A SYSTEMS PERSPECTIVE ON CHARACTERISING RESILIENCE IN URBAN WATER MARKETS

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KEYWORDS

Urban water markets, social, economics, systems, trade-offs, resilience

ABSTRACT

Results from two decades of accumulated big data and systems analysis of Greater Melbourne and Sydney was investigated to develop insights into the resilience of each city. The key resilience parameters are distributed water sources and conservation in an urban water market, household welfare, government policy and regulation, pricing strategies, total dam storage and supply of desalinated water. These parameters have different levels of impact and significance across the two cities. Further studies are needed to better define the attributes and benefits of these parameters.

INTRODUCTION

The Greater Melbourne and Sydney regions have been subject to multiple shocks during the last two decades including floods, droughts, fires, climate change, economic recession and growth, variable political decisions, town planning choices and pandemic. Meadows (2008) found that system behaviours can only be deduced by observing the operation of a system, and highlighted the need for bottom up and hierarchical systems frameworks to understand key behaviours and resilience. The resilience of water cycle systems is characterised by resistance, recovery and robustness (Grafton et al., 2019).

This investigation examines the rich dataset from two decades of accumulated big data and systems analysis of Greater Melbourne and Sydney regions by the author to gain insights about key resilence parameters. The urban water market was characterised to include all activities and participants that provide or save water or influence water impacts across the urban regions. Bottom up systems framework models (see Coombes et al., 2018; Coombes and Barry, 2014) that include behavioural algorithms were utilised to evaluate the historical big data to understand the responses to options which can also reveal key drivers of resilence. This information was used to provide insights into parameters than can be used evaluate social, ecological and economic resilience of urban areas.

INVESTIGATIONS AND SIMULATIONS

The collection of multiple big data sources and the processes of developing systems analysis of the Greater Melbourne and Sydney regions over the last two decades has produced a rich source of collated data. Building on the findings of Meadows (2008) and Grafton et al (2019), examination of this data and the responses to systems analysis of options was expected to provide insights into the parameters and thresholds that describe the resilience of both regions. This investigation provides insights derived from historical observations of dam storage levels, demand for utility water supply, growth in utility water connections, utility costs, residential utility bills, demand for desalinated water, rainfall, take up of water efficient appliances and rainwater harvesting, and distributed sources of water.

The big data has been collated from the National Water Commission (NWC, 2004 – 2013), Bureau of Meteorology (BOM, 2014 – 2022), Pricing determinations by the Independent Pricing and Regulatory Tribunal (IPART, 2020) and the Essential Services Commission (ESC, 2018). Historical data from water utilities, NWC (2003 – 2013), BOM (2013 - 2022), water utility annual reports, and regulatory processes (ESC, 2018; IPART, 2020) was used to examine total dam storages, water demands, growth in water connections, utility costs and household utility costs.

Systems Framework

An overview of the Systems Framework and the Greater Melbourne and Sydney systems is presented in this Section to provide the context for this investigation into spatial utility costs and future options (see Coombes and Barry, 2014 and Barry and Coombes, 2018 for a full description).

The Systems Framework approach incorporates local scale inputs as a fundamental element of the method. Analysis is constructed from continuous simulation of local land uses and dwellings that drive system behaviours and accounts for distributed transactions to simulate spatial and temporal performances of a system. This structure is anchored on detailed “big data” inputs, such as demography, socioeconomics, topography and climate, and linked systems that account for water demands, water supply, sewerage flows, stormwater runoff and economic considerations.

The Systems Framework is a series of linked applications for continuous simulation of water balances and finances that interact to span a heirarchy of relevant spatial and temporal scales from household or land use to catchment to city or regional scales at timelines of one second to 50 years. The process includes multiple replicates of climate sequences and linked responses that yield probabilistic understanding of behaviour and risks. This includes water use and linked generation of wastewater and stormwater runoff at the local scale that are combined at the transition scale using demographic information.

Outputs from the transition or zone scale are inputs to distribution infrastructure and waterways in the network scale that includes operational information and structures. The network scale is linked to regional behaviours and infrastructure such as water extractions from dams and discharges of sewage to wastewater treatment plants, and ultimately to environmental receiving waters. Water restrictions were assumed to commence when total dam storages are drawn down to less than 60%. The timing of water security augmentation was estimated to be triggered by a probability of water restrictions that is greater than 10% or a 1% risk of total dam storage less than 10% in any year. The analysis includes two water security augmentation options at (1) 50 GL supply at a cost $1 billion followed by (2) 150 GL of supply at a cost of $3 billion.

Augmentation of local water and sewage treatment plants was triggered by simulated exceedences of published capacity at a cost of $3.5 million/ML daily capacity. Upgrades, maintenance and renewal of transfer infrastructure is dependent on current capacity and changes in flowrates with costs from historical rates (see ESC, 2018 & IPART, 2020).

Greater Melbourne

Analysis of the water supply system for Greater Melbourne employed daily streamflow, and network operational data and rules provided by Melbourne Water Corporation and the Victorian government (Coombes and Barry, 2014; Barry and Coombes, 2018). The projections of population and dwelling growth for Greater Melbourne from DELWP (2019) for 36 local government areas (LGA) were included in the analysis. Streamflow is harvested from Thomson, Yarra, Bunyip and Goulburn River catchments by Melbourne Water to supply the region and surrounding areas.

Water from storages in these catchments is transferred to a seasonal balancing network of Cardinia, Silvan and Greenvale Reservoirs. Water from these seasonal reservoirs is then transferred to local distribution networks within the water retail areas of Yarra Valley Water (YVW), South East Water (SEW) and City West Water (CWW) to supply water demands in each LGA.

The regional water network also provides water to Barwon Water, Western Water, Gippsland Water and irrigation districts. This investigation assumed that Wonthaggi desalination plant supplies water to Cardinia Reservoir when dam levels are less than 65% and streamflow is harvested from the Goulburn River via Yea-Sugarloaf pipeline into Sugarloaf Reservoir when dam levels are less than 30%.

Greater Sydney

The population of the Greater Sydney region is expected to increase from 5.3 million in 2020 to more than 8 million in 2050 (DPIE, 2020). The region includes twelve different water utility demand zones that are supplied from the Warragamba, Upper Nepean, Shoalhaven and Woronora river catchments. Water demands for the 45 local government areas in the Greater Sydney region and data from the nearest weather stations were combined in the regional analysis. Observations of daily water demand from 1976 to 2020 for the 14 water supply catchments and 45 local government areas were included in this investigation. This data sourced from Sydney Water, the NSW Government and the Bureau of Meteorology (BOM, 2013 – 2022) enabled development of local behavioural water demands and verification of these water demands at different scales (Barry and Coombes, 2018).

Streamflow from the Warragamba catchment is captured at Warragamba Reservoir. Water from the Cataract, Cordeaux, Avon and Nepean Dams located in the Upper Nepean catchment is conveyed via a system of pipes, natural river channels, weirs, tunnels and aqueducts to Prospect Reservoir whilst also supplying various communities along the transfer routes. The South Coast region is supplied with water from the Avon and Cordeaux Dams and Nepean Dam via the Nepean–Avon tunnel.

Streamflow from the Shoalhaven catchment is captured in Lake Yarrunga and Tallowa Dam where water is pumped to Wingecarribee Reservoir via Fitzroy Falls Reservoir when the water storage volume in Warragamba Dam is less than 65%. Water from the Wingecarribee Reservoir is distributed to Nepean Dam and Lake Burragorang via the Wingecarribee and Wollondilly Rivers. The townships of Mittagong and Bowral are also supplied with water from the Wingecarribee Reservoir. Desalination is used to supplement the water supply from the Potts Hill reservoir when total storages in dams are less than 80%.

Spatial costs

Coase (1947) found that marginal costs of water supply were dependent on the quantity of demand and distance from the water source for each consumer. Clarke and Stevie (1981) analysed the costs of sourcing, treating and distributing water, and found that marginal costs of water supply increases with the quantity of demand, population density and transfer distances.

The spatial variation of the costs of utility water supply were estimated as a function of demand, population density, the distance and sum of increased elevation in the route of trunk infrastructure from nearest water sources to the centroid of each local government area. This relationship was also employed to estimate the spatial costs of sewage services as function of the distance and sum of increased elevation in the route of trunk sewage infrastructure from the centroid of each local government area to sewage treatment plants. These spatial costs were determined using the classic economic perspective that in the long run all costs are variable and must be counted in economic analysis (Coase, 1947).

Options

The resilence of urban water systems can be revealed by examining responses to different options in a systems analysis (Grafton et al., 2019; Meadows, 2008). These responses can highlight key parameters and thresholds in the system. The following options were examined. Business as usual – the BAU option - continues with the current regime of regulated utility water, sewage and stormwater services to the Greater Melbourne and Sydney regions. This option continues the utility costs and pricing frameworks set by the regulators IPART (2020) and ESC (2018), based on the building block method, regulatory asset base and nominal revenue requirements.

Water efficient applicances and behaviours - the WEA option - includes water efficient showers (< 9 L/s), clothes washers (< 9 L/kg load) and toilets (4.5/3 L/flush) in all new and renovated dwellings. In addition, 8%/annum of renovated dwellings, 10%/annum of new detached dwellings and 5%/annum of new units include rainwater harvesting for toilet, laundry and outdoor uses. The minimum rainwater storage size is 5 kL for renovated and new detached dwellings, and 2 kL/dwelling for new units and semi-detached dwellings.

The BASIX policy for the Greater Sydney region currently includes targets for reductions in utility water use of up to 40% that apply to most new dwellings. In contrast, the six star policy for Greater Melbourne presents a choice between a solar hot water heater and a 2 kL rainwater storage supply toilet demand. An additional NoBasix option was examined for the Greater Sydney region to account for the reduced household demand for utility water services embedded in the BAU option created by the NSW BASIX policy.

Full variable prices (no fixed tariffs) for water and sewage services – the Price option - was assumed to commence in 2020 based on the total water bill in the previous period. The usage price for water and sewage services was altered on an annual basis as a ratio of current demand to demand in the previous year in each LGA as an indicator of changes in the costs of providing services.

The quantity of water supply and associated wastewater discharges from each property is impacted by the price elasticity of demand (E_p) which is defined as a function of the base price (P), change in price (ΔP) and quantity (Q) demanded:

$$E_p = \frac{\Delta Q/_Q}{\Delta P/_P}, \xrightarrow{yields} \Delta Q = E_p \frac{\Delta P}{P} Q \qquad (1)$$

The price elasticity of indoor, outdoor, unit and non-residential demand for utility water and sewage services was defined as shown in Table 1.

Table 1: Price elasticity of demand for utility water and sewage services for Melbourne and Sydney

Water use	Melbourne	Sydney
Residential Indoor	0.13	0.1
Residential Outdoor	0.38	0.14
Units & Non-residential	0.1	0.05

These values for price elasticity of utility supply were derived using regression analysis for Greater Melbourne and were consistent with published research by Veck and Bill (2000) and Dalhusen et al (2003). Price elasticity for Greater Sydney was sourced from Abrams et al (2011) and is lower than other published estimates.

DISCUSSION

Historical observations since 2000

The historical resilience of the water supply to Greater Melbourne and Sydney is considered by examination of the total dam storage volumes in Figure 1.

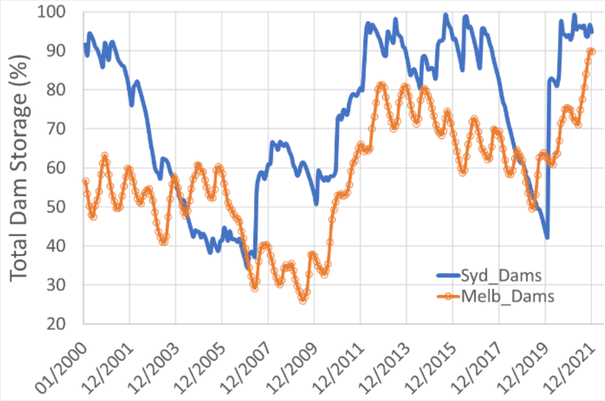

Figure 1: Dam storage levels in Melbourne and Sydney

Figure 1 shows that dam storage levels for Greater Melbourne were persistently lower than 60% since 2000 and were drawn down to 26% in 2009 and 49% in 2019. Dam storage levels for the Greater Sydney region were drawn down from 92% in 2001 to 34% in 2007 and to 42% in 2020.

Sydney experienced severe reductions in catchment runoff into dams and implemented water use restrictions during the periods from October 2003 to June 2009, and from June 2019 to December 2020. Water wise rules for permanent water savings now apply to the Greater Sydney region.

Declining catchment runoff and dam storage levels for Melbourne prompted water restructions from

August 2006 to December 2012. Since 2015, Melbourne has employed permanent water saving rules via the Target 155 policy.

The regional demands for utility water supply and growth in connections to utility water services are presented in Figure 2.

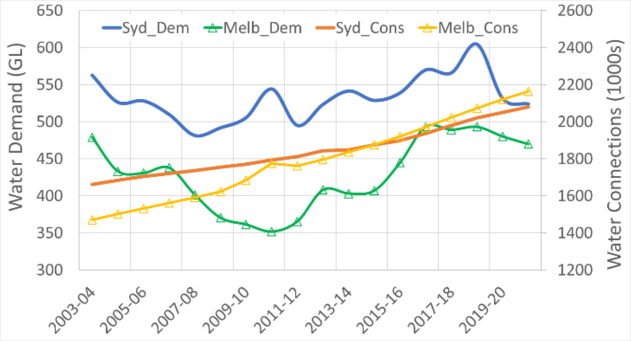

Figure 2: Water demand and growth in water connections in Melbourne and Sydney

Sydney demand decreased by 6.9% and Melbourne demand increased by 1.9%. Growth in connections is 25.3% in Sydney and 47.1% in Melbourne.

Sydney demand declined from 563 GL in 2000 to 482 GL in 2007, increased to 604 GL in 2019 and is currently 524 GL. Melboourne demand declined from 479 GL in 2000 to 352 GL in 2010, increased to 493 GL in 2019 and is now 470 GL.

The Wonthaggi desalination plant with annual capacity of 150 GL was commissioned in 2012 to supply Melbourne and the Kurnal desalination plant with 91 GL/year capacity commenced supplying Sydney in 2010. Rainfall and supply of desalinated water during the period 2003 to 2021 is presented in Figure 3.

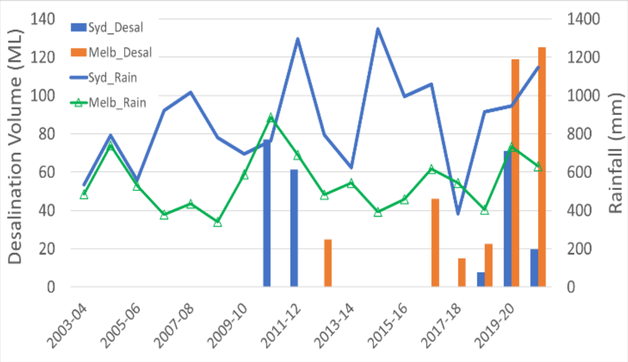

Figure 3: Rainfall and desalination supply in Melbourne and Sydney

Figure 3 reveals that Sydney (Parramatta rainfall) experienced maximum rainfall of 1348 mm in 2014-15 and minimum rainfall of 383 mm in 2017-18. Melbourne received maximum rainfall of 886 mm in 2010-11 and minimum rainfall of 341 mm in 2008-09. Average annual rainfall was 12% and 18% below average in Sydney and Melbourne. However, both urban areas experienced significant annual rainfall during the drought periods. Desalination assisted the recovery of Sydney's dam storage levels from 2010 to 2012 and after 2018. Meboure's water supply was suplemented by desalination since 2016.

The residential utility bills and utility costs per water connection for Melbourne and Sydney are presented in Figure 4. These values were sourced from the National Performance Reports (NWC, 2003 – 2013; BOM, 2014 – 2022) and were adjusted to present values using the consumer price index from ABS (2021).

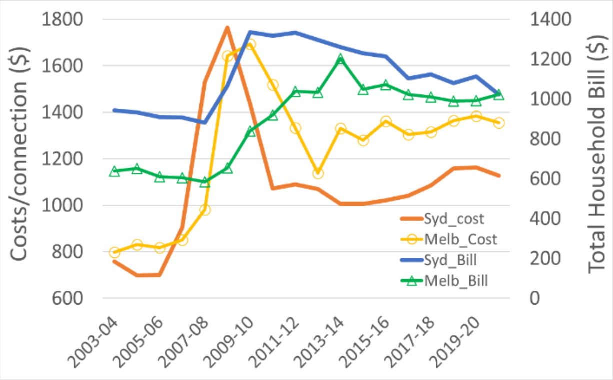

Figure 4: Residential water utility bills and total utility costs per connection for Melbourne and Sydney (2021 dollars)

Figure 4 shows that Sydney experienced 8.4% real increase in household utility bills and 49% real increase in utility costs. The real increase in household utility bills and utility costs in Melbourne were 60% and 70%. These substantial real increases in utility costs also included augmentation of sewage and stormwater assets.

Some of the differences in residential use and costs of water and sewage services between Sydney and Meboune could be explained by differences in pricing policy. Note that non-residential tariffs are not included in Figure 4.

The residential utility tariffs in Sydney currently include lower fixed charges ($39.90) with a high proportion (89%) of lower variable charges ($2.35/kL) for water use and higher fixed charges for sewage services of $544. In contrast, Melbourne has higher fixed charges for water use ($211) with lower proportion (59%) of higher variable charges ($2.77/kL) with lower fixed charges for sewage services ($253). The higher average fixed charges ($584) in Sydney in comparison to Melbourne ($464) could diminish any price effects on demands.

The residential utility bills and utility costs have been held low due to the very low Australian interest rate environment (RBA, 2022). Nevertheless, these real increases in household bills for utility services are significant in the context of persistent stagnant wage growth in the Australian economy (Gilfillan, 2019). Installation of water efficient appliances and rainwater harvesting was encouraged for both cities by state and federal government subsidies until 2011. The Building Sustainability Index (BASIX) policy has required new housing to meet water and energy efficiency targets (40% reduction) in Sydney since 2004. New houses in Melbourne are required to install a 2 kL rainwater for toilet flushing or a solar hot water heater. The instation of water efficient appliances and rainwater harvesting from ABS (2017), government departments and the rainwater industry was combined to estimate mains water savings since 2007. This analysis builds on the investigation by Coombes et al. (2018) to define the proportion of houses with greater than 3 Star water efficiency (WEA) or rainwater harvesting (RWT) and associated water savings as shown in Table 1.

Table 1: Property scale reductions in utility water use in Sydney and Melbourne

Item	**Year**			
	2007	**2010**	**2013**	**2021**
Greater Sydney				
WEA (%)	27.8	34.7	37	41
WEA (GL)	19	40.6	47.7	70.1
RWT (%)	12.8	15.5	20	31.4
RWT (GL)	16.3	19.3	25	43.2
Greater Melbourne				
WEA (%)	12.1	26.4	34.9	50
WEA (GL)	18	39.4	48	68.3
RWT (%)	16.9	22.8	23.3	22.9
RWT (GL)	11.2	16.7	19	21.6

Table 1 shows that property scale water savings from water effiency and rainwater harvesting have increased to 102 GL in Sydney and 90 GL in Melbourne. These decreasing demands of utility water and sewage services will increase the resilience of water resources in each city. The higher yield for rainwater harvesting in Sydney is due to a greater level of indoor use of rainwater (42%) compared to 29% for Melbourne, and higher rainfall depths in Sydney.

The urban water markets

The componants of the urban water market are important to understand the characteristics and resilience of each city. Data from BOM (2022), utility, regulators (IPART and ESC) and government reports were utilised to define utility and commercial water sources. These values were combined with the results for residential rainwater harvesting and water efficiency from Table 1. The market for urban water services was estimated for Greater Melbourne and Sydney as shown in Figures 5 and 6.

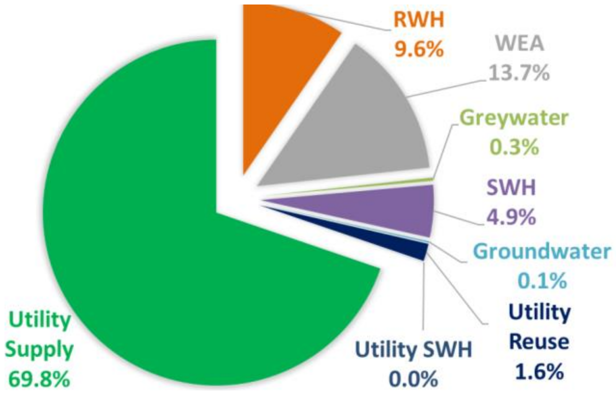

Figure 5: Water Balance for Greater Melbourne in 2021

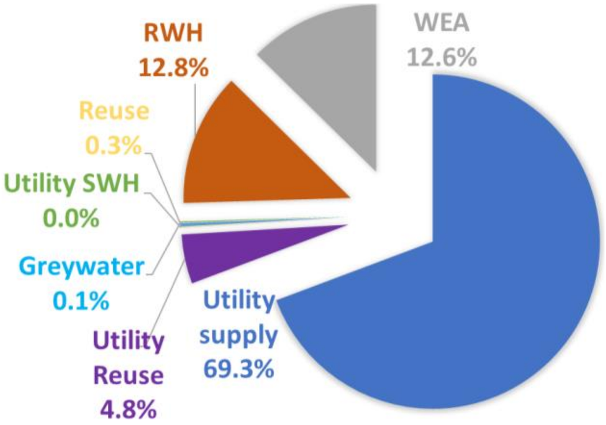

Figure 6: Water Balance for Greater Sydney in 2021

Figures 5 and 6 show that significant proportion (about 30% and 190 GL/annum) of the urban water market in both regions includes water sources and savings from households, commerce, industy and governments that supplement utility sources of water. This additional non-utility water solutions make a strong contribution to the resilience of the regions and these contributions have demonstrated flexibility to meeting urban water security challenges as outlined by Aisbett & Steinhauser (2011). The proportions of the urban water market solutions presented in Figures 5 and 6 are based on limited collated reporting on non-utility water solutions and utility demand management, and will vary across years and with government policy settings and market processes.

Systems analysis – spatial costs

The spatial costs of utility water and sewage services to 2050 in the BAU scenario are provided in Figures 7 (Greater Melbourne) and 8 (Greater Sydney) as total costs in 2021 dollars divided by total water demand. This result indicates strong spatial variation in the costs of water and sewage services ranging from $2/kL to over $11/kL for Greater Melbourne, from from $2/kL to over $24/kL for Greater Sydney.

These spatial costs maps reveal differences between the cities. In the Greater Melbourne region, the highest costs are experienced in higher density growth areas, such as the inner city, areas with older infrastructure and in new growth corridors distant from water sources and sewage treatment in the west.

The Greater Sydney region experiences the highest costs in the western growth corridor distant from water sources and sewage treatment infrastructure, and the north shore areas with older infrastucture distant from water sources. Sydney's water saving targets may have reduced the impacts of higher density inner city development on utility costs. This information can serve a map of shadow prices that can be used to test the financial vaibility of alternative options such was water efficiency strategies.

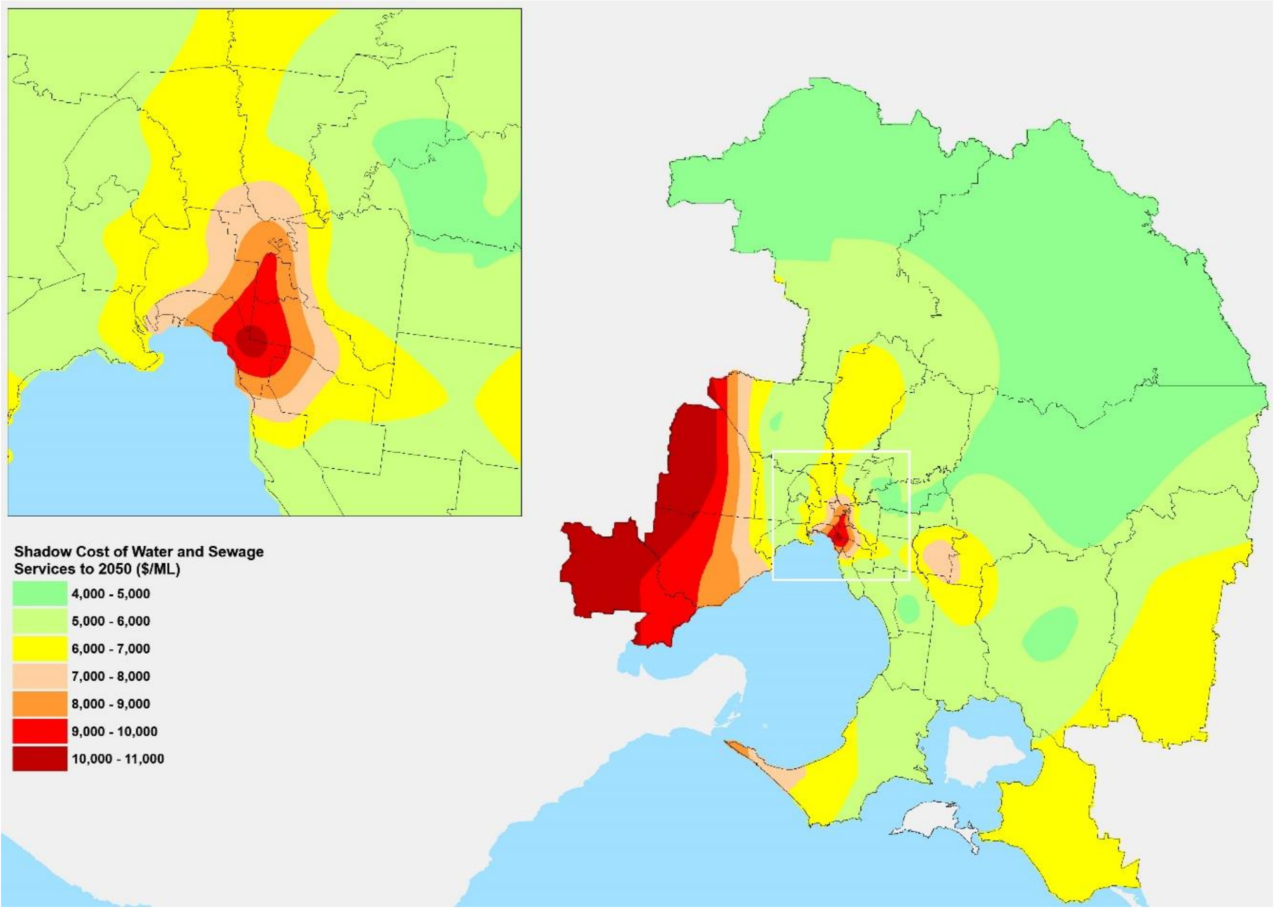

Figure 7: Spatial variation of utility water and sewage costs for Greater Melbourne to 2050 for BAU

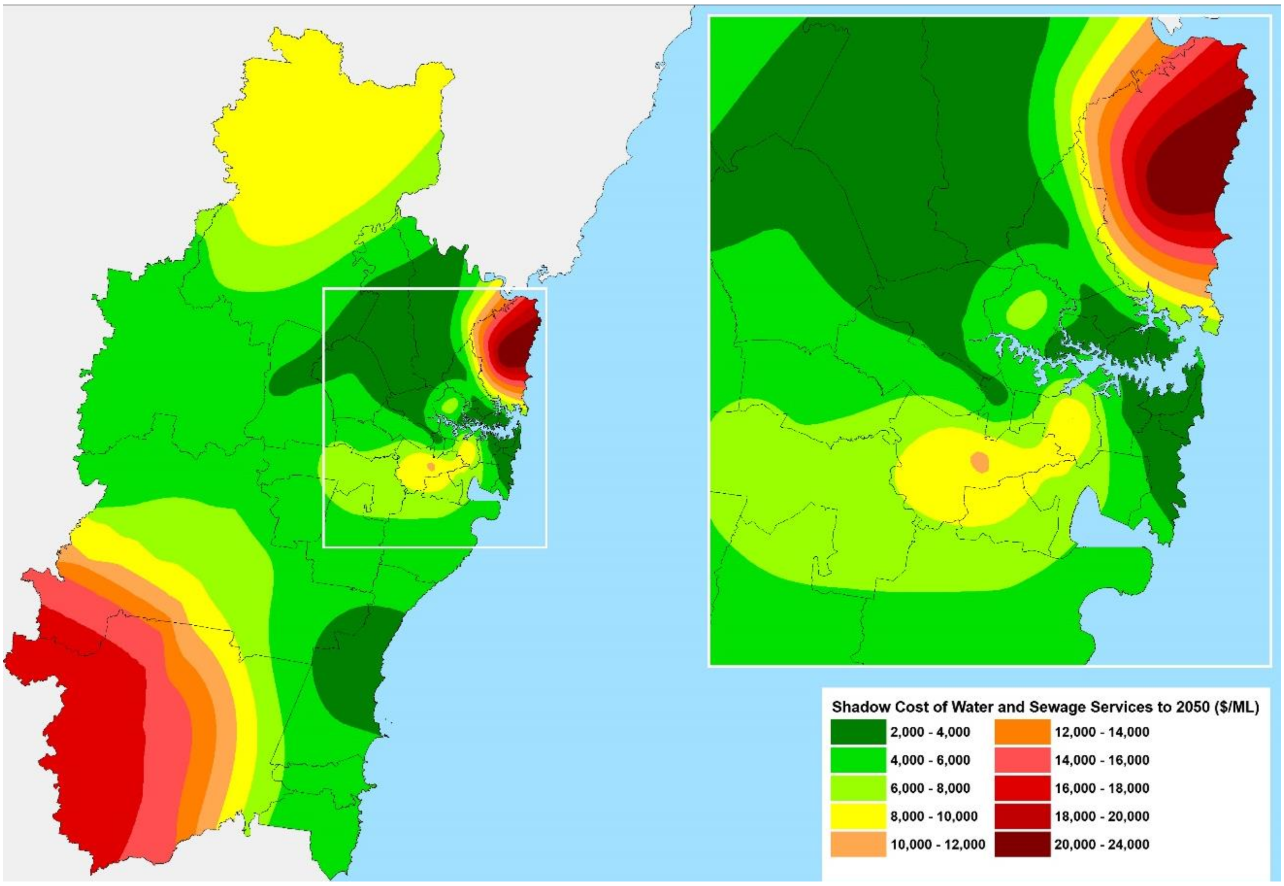

Figure 8: Spatial variation of utility water and sewage costs for Greater Sydney to 2050 in the BAU scenario

For example, a strategy that reduces utility water demands in the inner city or western growth coridor of Greater Melbourne will provide $8 – 11/kL value to the water utility. Similarly, reductions in utility water demands in the South West Growth coridor or nothern areas of Greater Sydney could provide $12 – 24/kL value to the utility.

Systems analysis – response to options

Analysis of options provides understanding of the performance of different solutions and can also reveal the attributes of urban water systems. The demands for utility water supply in response to the BAU, WEA and Price options for Greater Melbourne are presented in Figure 9.

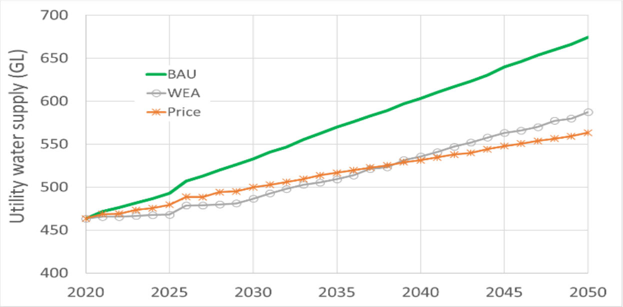

Figure 9: Utility water supply for Greater Melbourne to 2050

Figure 9 shows that the Greater Melbourne region will experience 46% growth in demand for utility water supply to 2050 in the BAU option. The WEA and Price options diminish growth in demand to 27% and 16%. These options make strong contributions to the resilence of Melbourne's water supply by reducing demands by 13 – 16% (87 – 111 GL). The demands for utility water supply in response to the BAU, WEA, Price and NoBasix options for Greater Sydney are presented in Figure 10. The NoBasix option was evaluated to test the significance of the embedded water savings provided by BASIX to the region.

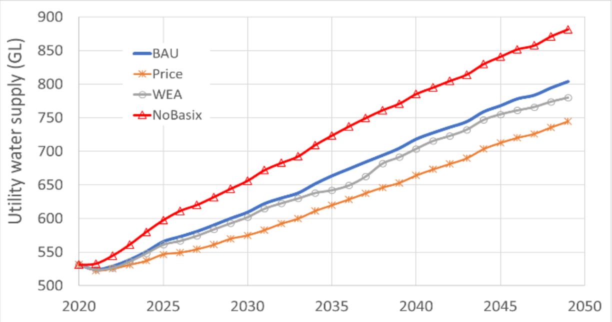

Figure 10: Utility water supply for Greater Sydney to 2050

Figure 10 reveals an expected 51% growth in demand for utility water services to 2050. The WEA and Price options reduce this growth to 47% (24 GL) and 40% (59 GL) respectively. The relatively diminished impact of the WEA option, as compared to Melbourne, is due the significant level of water savings provided to the Sydney BAU option by the BASIX policy. The significance of these embedded water savings provided by BASIX is highlighted by 10% (78 GL) higher growth in utility water demands in the NoBasix option. Some of the differences in responses to changing prices (Price option) in Sydney as compared to Melbourne can be explained by the lower demand price elasticity assumed for Sydney. The estimated total utility costs for the BAU, WEA and Price options in Greater Melbourne are presented in Figure 11.

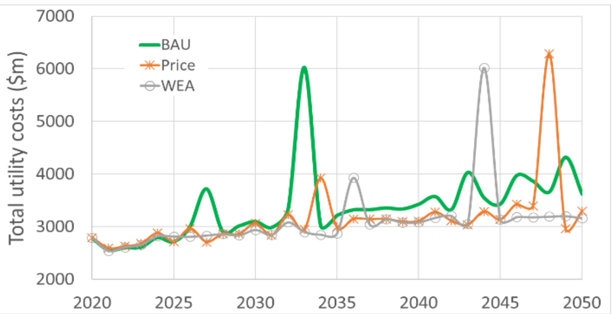

Figure 11: Utility costs for Greater Melbourne to 2050

Figure 11 shows that the Price and WEA options change the timing of water security augmentation, and reduce the magnitude and variability of total utility costs for Greater Melbourne. By 2050, the annual costs are reduced by 9% and 13% for the Price and WEA options. The reduction in the present value of these costs, assuming a 4% real discount rate, is 6.5% and 8% for the Price and WEA options. The total utility water costs for the BAU, WEA, Price and NoBasix options for Greater Sydney are presented in Figure 12.

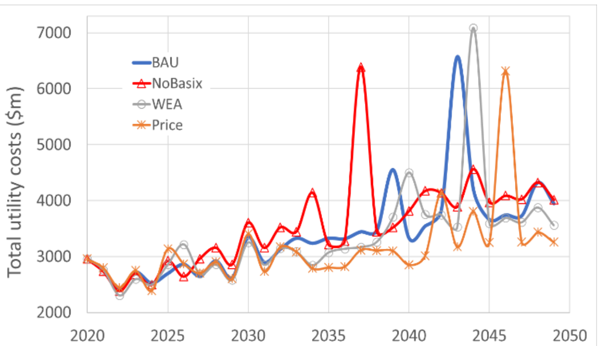

Figure 12: Utility costs for Greater Sydney to 2050

Figure 12 reveals that the Price and WEA options delay the need for water security augmentation, and the NoBasix option brings forward the need for augmentation. The Price and WEA options reduce annual costs by 10% and 17% by 2050, and the NoBasix option increases annual costs by 2%. The present value of these costs, assuming a 4% real discount rate, is diminished by 5.9% and 1.8% for the Price and WEA options, and is 4.6% higher for the NoBasix option.

CONCLUSIONS

The accumulated data and systems analysis from the last two decades was utilised with systems analysis of options to gain insights into the resilience of the water resources systems servicing Greater

Melbourne and Sydney. Utility water services in both cities have been subject to droughts, floods, fires, economic shocks and pandemic. The similar total dam storage volumes for Mebourne and Sydney displayed different resilience to changes in population and weather. Sydney's storage levels were more variable and demonstrated greater recovery than Melbourne's storages that remained at persistently low levels until the recent constant inputs from desalination. These persistently low dam levels in Melbourne may have prompted greater demand management responses in households.

Sydney experienced higher and more variable rainfall than Melbourne which increases the impact of distributed water sources and water effiency. Water restrictions, distributed water sources and efficiency significantly mitigated water demands and drawdown of dam levels for both cities. Water demands in Melbourne were more responsive to these measures than Sydney. These differences could be attributed to pricing policy where total household utility bills in Sydney include higher proportions of fixed charges with lower variable tariffs in the context of higher disposable income. Real increases in utility costs and household utiity bills were substantially higher in Melbourne (70%, 60%) than Sydney (49%, 8%). There is a significant difference in household welfare.

Higher spatial costs of utility water and sewage services ($2 - $24/kL) than Melbourne ($2 - $11/kL). Both cities experience the highest utility servicing costs in the growth coridors and location distant from sources of water or wastewater treatment. Melbourne also has relatively higher utility servicing costs for high density inner city areas. These high density impacts are mitigated by greater water efficiency and alternative water sources in Sydney. The urban water market includes similar proportions (probably greater than 30%) of supplementary (non-utility) water sources and conservation in both regions. Changes to pricing policy and policies supporting higher water efficiency is expected to produce significant reductions in future utility water demands and costs. Greater impacts on diminished demands are expected for Melbourne and higher reductions in costs for Sydney.

This study has revealed that the key resilience parameters are distributed water sources and conservation in an urban water market, government policy and pricing strategies, household welfare, total dam storage and supply of desalinated water. These parameters have different levels of impact and signicance across the two cities. Further investigation can reveal the extent and benefits of these parameters.

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