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Modelling urban water management transitions: A case of rainwater harvesting

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ABSTRACT

A promising way to address the growing demand for water supply and improve the liveability of cities is to invest in decentralised multifunctional urban water technologies. However, the adoption of multifunctional water technologies is a complex issue that requires cross-disciplinary approaches. This paper uses an agent-based model that integrates economic and environmental factors to explore and simulate the decision-making and interactions of two types of agents: a regulator and households. The model is applied to evaluate strategies to increase the adoption of rainwater tanks in a suburb of Melbourne, a city that has often suffered from severe droughts. The model was able to replicate the uptake of rainwater tanks by households for 2005–2014, the period known as the 'Millennium Drought'. Results indicate that using economic instruments alone may have been insufficient to promote the adoption of rainwater tanks, and that water restrictions have had a major impact on the uptake.

Software availability

Name of software: DynaMind – Toolbox v0.11.5
Developers: Dr Christian Urich
Contact details: Dr Christian Urich, address: 23 College Walk (Bld 60), Clayton Campus, Clayton VIC 3800, Australia, email: Christian.Urich@monash.edu, phone: +61 3 990 51562
Availability: Online for free download at https://github.com/iut-ibk/DynaMind-ToolBox
Cost: Free
Year first available: 2013
Hardware required: 32-bit (x86) or 64-bit (x64) processor
Software required: C++, python, GDAL
Programming language: C++, python
Program size: 37.2 MB

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 residents affected by perennial water shortage is likely to reach 1.1 billion by 2050 from an estimated 150 million in 2000 due to climate change, land use change and demographic growth (McDonald et al., 2011). One in four large cities globally are currently water-stressed due to geographical and financial limitations (McDonald et al., 2014) and cities in dry areas are likely to suffer from lower rainfall and greater need for infrastructure due to the combined effect of climate change and population growth (McDonald et al., 2011).

Green infrastructure and decentralised water solutions can provide a reliable and fit-for-purpose additional source of water while delivering additional benefits such as flood reduction, heat mitigation and amenity (De Haan et al., 2014). However, the diffusion of decentralised water technologies is hampered by various barriers, such as uncertainty around costs and benefits (for both policy-makers and technology adopters), fragmentation of government responsibilities and resistance to change (Roy et al., 2008). For this reason, there is a need to investigate the behaviour of stakeholders involved in the installation of technologies.

There is also a need for better evaluation of the dynamics of the urban water socio-technical system; modelling of the dynamics can improve the understanding of the impact of different policy

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interventions (e.g. incentives or regulations) to facilitate technology diffusion. Agent-based modelling has been used to explore stakeholder interactions and decision-making (Müller et al., 2013). In particular, such models have been applied to investigate the processes of adoption of novel technologies (Kiesling et al., 2012; Rai and Robinson, 2015; Jensen and Chappin 2017) and to simulate transition of socio-technical systems (Bergman et al., 2008; Lopolito et al., 2013; Holtz et al., 2015).

In the urban water sector, agent-based models have mostly been used to simulate urban water demand and supply (Tillman et al. 1999, 2001; Ducrot et al., 2004; Athanasiadis et al., 2005; Zellner, 2007; Moglia et al., 2010; Kanta and Zechman, 2013; Linkola et al., 2013; Yuan et al., 2014; Koutiva and Makropoulos, 2016; Darbandsari et al., 2017; Mashhadi Ali et al., 2017) and to explore the adoption of water appliances (Chu et al., 2009; Galán et al., 2009; Jensen and Chappin 2017), but few authors have investigated the adoption of decentralised water supply or stormwater technologies (Schwarz and Ernst, 2009; Montalto et al., 2013; Giacomoni and Berglund, 2015; Kandiah et al., 2017) and the modelled results have yet to be compared with observed uptake.

The impact of policy interventions on the adoption of household-scale technologies has been explored in other fields, for instance on the uptake of energy-efficient vehicles (Schwoon, 2006; Mueller and de Haan, 2009; Querini and Benetto, 2014; Silvia and Krause, 2016), decentralised energy supply technologies (Faber et al., 2010; Zhao et al., 2011; Sopha et al., 2013; Palmer et al., 2015) or smart meters (Zhang and Nuttall, 2011; Rixen and Weigand, 2014; Vasiljevska et al., 2017). For decentralised water technologies, only Montalto et al. (2013) explored the impact of economic incentives on the adoption of green roofs and raingardens.

To address these gaps and better understand the influence of different policy interventions on the uptake of decentralised water technologies, we present in this paper an empirically-grounded model to explore the decision-making and interactions of two types of stakeholders, i.e. households and a regulator, with the following objectives:

- to develop a model able to simulate the uptake of decentralised and multifunctional water technologies, focusing in the first instance on rainwater tanks;
- to validate the model using the observed data on installation of rainwater tanks in a suburb of Melbourne, Australia;
- to understand the sensitivity of model results to the variation of uncertain parameters;
- to explore the main drivers (key factors) in the uptake of rainwater tanks.

The paper is organised as follows. First, we provide the rationale for developing the model and review the main determinants of rainwater tank uptake. Then, we describe the model components and processes, as well as the method used for validating the model. Finally, we present the performance of the model and key findings before concluding with a discussion on the advantages, limitations and potential future applications of the model.

2. Case study

2.1. Melbourne and the Millennium Drought

The model stems from a severe drought that occurred in Melbourne, Victoria known as the Millennium drought, which lasted from 1995 until 2009. Record-low rainfall and dam inflow to the main reservoir for several years consecutively triggered the search for alternative water resources (Low et al., 2015). This included seawater desalination, recycling of harvested stormwater and recycling of treated wastewater (Ferguson et al., 2013). The State government committed 10 million AUD over 4 years to provide an incentive for Victorians connected to a reticulated water supply system to conserve water (Khastagir and Jayasuriya, 2011). For instance, the Victorian Government has recognised the importance of plumbing rainwater tanks for non-potable use (e.g. to toilet and/or washing machine) and offered rebates for the installation of rainwater tanks connected to houses. Media coverage and awareness campaigns promoting reduction of residential water use were initiated in an attempt to curb residential water demand (Hurlimann and Dolnicar, 2012; Ferguson et al., 2013), which accounts for 65% of total water demand in the city (Melbourne Water, 2016b).

However, two years prior to the end of the drought, the construction of a desalination plant was announced for a price of 4.9 billion AUD to provide 150 GL of potable water per year (Porter et al., 2015). The drought ended with high rainfall and flash flooding events occurred in several parts of the city in the following years and the desalination plant was not used (Ferguson et al., 2013). Following the end of the drought, the expensive desalination plant construction highlighted the need to improve the understanding of the impact of different policy instruments on the decision-making of households regarding the uptake of flexible and multifunctional decentralised water technologies to avoid technological lock-in.

2.2. Rainwater tanks uptake

Several factors may influence the decision of households to install a rainwater tank. Economic factors, including the water savings benefits, the costs, the net benefit and payback period of tanks have been investigated in several cities (Tam et al., 2010; Rahman et al., 2012; Devkota et al., 2015). However, households may not act entirely upon economic factors. Other social, cultural and behavioural factors such as risk and threat perception, trust and education, may influence the acceptance and adoption of decentralised water systems (Mankad and Tapsuwan, 2011).

The main reasons for installing a rainwater tank highlighted by the last census (Australian Bureau of Statistics, 2013) were to: save water, avoid water restrictions on mains water and to save on water costs. From a survey with 1425 households in the Illawarra region, Australia, Delaney and Fam (2015) found that water restrictions changed the emotional experience of using alternative water sources for outdoor uses. Mankad et al. (2013) concluded that the main determinants for installing a rainwater tank as a response to water shortage in South East Queensland, were the efficacy of tanks to address the water shortage threat, the appraisal of water shortage as a threat and the costs related to tanks. This response to water shortage depends not only on the intensity of water shortage but also on the water supply options available. For example, Lindsay et al. (2016) found that residents in Melbourne, Perth and Brisbane reacted differently despite being similarly affected by water shortage and restrictions. The behaviour of households regarding water conservation, triggered by a sense of water crisis, was observed in Brisbane and Melbourne whereas water conservation behaviour was negligible in Perth due to access to water sources from desalination plants and household bores (Lindsay et al., 2016). As a result, rainwater tank uptake reached 31% and 47% in 2013 in Melbourne and Brisbane, respectively, compared to only 9.3% in Perth (Australian Bureau of Statistics, 2013). Normative factors or