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Addressing the water-energy-climate nexus conundrum: A systems approach

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Abstract: Australia has the highest per capita surface water storage capacity of any country in the world. However, this storage capacity is at the mercy of Australia's rainfall, which is the most variable of any continental region. Recent drought shaved more than 1% off the nation's economy and saw unprecedented widespread water scarcity. In South-East Queensland (SEQ), six consecutive annual drops in storage level forced the introduction of water restrictions, limiting over 2 million citizens to less than 30% of pre-drought per capita usage. Moving forward, forecasts of high population growth and climate change will simultaneously increase water demand and significantly reduce reservoir inflows. To respond to these challenges, water authorities are increasingly considering rain-independent supply alternatives, such as large scale recycling and desalination, for both base load supply and rapid drought response. This water-energy-climate nexus is complex and requires a planning process that accounts for interdependencies, feedbacks and non-linear relationships. A system dynamics approach offers such a suitable platform, and has been utilised by this project to develop a model for evaluating the SEQ bulk water supply system water balance over a 100 year life cycle. The model provides a determination of the best long-term mix of rain-dependent and rain-independent supply sources, under a growing population and falling annual rainfall, to ensure that a secure water supply is always provided. The model incorporates the GHG implications of such a climate resilient bulk supply source portfolio and provides analysis of some best practice design options to mitigate potential high GHG levels

***Keywords**:* Desalinated Water Supply; Water-Energy-Climate Nexus; Water Resource Management; System Dynamics; Water Supply and GHG

1 BACKGROUND

Australia is the driest inhabited continent and has the highest per capita surface water storage capacity of any country in the world (ABS, 2012). The large number and size of water storages is a function of both Australia's aridity and the highly variable rainfall, and yet until recently, Australia's water supply relied solely on precipitation. However, having a large storage capacity, mainly at the mercy of rainfall, does not provide water security. As observed during the recent drought, which shaved at least 1% off the country's GDP in 2006/2007 (World Economic Forum Water Initiative, 2011), unprecedented water scarcity had been experienced with inflows reduced by 70% (Pittock and Connell, 2010).

In South-East Queensland (SEQ), as a result of six consecutive years of declines in the total storage level, the accessible volume fell below 40% of capacity in 2007. Subsequently more than two million people in the region were subject to the highest level of water restrictions, which limited residential consumptions from about 450 litres per person per day to 140 litres per person per day in 2007 (QWC, 2010). Furthermore, climate change is expected to cause significant reductions in water supply and in annual mean dam inflow by 2100 (Hennessy et al., 2007). Concurrently, the increased water demand due to rapidly growing population in the SEQ region would intensify the pressure on supply availability over time.

Without sufficient rainfall, the large existing SEQ reservoirs are ineffective. Given the inherent uncertainty of climate variability and change, and the changing temporal and spatial patterns of rainfall, a key question is: *What should be done to reduce uncertainty and provide assurances of long-term water security to cope with the water scarcity problems caused by a changing climate and population growth?*

To respond to the challenges, water authorities are increasingly considering rain-independent supply alternatives such as large scale recycling and desalination for both base load supply and rapid drought response. While the inclusion of some rain-independent bulk supply sources such as desalination significantly enhances the resilience of the SEQ water supply to higher rainfall variability due to a changing climate, they also adversely contribute to the greenhouse gas (GHG) problem due to their high energy intensity unless they can be supplied by renewable energies.

However, this water-energy-climate nexus is complex and requires a planning process that accounts for the interdependencies, feedbacks and non-linear relationships involved. Furthermore, adapting the SEQ bulk water supply portfolio to one that can reliably handle future projections of rapid population growth in the region and reduced rainfall reliability and dam inflow due to climate change, while concurrently mitigating GHG impacts of such rain-independent supply sources through their integration with renewable energies will have significant cost implications that need to be considered and also communicated clearly to the public.

In this context, this paper focuses on evaluating the SEQ bulk water supply system water balance for a number of bulk water supply source futures over a 100 year life cycle.

2 APPROACH

2.1 Systems Approach and System Dynamics

In, this project, we apply System Dynamics (SD) modelling to investigate the water system in SEQ. It provides an appropriate modelling framework for assessing this water-energy-climate nexus because it can explicitly account for the feedbacks, interdependencies, and non-linear relations that inherently characterise such systems.

SD is a powerful methodology and computer simulation modelling approach, which was originally rooted in the management and engineering sciences (Forrester, 1961). Gradually, the SD approach has evolved and spread into other fields to simulate complex systems behaviour such as in the social, economic, physical, chemical, biological, and ecological systems (Fiddaman, 1997; Ford, 1999; Sterman, 2008; Zhang, 2008; Sahin and Mohamed, 2009; Sahin, 2011; Sahin and Mohamed, 2013).

2.2 Model Architecture

System diagrams (also labelled conceptual models) are important tools in systems analysis, providing an early stage of developing SD models. A system diagram represents cause–effect relations between elements or sub-systems of the overall system (Loucks and van Beek, 2005). These components form feedback loops that are linked with other feedback loops. Feedback is a process whereby an initial cause ripples through a chain of causation, ultimately to re-affect itself (Roberts, 1983). However, the interaction between these feedback loops is not linear and an identical change in one component may not always cause the same system behaviour as there may be a change in the state of the system, over time. A sample system diagram used in this project for analysing water resources problems is presented in Figure 1.

Essential variables for model operation were identified by reviewing locally based literature for region specific inputs and examining world literature for more generic variables and their behaviour. System norms and rules were informed by the SEQ Water Strategy Reports in combination with other literature (QWC, 2010, 2012).

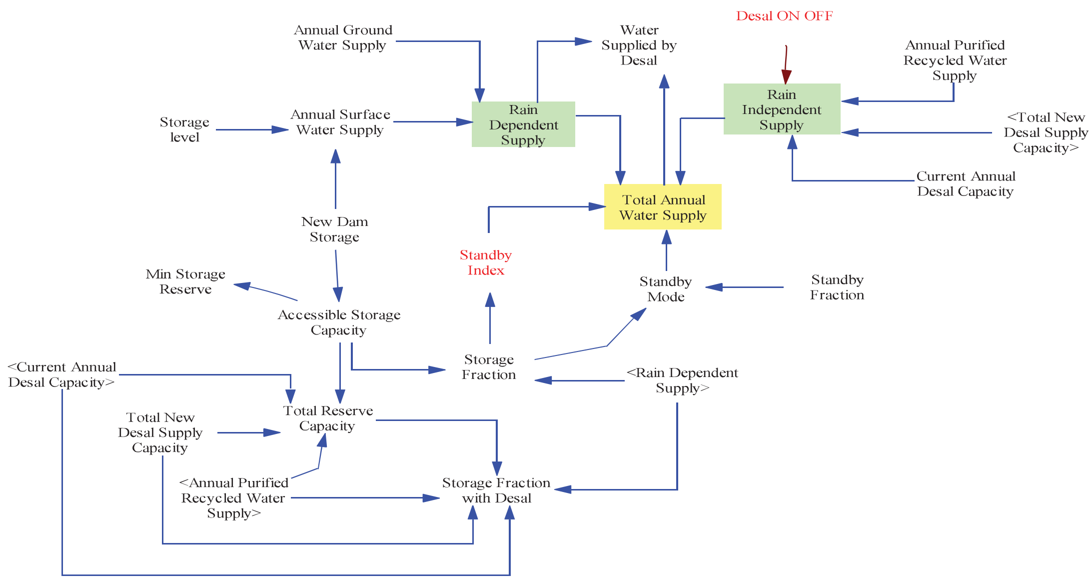

Figure 1 A SD sub-model representing water supply system

The model framework focuses on demand, supply, climate change, population growth, and the resulting water balance when adding a range of future rain-dependent and rain-independent bulk supply sources in the region over a 100 year modelling period. In summary, this paper encompasses the following steps:

Step 1: A literature review and expert consultations to benchmark the current state of knowledge in modelling parameters relevant to this project; obtain model input data, such as per capita water use, annual water supply capacity of existing water resources, population, historical rainfall data, climate change projections, the parameters of bulk supply source options (i.e. dams, desalination, bulk recycled, etc.), construction and operation costs of different bulk supply alternatives, and their energy-intensity and GHG implications.

Step 2: Build a system dynamics model using the software platform VENSIM (vensim.com) to simulate the water balance, future bulk supply infrastructure portfolio, life cycle cost and GHG implications for a particular future SEQ bulk supply portfolio will be developed.

Step 3: Analyse the current and future conditions (0-100 years) under a range of scenarios (e.g. different number of new desalination/recycling plants and dams, changes in precipitation due to climate change, demand and population growth, energy supply source, etc.).

Step 4: Examine the GHG implications of resilient bulk supply portfolios. This is based on the modelled future bulk supply infrastructure requirements and projections of the needs for future energy intensive rain-independent bulk supply sources (e.g. desalination) required for the region.

Step 5: Economic modelling to determine the present value of capital and operation costs ($/kL) of the rain-dependent and rain-independent supply sources that provide sufficient climate resilience for the region.

3 RESULTS

We describe the process of Model Development as part of the Results, reflecting the outcomes of the steps outlined in the previous section.

3.1 Water Supply and Demand Projections

Annual Water Demand is a function of the *Population* and *Per Capita Water Demand.* Therefore, the first step in forecasting water demand is estimating the size and future growth of the population in

SEQ. The projected annual growth rate averaged over the 45 year period 2011 to 2056 is 1.5 % (Queensland Treasury, 2011). Using this growth rate, the population of SEQ Region was projected to grow from about 3 million to 6.5 million over the next 50 years, and to 13.7 million over the hundred year projection period.

Three variables, Annual Water Demand (Ml/year) and Population (Person) were computed using the following equations:

$$AWD = P \times WDpc \quad (1)$$

$$P = \int (PCh)\, dt + [Pi] \quad (2)$$

Where: AWD: Annual Water Demand; P: Population; PCh: Population Change; Pi: Initial Population; and WDpc: Per Capita Water Demand.

3.2 Desalination Plants and GHG implications: PRO Technology

Three likely future scenarios of per capita demand in the SEQ region were used: (1) low demand (300 L/p/d); (2) pre-drought demand (450 L/p/d); and (3) the SEQ Level of Service objectives level (375 L/p/d). As shown in Figure 2, Water Demand at the end of 100-year period ranges from about 1.5 million ML/year to 2.26 million ML/year.

Desalination is a highly energy intensive technology. Therefore, the construction and operation of desalination plants to augment surface supply would increase GHG emission levels from the region. Additionally, the future production cost of desalinated water will be heavily influenced by the cost of plant construction and the anticipated increasing cost of energy (Hoang et al., 2009b). This may be partly offset by improved utilisation efficiencies of desalination plants.

A potential means of addressing the high-energy intensity of traditional desalination plants is the continuing development of pressure retarded osmosis (PRO) technology, which could significantly enhance community perceptions towards, and lower the life cycle costs of, desalinated water. Moreover, osmotic power, for its zero carbon-dioxide footprint, would indirectly reduce the environmental impact of the desalination process by reducing its reliance on fossil fuel consumption (Helfer et al., 2013; Helfer et al., 2014) and consequently, diminish the discharge of greenhouse gases in to the atmosphere.

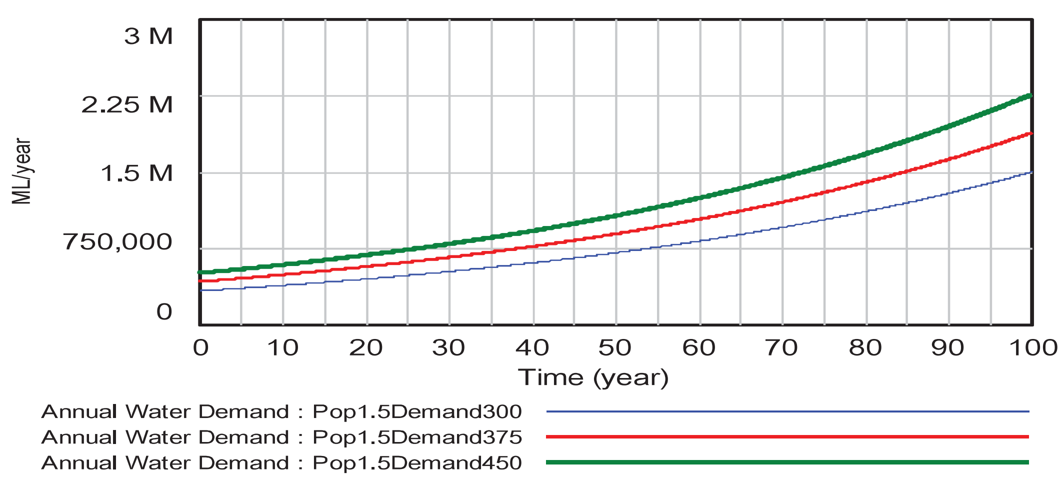

Figure 2 Annual water demand projections under three scenarios

The conundrum facing government and water businesses is that in rainfall periods when dam levels are full and potentially overflying, their portfolio of desalination plants have limited value and are put to standby mode. The use of dual-purpose membrane technology would allow desalination plants to generate electricity through PRO when not being used for potable water production (Helfer et al., 2013). Currently desalination plants consume 3-4 kWh/m^3 when producing freshwater from seawater

(Hoang et al., 2009a). Thorsen and Holt (2009) report that up to 0.74 kWh/m^3 can be generated from mixing seawater and freshwater at 20 °C, while successful trials of PRO technology have occurred in Norway (Achilli and Childress, 2010).

With this in mind, we incorporated the utilisation of dual-function desalination plants that utilise both traditional reverse osmosis (RO) and new-age pressure-retarded osmosis (PRO) technology in our model. The use of desalination plants is controlled by a logic relationship, mirroring the actions of a water governance body (QWC, 2010). It would be counterintuitive to utilise desalination plants to generate electricity in times of water shortage, as this would further contribute to water scarcity. When dam levels are in excess of 80% capacity, desalination plants are used for energy production. The model reveals that over the 100 year simulation period RO desalination accounts for 25 % of the total possible utilisation available, while PRO accounts for a higher 66 %. The remaining times of non-utilisation (i.e. 9%) occur in years where only a portion of full plant capacity is required for RO desalination to augment water supply.

Emission factors for calculating direct emissions are generally expressed in the form of a quantity of a given GHG emitted per unit of energy. CommLaw (2013) defines indirect emissions (Scope 2) as the emissions which are physically produced by the burning of fuels (coal, natural gas, etc.) at the power station, and projects the *Indirect Emissions Factors* for Queensland as 0.82 kg $CO_{2\text{-}e}$/kWh. We used indirect emission factors to calculate CO_2 emissions from the generation of the electricity, or consumed by desalination as tonnes of CO_2-e per GWh of electricity used, or generated.

The simulation results (Figure 3) show that at the end of 100 year simulation period, use of PRO has the potential to generate enough energy (15,400 GWh) to counterbalance the energy used for water production (11,300 GWh), and offset 100% of the CO_2 generated during the water production.

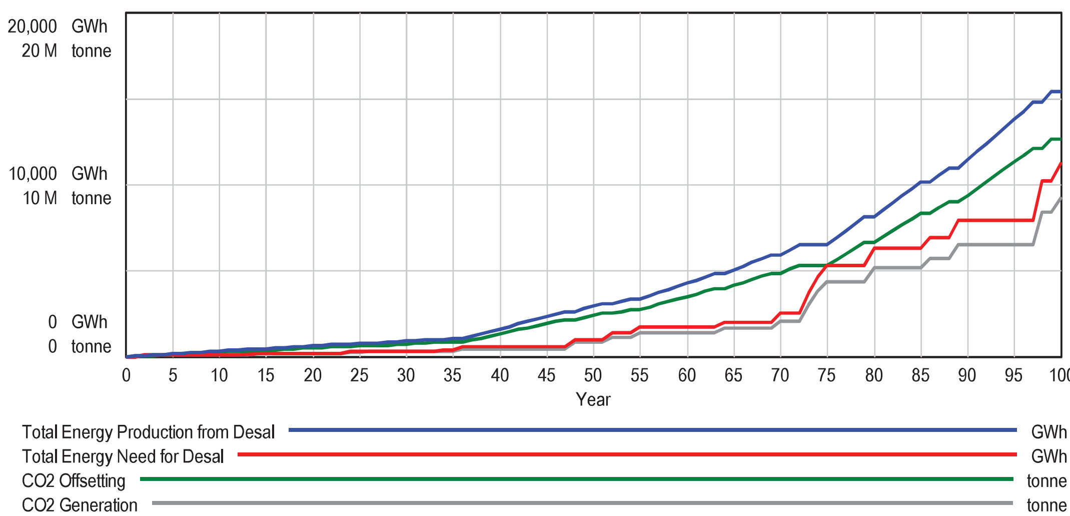

Figure 3 Energy - CO_2 used and offset by Desalination through PRO technology

3.3 NPV Analysis of Water Supply Options

Using the SD model, additional storage capacity to maintain current water security level in the region was calculated. Since the accessible volume of water at any given time is one of the most important factors affecting water security, an indicator of water supply security used in this research is the water security index (WSI). This index reflects the ratio of water storage to annual usage and the storage buffer required against low rainfall years. Marsden and Pickering (2006) reported that the ratio of storage to annual usage in SEQ is six. Given this baseline value, required new infrastructure investments for desalination plants and dams were calculated over the simulation period. The results show the need for long term planning to meet the challenges of likely water shortfalls between demand and supply. As population increases from 3.2 million to 13.6 million, the total additional water supply required over the projection 100 year period could increase by 5,000 GL for the demand

scenario. Finally, Net Present Values (NPV) of the rain-dependent and independent supply options by considering capital and operation costs were calculated to compare the economic viability of these two options. Figure 4 shows the sensitivity of the results of the comparison of water supply augmentation costs between dam construction and investing in desalination capacity (including both operating and capital investment costs). This analysis is based on discount rates of 1.5%. This is in line with the literature which suggests that lower discount rates are more appropriate over longer time horizons (Weitzman, 1998; Harrison, 2010; Weitzman, 2013).
As illustrated in Figure 4, the NPV of new dam infrastructures would be approximately 48 billion Australian dollars, about four times larger than the NPV of the desalination plants infrastructure.

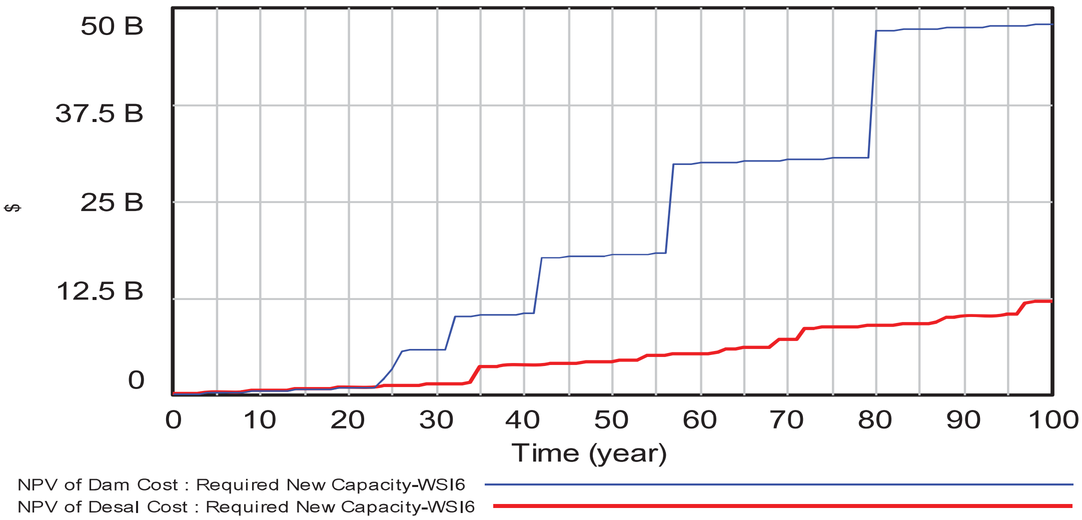

Figure 4 NPV comparison of rain-dependent and independent supply options

In the longer term, the cost of desalination investment in water supply augmentation is considerably lower than the cost of dam construction. Noticeably, over the longer time horizon, the cost comparison drastically changes in favour of desalination.

4 CONCLUSIONS

This paper detailed the development of an SD model built to explore the behaviour of the SEQ water resource system over the next 100 years under systemic change brought about by climate change and population growth. We have demonstrated that the SD framework allows rapid evaluation of the effects of a range of management scenarios through providing realistic visualisation of how water supplies and demands could change over time. Therefore, the framework would improve decision makers' ability to develop sustainable water resource management strategies, and thus respond to water scarcity in a timely manner to optimise supplies given the various constraints.

Through our SD modelling, we found that Desalination plants may be a useful insurance policy to deal with uncertainty surrounding water supply resources due to high rainfall variability, but like any insurance policy, this would see them sit idle for great lengths of time, only called into action intermittently. The energy intensity of current Australian desalination plants is up to 10 times greater than the energy presently consumed in supplying bulk water in SEQ (Hoang et al., 2009a; White, 2009). This raises two significant arguments, utilisation efficiency of desalination plants and high energy need, against their implementation

The continuing advent of PRO technology could greatly nullify these problems and provide other supplementary benefits. For existing desalination plants, Helfer et al. (2013) discussed replacing existing single purpose membranes with dual purpose alternatives, thereby transforming RO desalination plants into dual-purpose water supply and renewable energy production facilities. As demonstrated in the results section, this could realistically occur at SEQ's Tugun plant when the existing membranes reach their lifespan limitations. Additional power generation capacity would also decrease the need for fossil fuel exploitation, or the development of other renewable power supply plants.

Clearly, there are a myriad of potential benefits of integrating this technology into the operation of the water resource system. The SD model indicates that under predicted future SEQ climatic conditions, desalination plants will be inactive for sufficient periods of time to allow generation of nearly half the energy consumed in manufacturing water. Thus, depending on capital costs, the investment in PRO technology in the future would be worthwhile in SEQ.

Finally, the context of our water security assessment is not unique to SEQ, or Australia for that matter. Therefore, because we have used a system dynamics approach, our model provides a framework for assessing water security for any situation where a water-energy-climate nexus conundrum exists. We conclude by stating that it is hard to conceive of any water management situation existing where this is not the case.

5 ACKNOWLEDGMENTS

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