams and groundwater. Significantly, this enhanced reliability also translates into financial savings for the water provider and eventually customers, as well as a form of heightened water security for the city or region against threats to water security.

4.2 Role of desalination in stabilising water prices and consumption restrictions

The inclusion of desalination plants or other manufactured supply source alternatives in the overall grid supply portfolio provides greater price stability and/or reduced requirements for harsh consumption restrictions when compared to the traditional rain-dependent supply source portfolios. Traditional supply resources are highly dependent on rainfall, meaning that the region they supply is more susceptible to drought events. Consequently, more frequent price adjustments (i.e. TDP in the case of this study) and/or harsh restrictions would be required to contain demand in these periods with the likelihood of crisis events to increase as a region's population grows. Alternatively, having a good proportion of the supply portfolio as

desalination would enable water providers to offer more stable water prices and reduce the need for restrictions due to the heightened degree of water supply reliability offered by manufactured water resources.

4.3 Pricing water scarcity coupled with supply side augmentation versus restrictions

Monopoly government-owned water providers, which are common across Australia, often suffer from a planning process that is subject to political interference, delays and indecision. As evident in SEQ, Sydney, Melbourne and Adelaide in the drought of the late 2000's, this constrained planning process was exposed as being vastly inadequate. To make matters worse, in order to handle impending water security risks in these States an intensive command-and-control planning process took its place. In this situation government is forced to outlay significant capital to provide urgent supply sources, while concurrently implementing severe restriction regimes, which lower not raise finance.

The above conventional command-and-control planning approach creates a number of perverse outcomes that come to light when abundant supply is returned through rainfall. These include, the realisation that water prices must increase considerably to fund an increased marginal cost of water supply due to the debt load accumulated in the drought, as well as dealing with reduced demand/revenue levels due to consumers experiencing sustained restrictions. The resulting escalated price trajectory often introduces political interference through subsidies (or suppression of tariff increases), which constrains forward planning, thereby setting the scene for a new water security crisis a decade on.

There is nothing surprising in this crisis financing model of government – it is what would happen, say in the food market if there were not automatic market price rises after some shortage developed, with the price rise inducing increased production or imports or both. This stabilises prices and expands investment. So too for the bulk water supplies if the lessons of this model are applied – it creates stability in the bulk water market. It should be mentioned here that in the context of water supply, we are not advocating that a market driven expansion should not be at the expense of the environment (Ayres et al., 2013). Desalination and other recycled water technologies have historically been energy intensive, but their efficiency is improving significantly with recent advancements in membrane technologies. Future rain-

independent factory water expansion should consider best-practice energy efficient RO technologies coupled with a greater use of renewable energy generation sources.

It thus becomes clear that a paradigm shift from this conventional utilities planning approach to a price and investment response mechanism (here, TDP) promotes proactive and more efficient supply investment decision making. Specifically, this market oriented approach would provide improved long-term price stability, increased self-funding and reductions in the requirement for draconian restrictions.

The lower the level of available supplies relative to demand, and the higher the scarcity price (TDP), the greater the community pressure on governments to subsidise water consumers and implicitly burden others. So while the socially responsible outcome is achieved with TDP, as increasingly valuable uses of water get curtailed, the pressure will always be there for government to intervene – and pass the costs to taxpayers or other target groups. The need then is for good communications and better economic education across the water industry.

What is very desirable about the TDP strategy is that pricing reflects the *opportunity* cost of a unit of water, and so is driven predominantly by the values placed on the foregone consumption of others – and the increased likelihood of running out of water in the future – rather than just the marginal costs associated with the infrastructure used to supply the water by the water authority (Frontier Economics, 2008). In other words the new paradigm is more sensitive to customer needs and their differing dimensions, as well as to sound financing requirements. The resulting capital savings over the long haul also mean lower average total costs, including capital, thanks to reduced wastage of capital infrastructure. Unfortunately, the recent Australian desalination investments made in SEQ, Sydney, Melbourne and Adelaide, were not planned considering their opportunity cost and the associated efficient use of capital, but instead as a reactionary response to a water security crisis (i.e. guaranteed supply expansion at any cost).

The developed SDM was utilised to examine the water providers' change in revenue for a planning strategy employing both a TDP coupled with proactive desalination plant construction versus one that relied on restrictions to reduce demand in drought periods coupled with desalination plants to meet supply shortfalls. The model indicated foregone revenue that resulted from restrictions of the order of AUD\$4.9B by year 50, increasing to

\$18.9B in year 100. This comparative analysis highlights how restrictions on water usage have significant negative effects on the financial capabilities of water providers to proactively invest in much needed supply infrastructure. Inevitably, insufficient investment in appropriate new supply will lead to a water security crisis and a subsequent taxpayer funded injection, ultimately leading to a higher public cost of water. As demonstrated in this study, installing a TDP regime well in advance of a water crisis coupled with a plan to use surplus revenues generated from the TDP for funding new rain-independent capital infrastructure (i.e. surplus revenues quarantined for only supply extension purposes) will not only improve a regions water security but also not burden it with post-drought interest costs due to resulting debt burdens from inadequate price signals.

5. CONCLUSIONS, IMPLICATIONS AND FUTURE RESEARCH DIRECTIONS

5.1 Conclusions

Rationing a scarce good equally among all consumers is not economically efficient if consumers are heterogeneous and have different marginal valuations for the good in question (Grafton and Ward, 2008). Despite these known economic inefficiencies, as observed during the recent drought (2002-2008) experienced by all of the state capitals in Australia, most water authorities chose to implement water restriction policies during this crisis period. The residential sector often bore the brunt of restriction rules mainly targeted at outdoor use, while the commercial and industrial sector were not restricted per se but required to demonstrate best practice through water efficiency management reports submitted to a government department or the water business.

Sustained water restrictions in lieu of immediate higher volumetric prices to reduce consumption are not appropriate due to the following reported reasons: (1) average water and waste water bills account for a small percentage of household expenditure; (2) Australia has a well-developed welfare system to support disadvantaged households; and (3) most metropolitan households in Australia have water meters, therefore, higher volumetric prices would provide encouragement to most Australian households to reduce water consumption (Grafton and Ward, 2008). Similarly, adopting price-based approaches to regulate water demand rather than water restrictions creates a self-financing capacity for needed water investment as demonstrated in a recent study conducted in the USA (Mansur and Olmstead, 2012).

Our findings support the findings and arguments of these prior studies. An augmented SDM was utilised to demonstrate that adding the pricing of water scarcity through TDP is a considerably more effective strategy for reducing demand while simultaneously generating the additional revenues necessary to fund bulk supply infrastructure. The resulting reduced long-term debt burdens on State and Local Governments and the respective communities they serve benefit customers and taxpayers alike over the longer run.

The SDM indicates that TDP coupled with desalination augmented supply has considerable benefits over traditional reactive planning. The former strategy was shown to actually reduce the level of additional supply capacity required for the SEQ region over the longer term while also having a lower average long-run marginal cost. The study provides evidence that the TDP approach is advantageous considering both the monetary and non-monetary considerations. Also, the study indicates that as the supply portfolio includes greater proportions of rain-independent supply sources such as desalination plants, the requirement for implementing the TDP regime diminishes since there is less reliability on inflow to dams and groundwater. The outcomes of the study have implications for government agencies and water supply utilities/businesses seeking to better manage their cities long-term water security interests.

5.2 Implications for practitioners

The water supply industry often conducts its strategic planning in a fragmented nature, often resulting in less than ideal planning decisions and inefficient use of capital. While bulk and distribution water entities often have comprehensive planning processes and sophisticated modelling tools for water balance planning, financial modelling, etc., they are often completed independently of one another in a sequential planning fashion (i.e. water demand forecasts informs water supply planning which in turn informs infrastructure requirements which in turn informs capital requirements which in turn informs water price paths). This typical sequential approach fails to capture the interconnected nature of water supply planning and can often lead to a range of unintended perverse outcomes (e.g. long-term water restrictions coupled with a lagged stepwise increase in supply will reduce revenue streams to fund capital investments made in a water scarcity period). SDM is an ideal strategic water supply modelling tool since it addresses the deficiencies of the commonplace planning

approach by enabling all facets of the planning process (e.g. water supply and demand forecasts, infrastructure planning, demand planning, revenue and expenditures, etc.) to be connected in one comprehensive model and numerous scenarios to be explored through an adjustable ‘dashboard’ display. Specifically, systems models such as the one built herein, offers water executives and senior planners in the water entity a relatively inexpensive platform to logically walk through a range of future scenarios and identify the advantages and disadvantages of various approaches contemplated. Moreover, it enables them to conduct the above-mentioned resource intensive detailed planning processes with a reduced number of planning scenarios, thereby minimising the amount of wasted planning. Also, from the perspective of State and Federal government water commissions and strategic planning agencies, this model offers an ideal platform for road testing contemporary policy options.

5.3 Future research directions

The authors seek to build systems models for almost all major capital cities in Australia and explore a range of local (e.g. groundwater and river system sustainability), national (e.g. desalination utilisation rates) and international (e.g. rain-dependent supply reliability under future climate variability) water supply/demand planning issues. Moreover, as researchers we seek to use the SDM modelling platform to road test a range of novel contemporary water supply planning concepts such as the TDP in this paper.

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