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Modelling urban transition: a case of rainwater harvesting

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Abstract: Cities are increasingly exposed to extreme climate events such as floods and droughts. Land use change is also expected to reduce the availability of green spaces and intensify extreme heat events. Given these pressures on the quality of life of urban dwellers, there is a great need to improve the integrated management of water to enable sustainable development of rapidly growing cities and improve human well-being. A promising way to make urban communities more liveable is to invest in green water technologies, that is, decentralised and low-energy water supply, wastewater and stormwater solutions, to foster the transition to more sustainable and resilient cities. However, the adoption of multifunctional water technologies is a complex issue that requires cross-disciplinary approaches, demanding innovative thinking and practice. Despite the increasing body of literature on the benefits of decentralised water technologies, several barriers to their adoption remain. This paper uses an agent-based model that integrates social and environmental factors, as well as economic evaluation of water services provided by water technologies to assess the decision-making of two types of agents. The model is applied to evaluate incentive-based strategies to increase the adoption of rainwater tanks in Melbourne, a city that has suffered from severe droughts over the last decades. The model shows that using economic evaluation may not be adequate to understand the dynamics of rainwater tank uptake. Social factors such as public education might have played a role on decisions of households. This tool will be further tested and validated to explore policies and robust strategies to enable sustainable water management in rapidly developing cities.

***Keywords**:* Rainwater harvesting; Agent-based model; Green infrastructure; Environmental policies.

1 INTRODUCTION

By 2050, 66% of the world population is expected to live in cities, compared to 30% in 1950 (United Nations 2014). The number of urban dwellers affected by perennial water shortage is expected to increase from an estimated 150 million in 2000 to 1.1 billion by 2050 due to climate and land use change and demographic growth (McDonald et al. 2011). Cities in dry areas, for instance in California or Australia, are likely to suffer from lower rainfall and higher water demand due to the combined effect of climate change and population growth. For instance, water storages dropped dramatically in Melbourne during the Millennium Drought and other sources of water were urgently needed to satisfy water demand. The system started to transition to a more water sensitive system but an expensive desalination plant was implemented (Ferguson et al. 2013). Thus there is a need for tools to explore the behaviors of stakeholders in the urban water sector and better understand strategies available to avoid expensive investments which may lead to technological lock-in.
To contribute to this knowledge gap, in this paper we present an agent-based model for water technology adoption, with an application to rainwater harvesting in Melbourne. Agent-based models have been used to simulate urban water demand and supply (see Berglund 2015 for a review of agent-based models applied to the urban water sector) and the adoption of water appliances (Galán et al. 2009; Schwarz & Ernst 2009) but to our knowledge few authors have investigated the adoption of

decentralised water sensitive urban designs (Montalto et al. 2013). This paper aims to examine how the interactions between agents can simulate the transition to a water sensitive city and increase the sustainability and resilience of the system under future shocks such as droughts. As a demonstration we focus on the adoption of rainwater tanks, which are known to deliver several environmental benefits, such as water supply, nutrient retention and runoff reduction (Burns et al. 2014). It should be noted that the tool developed is an exploratory rather than deterministic model. Consequently, it does not aim to forecast the adoption of water technologies but rather to provide insights into the suitability of policy instruments and the interactions between the main stakeholders and their environment. The economic values of three environmental services, i.e. water supply, pollution removal and flood protection are also investigated to evaluate the performance of incentive programs for rainwater tank installation.

2 METHODOLOGY

The methodology is divided in two parts. Firstly, the agent-based model, with the attributes and behavioural rules of agents, is described. Secondly, the methods used to quantify the economic value of water supply, nutrient removal and flood protection are defined.

2.1 Agents and interactions

The model is implemented within the DANCE4Water framework and includes two sub-models; a water demand and an urban development module (Urich & Rauch 2014). DANCE4Water is a modelling platform allowing the integration of modules (working tasks or building blocks within a simulation) and facilitates the simulation of urban water systems in time and space (Urich et al. 2012).
The model includes two types of interacting agents: households and a policy-maker or regulator. A representation of the agents and their decisions is shown in Figure 1. The policy-maker is concerned with water supply at the city-scale and therefore its objective is to ensure that the water storage level remains above a certain threshold. This agent can use different policy instruments to achieve its objective, such as water restrictions, rebates and education campaigns. Based on water restrictions applied in Melbourne (Southeast Water Corporation 2012), the water utility sets four levels of restrictions, depending on the storage level. The reduction of outdoor water use for these four levels are assumed from the number of hours of irrigation of residential garden and lawn areas allowed daily (Table 1). The policy-maker can also offer rebates on rainwater tanks to improve the affordability of the technology to households.
Finally, education campaigns carried out by the government can be successful to restrain the water demand of households. Previous studies have shown that the willingness to comply with a water conservation campaign is one of the main determinants of household water consumption (Corral-Verdugo et al. 2002). In a study on beliefs, values and knowledge associated with decentralised water

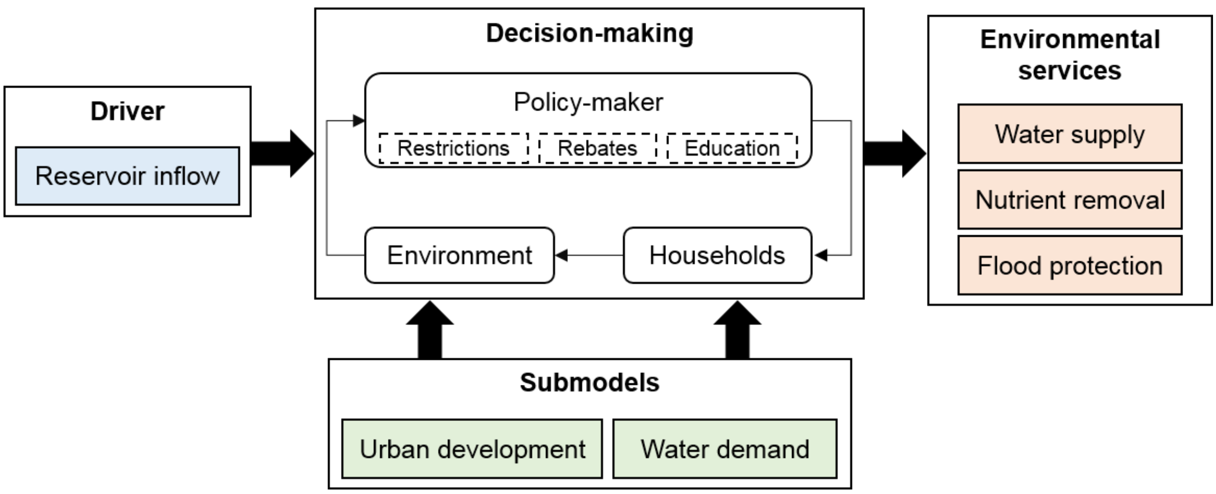

Figure 1 Schematic representation of rainwater tank adoption. The main driver of the model is the variation of the reservoir inflow. The decision-making process is influenced by an urban development and a water demand sub-model. The performance of the system can be assessed through the provision of environmental services.

supply options in Queensland, Australia, education was seen by households as an important tool to increase acceptance and adoption of alternative water supply options (Mankad et al. 2010). During the Millennium Drought in Melbourne, water storage levels were broadcast on different media such as TV, radio, and print news services by the Melbourne water industry (Grant et al. 2013). Billboards were used to summarize the latest water data, such as storage level, weekly rainfall and inflows. Advices were also provided describing different methods to reduce water use and providing a benchmark for daily consumption of 155L/person (Ferguson et al. 2013).

Table 1 Restrictions levels based on storage volume imposed by the policy-maker agent

Storage volume (in GL)	Restriction level	Number of hours allowed for irrigation
More than 980	0	16
Between 777 and 980	1	8
Between 575 and 777	2	4
Between 287 and 575	3	2
Less than 287	4	0

Households can invest in rainwater tanks and would maximise their preferences in terms of water use. The water consumption of households is determined by a water demand model that considers non-potable and potable, as well as outdoor water demand based on Roberts et al. (2011). The decision to purchase a rainwater tank is based on a cost-benefit analysis, using cost information from Tam et al. (2010) for three sizes of tanks and on the economic benefits derived from water savings based on the water cycle model. Willingness to pay to avoid water restrictions was also estimated for every households from a previous study (Brent et al. 2014). Households decide to adopt a rainwater tank if the total value TV_{sh} of tanks of different sizes *s* (2, 5 and 10 kL) for each households *h* is positive:

$$TV_{sh}=\begin{cases} PV_s * PE+WTP_h+I, & r > 0 \\ PV_s * PE+I, & r = 0 \end{cases} \tag{1}$$

where PV_{sh} is the present value of each tanks, *PE* the public education factor, WTP_h the willingness to pay to avoid restrictions of households, which is only considered when restrictions (*r)* are in place and *I* the rebates offered for rainwater tanks. A logistic function was used to represent the incremental pressure of public education and awareness campaigns that occurred during the Millenium Drought on the decision of households based on the varying level of storage level (*SL*):

$$PE=2\frac{1-e^{-0.01001SL}}{1+1000e^{-0.01001SL}} \tag{2}$$

2.2 Environmental services

Environmental benefits of rainwater tanks are assessed using the ecosystem services framework. Although rainwater tanks cannot be considered as an ecosystem, they provide similar services such as water supply, pollution removal and flood protection.

Water supply: For each household with a rainwater tank, the water collected for non-potable indoor and outdoor water use was estimated with the water cycle model. The annual savings of households is then measured using the market price method by taking the current price of water.

Nutrient removal: By retaining stormwater runoff, rainwater harvesting contributes to reduce nutrient loads in waterways (Fletcher et al. 2007). This benefit of pollution removal was measured through nitrogen removal from rainwater tanks. The economic value of nitrogen removal (*NR*) is estimated using the avoided cost method as follows:

$$NR = \sum_{i=1} CW_i * C * O \tag{3}$$

where *O* is the offset cost of nitrogen removal determined by Melbourne Water (2016), i.e. $6,645/kg N, C is the nitrogen concentration (kg/l), estimated at 0.0024 kg/l based on the concentration in medium density urban areas (eWater 2013), and *CW* the amount of water collected through rainwater harvesting.

Flood protection: Another major service provided by the water retention capacity of rainwater tanks is flood protection through stormwater peak flow reduction. The economic value of flood reduction benefit is assessed here using the avoided damage method with depth-damage curves or functions (Smith 1994).
To evaluate the benefit of flood reduction provided by a technology, the damage without the technology was first assessed. Curves to estimate the damage of flooding were taken from previous studies on flood damage estimation conducted in Australia to determine the damage on residential properties (Queensland Government 2002) and on commercial properties and vehicles (Melbourne and Metropolitan Board of Work 1986). The curves for damage to residential properties are defined for three types of properties, i.e. small, medium and large houses (Table 2), and include both direct and indirect damage.

Table 2 Functions to estimate the damage (in Australian dollars) to three types of residential properties based on Queensland Government (2002).

Flood depth	Small house (<80 m^2)	Medium house (80-140 m^2)	Large house (>140 m^2)
0m	9760*depth+905	25580*depth+2557	58700 *depth+5873
0.1m	10978*depth+783.2	17728*depth+3342.2	27216 *depth+9021.4
0.6m	11121.1*depth+697.3	5117.78*depth+10908.3	7694.4*depth+20734.3
1.5m	880*depth+16059	943.3*depth+17170	1640 *depth+29816
1.8m	17643	1868	32768

The damage curves represent the potential damage to assets. Melbourne and Metropolitan Board of Work (1986) defined two different functions for direct damage CDD_i, e.g. damage to infrastructure, and indirect damage CID_j to commercial or industrial property *j*, e.g. loss of income due to flood-induced business limitation or interruption:

$$NR = \sum_{i=1} CW_i * C * O \quad (4)$$

$$CDD_j = \begin{cases} 65.45 * d_j * a_j, & d_j < 2.75 \\ 180 * a_j, & d_j \geq 2.75 \end{cases} \quad (5)$$

$$CID_j = \begin{cases} 22.47 * d_j * a_j, & d_j < 4.45 \\ 100 * a_j, & d_j \geq 4.45 \end{cases} \quad (6)$$

$$TCD = \sum CDD_j + CID_j \quad (7)$$

where d_j is the depth and a_i the area of the flooded property. The total commercial and industrial damage *TCD* is the sum of CDD_j and CID_j. The damage to vehicles *VD* was also calculated as follow:

$$VD = 2000(1.4 \sum R + 2 \sum C) \quad (8)$$

where *R* and *C* are the total number of residential properties, and commercial and industrial properties, respectively, with flood depth of more than 0.5 m.
Actual damage, depending on factors such as warning before floods and previous experience of the community with flooding, would be less than the potential damage, i.e. between 40% and 90% (Queensland Government 2002). Because the damage assessment is undertaken for comparison only, potential damage was used. The results were adjusted to prices of May 2015 based on the Average Weekly Earnings per person, taken from the Australian Bureau of Statistics (2015).
Damage curves were used to assess the damage on flooded buildings in the catchment for 10-year and 100-year flood events. The flood depth and the number of flooded buildings were estimated from a 10-year and 100-year flood maps from MIKE-URBAN simulations.

Table 3 Potential damage for 10-year and 100-year flood events.

Flood event	Residences flooded	Commercial properties flooded	Residential damage ($)	Commercial damage ($)	Vehicles damage ($)	Total damage ($)
10-year flood	3	0	161,566	0	28,079	189,646
100-year flood	154	8	5,008,517	587,602	1,171,331	6,767,451

This results in a total potential damage of 6,767,451 AUD for a 100-year flood, 189,646 AUD for a 10-year flood (Table 3) and an annual average damage of 384,288$ per year.
To assess the value of reduced potential flood damage from rainwater tanks in the model, each purchased tank is assumed to convert the impervious area of the roof into pervious area. The flood reduction benefit *B* is therefore estimated as:

$$B=D*\frac{\sum RA_{pn}+\sum OIA_p}{\sum RA_p+\sum OIA_p} \tag{9}$$

Where *D* is the total potential damage of the simulated flood, RA_n is the roof area of households without a raintank *n*, RA_a is the roof area of all household and OIA_a is the outdoor impervious area of all households.

2.4 Case study location

The model was applied in the Scotchman's Creek catchment, southeast of Melbourne CBD. The catchment is mostly located within Monash City council, with an area of approximately 10.36 km^2 and a population of approximately 25,000 residents. Yarra Valley Water is the corporation responsible for providing water supply and sewerage services. Household agents were initialised using 2011 census data from the Australia Bureau of Statistics. Information concerning the number of persons living in households was estimated by distributing the number of people living in each statistical areas to the number of buildings in these areas. The market price of water determined by Yarra Valley Water (2016), i.e. 2.62 AUD per kilolitre, was used to estimate the economic benefit of non-potable water supply. Rebates were set up for three periods of time and averaged across the different sizes of tanks (2000-2008: 300$; 2009-2012: 750$; 2013-2015; 1175$) according to the Living Victoria Water Rebate Program (State Government of Victoria 2015) and the storage volume was initialised at 1,000 GL (the approximate volume at year 2000). The initial percentage of households with a rainwater tank was estimated at 10% from the earliest estimates from data on Melbourne (13%) in 2007 (Australian Bureau of Statistics 2013) and to account for a slight increase from 2000 to 2007.
The model was run with historical inflow for the period 2000-2015 to assess the validity of the model; i.e. simulation results were compared to historical uptake of rainwater tanks in Melbourne. However, only four points are available from 2007 to 2013 for the city of Melbourne (Australian Bureau of Statistics 2013). Additionally, historical data for the State of Victoria were used for comparison. Simulations were carried out with and without the public education component.
The environmental benefits associated with rainwater tank adoption were estimated and compared with the costs of offering rebates for the case study location and for the simulation with the public education factor.

3. RESULTS AND DISCUSSION

3.1 Rainwater tank uptake

The low annual inflow starting in 2006 led to a drastic decline of the storage level and a raise of the restriction levels from 2007 to 2011. Accordingly, restrictions caused a reduction in demand from 2006 to 2012 (Figure 2a). The model without the education component shows a similar trend with an increasing of uptake in 2010 and 2013 but the increase is negligible (Figure 2b).

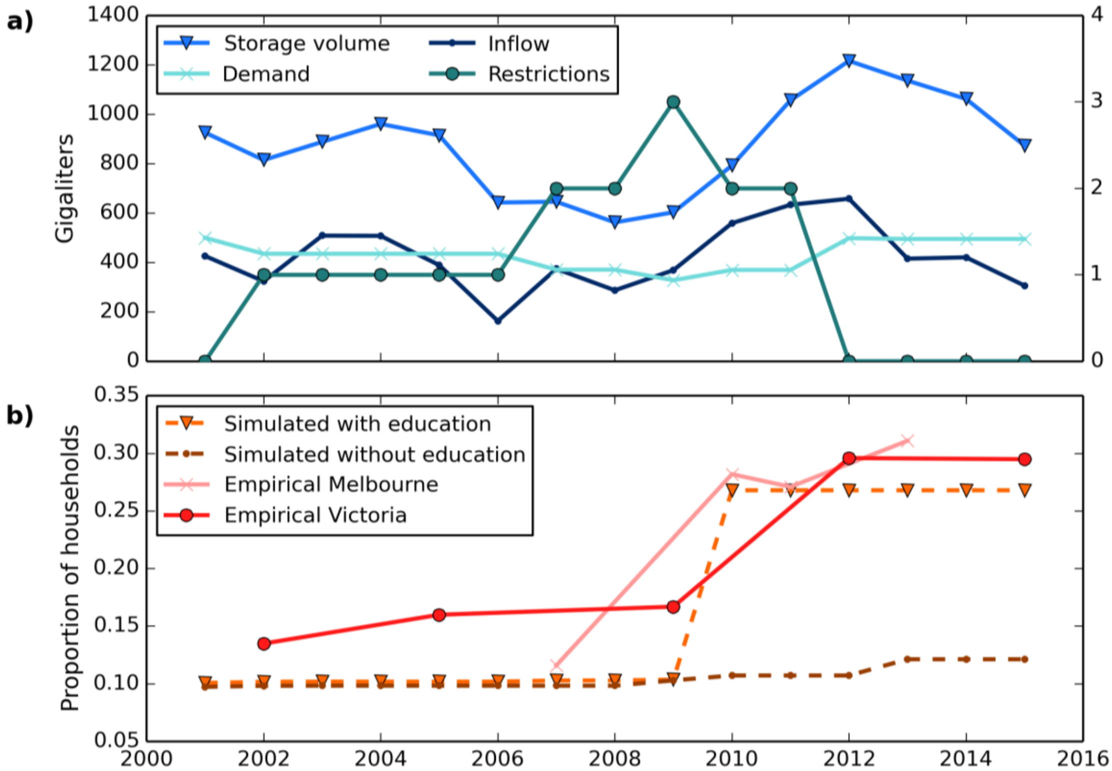

Figure 2 Simulated dynamics of the urban water system with historical inflow (**a**) and cumulative uptake of rainwater tanks with empirical data (**b**).

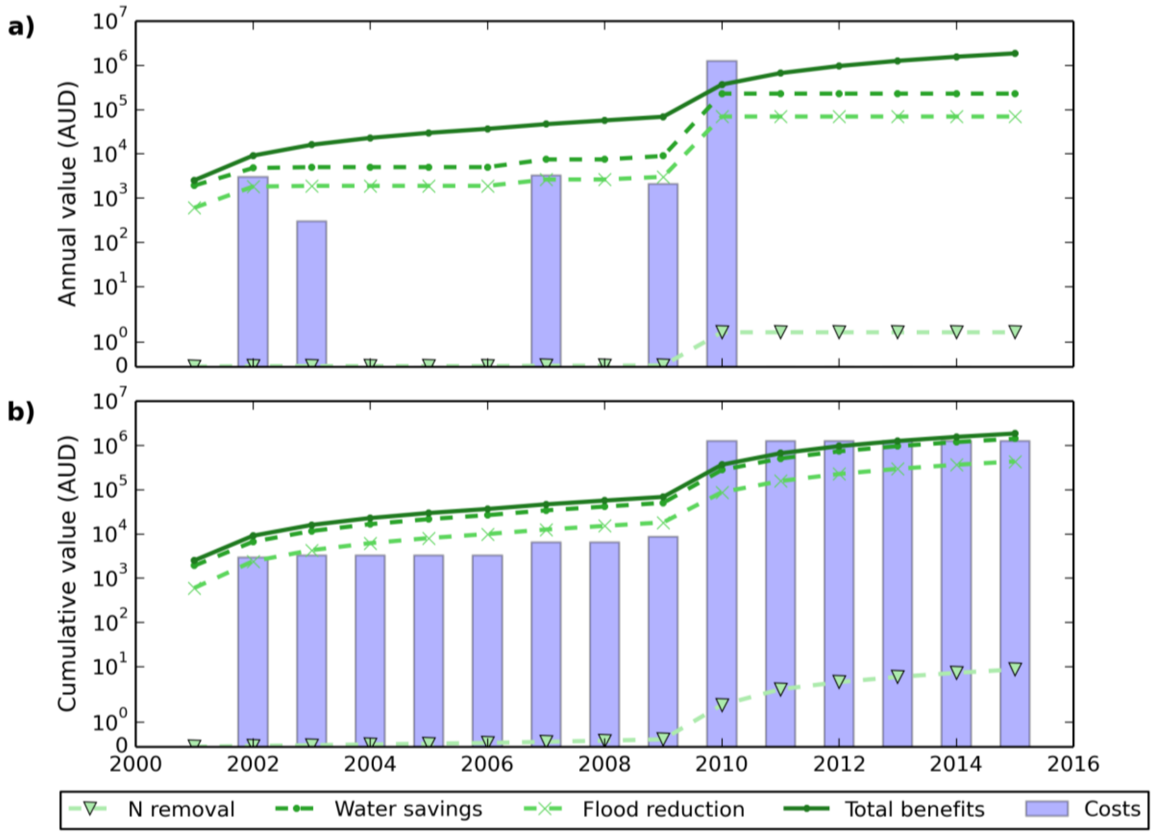

Figure 3 Annual (**a**) and cumulative (**b**) benefits of environmental services and costs of incentives from rainwater tanks.

On the other hand the uptake with the education component follows a more similar trajectory to the empirical data in Melbourne. However, the increase occurs only at year 2010 and the second increase seen in 2013 for the empirical data in Melbourne is not represented with the simulation with education.

3.2 Environmental services

Most of the incentives were given at year 2010 (1,252,500 AUD), which triggered an increase of environmental services (Figure 3a). Cumulative benefits at the end of the simulation from water savings (1,432,060 AUD) justify the application of rebates as they exceed their total costs (1,261,200 AUD) over time. However, cumulative benefits of flood reduction (437,674 AUD) and nitrogen removal (9 AUD) were not sufficient to cover the cost of rebates after 15 time steps (Figure 3b).
The costs considered in this study only include the costs borne by the policy-maker agent through offered rebates and omits the costs of purchasing and maintaining a rainwater tank paid by households. The amount of water saved is consistent with previous findings. For instance, Rahman et al. (2012) estimated the water savings for toilet, laundry and irrigation from rainwater tanks between 38 (for a tank of 2 kL) and 55 kL (for tank of 5 kL) for an annual rainfall of 650 mm as in Melbourne. In this study, the average water savings for households that adopted a tank of 2 kL was 43 kL and 60 kL for households with a tank of 5kL capacity.

4. CONCLUSIONS

This paper uses an agent-based model developed within the DANCE4Water framework to integrate different elements of the urban water system. The tool shows the potential to explore interactions between human, environmental and technical systems and provides insights into the capacity of economic instruments to enable urban water transition. The estimation of the environmental services showed that incentives are a cost-effective policy instrument when comparing the costs of rebates with the public benefits of water savings. However, the findings from this study show that considering only economic factors in the decision-making of households is insufficient to understand the dynamics of rainwater tank uptake. A public education factor was used to better represent the increase of uptake during the Millennium Drought in Melbourne. A social network model will be added to the decision-making process to further improve and compare the representation of the social impact on technology adoption decisions. The pollution removal benefit was found to be insignificant whereas flood reduction benefits were high but not sufficient to cover the costs of rebates. Future work will consists in evaluating the private and public costs and benefits not only for rebates but also for water pricing strategies. Furthermore, further drivers of change will be added to the simulations, such as population growth and the number of simulation runs will be extended to provide the range of possible outcomes and the long term impacts of each strategies on the resilience and adaptive capacity of the system. The model will provide insights to policy-makers into the different policy instruments, for instance relating to their long term effectiveness to improve the sustainability of urban water management by increasing the delivery of environmental services and improving the resilience of the urban water system to shocks such as droughts and floods.

REFERENCES

Australian Bureau of Statistics, 2013. Rainwater tanks. http://www.abs.gov.au/ausstats/abs@.nsf/Lookup/4602.0.55.003main+features4Mar%202013.

Australian Bureau of Statistics, 2015. Average Weekly Earnings, Australia. http://www.abs.gov.au/ausstats/abs@.nsf/mf/6302.0/.

Berglund E. Z., 2015. Using agent-based modeling for water resources planning and management. *Journal of Water Resources Planning and Management* 141(11).

Brent D. A., Gangadharan L., Leroux A. and Raschky P. A., 2014. *Putting One's Money Where One's Mouth is: Increasing Saliency in the Field*, Monash University, Department of Economics.

Burns M. J., Fletcher T. D., Duncan H. P., Hatt B. E., Ladson A. R. and Walsh C. J., 2014. The performance of rainwater tanks for stormwater retention and water supply at the household scale: An empirical study. *Hydrological Processes* 29(1), 152-160.

Corral-Verdugo V., Frías-Armenta M., Pérez-Urias F., Orduña-Cabrera V. and Espinoza-Gallego N., 2002. Residential Water Consumption, Motivation for Conserving Water and the Continuing Tragedy of the Commons. *Environmental Management* 30(4), 527-535.

eWater, 2013. *MUSIC Version 6-User Manual*, eWater.

Ferguson B. C., Brown R. R., Frantzeskaki N., de Haan F. J. and Deletic A., 2013. The enabling institutional context for integrated water management: Lessons from Melbourne. *Water Research* 47(20), 7300-7314.

Fletcher T. D., Mitchell V. G., Deletic A., Ladson T. R. and Séven A., 2007. Is stormwater harvesting beneficial to urban waterway environmental flows? *Water Science and Technology* 55(4), 265-272.

Galán J. M., López-Paredes A. and Del Olmo R., 2009. An agent-based model for domestic water management in Valladolid metropolitan area. *Water Resources Research* 45(5), W05401.

Grant S. B., Fletcher T. D., Feldman D., Saphores J.-D., Cook P. L. M., Stewardson M., Low K., Burry K. and Hamilton A. J., 2013. Adapting Urban Water Systems to a Changing Climate: Lessons from the Millennium Drought in Southeast Australia. *Environmental Science & Technology* 47(19), 10727-10734.

Mankad A., Tucker D., Tapsuwan S. and Greenhill M. P., 2010. *Qualitative exploration of beliefs, values and knowledge associated with decentralised water supplies in South East Queensland communities,* Report Technical Report No. 25, Alliance UWSR.

McDonald R. I., Green P., Balk D., Fekete B. M., Revenga C., Todd M. and Montgomery M., 2011. Urban growth, climate change, and freshwater availability. *Proceedings of the National Academy of Sciences of the United States of America* 108(15), 6312-6317.

Melbourne and Metropolitan Board of Work, 1986. *Maribyrnong river flood mitigation study*, Melbourne and Metropolitan Board of Works, Melbourne.

Melbourne Water, 2016. Stormwater offsets explained. http://www.melbournewater.com.au/Planning-and-building/schemes/offset/Pages/What-are-stormwater-quality-offsets.aspx.

Montalto F. A., Bartrand T. A., Waldman A. M., Travaline K. A., Loomis C. H., McAfee C., Geldi J. M., Riggall G. J. and Boles L. M., 2013. Decentralised green infrastructure: The importance of stakeholder behaviour in determining spatial and temporal outcomes. *Structure and Infrastructure Engineering* 9(12), 1187-1205.

Queensland Government, 2002. *Guidance on the assessment of tangible flood damages,* Report QNRM02081, Department of Natural Resources and Mines.

Rahman A., Keane J. and Imteaz M. A., 2012. Rainwater harvesting in Greater Sydney: Water savings, reliability and economic benefits. *Resources, Conservation and Recycling* 61, 16-21.

Roberts P., Athuraliya A. and Brown A., 2011. *Yarra Valley future water: residential water use study, vol. 1 (winter)*, Water YV, Victoria

Schwarz N. and Ernst A., 2009. Agent-based modeling of the diffusion of environmental innovations — An empirical approach. *Technological Forecasting and Social Change* 76(4), 497-511.

Southeast Water Corporation, 2012. Water Restriction By-law 001/2012. http://southeastwater.com.au/SiteCollectionDocuments/AboutUs/Water_Restrictions_By-law.pdf.

State Government of Victoria, 2015. Living Victoria Water Rebate Program: Home & Garden. https://www.yvw.com.au/yvw/groups/public/documents/document/yvw1003413.pdf.

Tam V. W. Y., Tam L. and Zeng S. X., 2010. Cost effectiveness and tradeoff on the use of rainwater tank: An empirical study in Australian residential decision-making. *Resources, Conservation and Recycling* 54(3), 178-186.

United Nations, 2014. *World Urbanization Prospects: The 2014 Revision, Highlights. (ST/ESA/SER.A/352)*.

Urich C., Burger G., Mair M. and Rauch W., 2012. DynaMind–A Softwaretool for Integrated Modelling of Urban Environments and their Infrastructure. In: *10th International Conference on Hydroinformatics*, p. 18.

Urich C. and Rauch W., 2014. Exploring critical pathways for urban water management to identify robust strategies under deep uncertainties. *Water Research* 66, 374-389.

Yarra Valley Water, 2016. Residential water and sewerage prices. http://www.yvw.com.au/Home/Youraccount/Understandingyourbill/Residential/Prices/index.htm.