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Modelling domestic water demand: An agent based approach

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ABSTRACT

The urban water system is a complex adaptive system consisting of technical, environmental and social components which interact with each other through time. As such, its investigation requires tools able to model the complete socio-technical system, complementing "infrastructure-centred" approaches. This paper presents a methodology for integrating two modelling tools, a social simulation model and an urban water management tool. An agent based model, the Urban Water Agents' Behaviour, is developed to simulate the domestic water users' behaviour in response to water demand management measures and is then coupled to the Urban Water Optioneering Tool to calculate the evolution of domestic water demand by simulating the use of water appliances. The proposed methodology is tested using, as a case study, a major period of drought in Athens, Greece. Results suggest that the coupling of the two models provides new functionality for water demand management scenarios assessment by water regulators and companies.

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1. Introduction

The urban water system is a complex adaptive system composed of technical, environmental and social components (water infrastructure, water resources and water users respectively) which interact dynamically and continuously with each other and whose relationships evolve in time, particularly in view of the dynamic and bottom up nature of water demand behaviours and patterns, thus increasing the uncertainty regarding its response to changes and interventions (House-Peters and Chang, 2011). More integrated, system-level approaches to the urban water cycle, attempting to manage both supply and demand, through an unified urban cycle management framework have recently been emerging in the literature (including for example Rozos and Makropoulos, 2013; Behzadian et al., 2014; Bach et al., 2014), but even these, leave the water end-user essentially out of the simulation domain.

Two of the main challenges in embedding the water end-user into the urban water cycle are (a) the estimation of the behaviour of households in terms of water demand and (b) the quantification of the way in which this behaviour is affected by water demand management measures such as awareness raising campaigns and water price changes.

In this paper, the water demand behaviour of urban households is simulated using theories from the social psychology domain, that provide a conceptual model of how human attitude is influenced and shaped by others (Allport, 1954; Hogg and Vaugnan, 2011) and of the potential association between attitudes, intentions and actual behaviours (Ajzen, 1991). The proposed methodology aims to explore the change of water conservation attitude (from negative to positive). Such a change may be attributed to influence by, inter alia, a small initial group of "water savers" whose own attitude differs from the social norm (Fell et al., 2009). The main social theory that provides the computational tools to investigate this influence while also taking into account social norms and external influences is Social Impact Theory (Latane, 1981) and as such it was selected for use within this framework.

The simulation environment, selected to setup and model the implications of social psychology theories on the behaviour of water users is Agent Based Modelling (ABM). ABM has the ability to capture emerging (bottom-up) behaviour, simulating the dynamic interaction between the socio-economic and the water system and hence to provide the missing link to modelling the complete socio-technical water system as one (Wheater et al., 2007; Koutiva and Makropoulos, 2011; Barthelemy et al., 2001; Filatova et al., 2013). ABM uses intelligent agents defined as "*computer systems situated in some environment, capable of autonomous action in this*

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environment in order to meet its design objectives" (Wooldridge, 1999). Essentially, ABM is a form of computational social science (Gilbert, 2008) where agents are able to support emergence thus creating complex behaviour from the interaction of simple components.

ABM is slowly gaining ground in the water sciences field, starting with the coordination for water management in the Balinese water temple networks (Lansing and Kremer, 1994) and followed by several research efforts to create ABMs to simulate social-physical system interactions. Becu et al. (2003) used ABM for simulating social dynamics for different control levels in a catchment in North Thailand, Athanasiadis et al. (2005) created an ABM for simulating water consumers' social behaviour and combined it with an econometric model for evaluating water-pricing policies while Barthel et al. (2008) used an ABM model within the DANUBIA DSS to simulate the behaviour of both the domestic water users and the water supply sector in the Upper Danube Catchment in Germany. More recently, Galan et al. (2009a, b) created an ABM to simulate domestic water demand in Valladolid, Spain. Another interesting application of ABM to the water resources management field is the contribution of van Oel et al. (2010) that explored feedback mechanisms between water availability and water use in a semi-arid river basin.

In this paper we develop an ABM, hereafter termed the Urban Water Agents Behavioural Model (UWAB), which simulates the urban household's water demand behaviour based on: (a) complex network theory (Newman, 2003) representing the links among the domestic water users of a city; (b) social impact theory (Latane, 1981) addressing the effects of society, policies and other external forces on the domestic users' behaviour; (c) the theory of planned behaviour (Ajzen, 1991) deconstructing the domestic water user's behaviour into components for modelling behavioural intention; and (d) statistical mechanics (Shell, 2014) employed to deal with the inherently stochastic nature of human behaviour.

These theories have been partially exploited to analyse similar research problems in the past. For example, the theory of planned behaviour has been combined with social research methods to assess water demand behaviour (Hurlimann et al., 2009; Jorgensen et al., 2009; Fielding et al., 2010), while the same theory coupled with ABM has been used to simulate individual domestic water habits (Schwarz and Ernst, 2009, Linkola et al., 2013). Social impact theory has been used together with cellular automata (Latane, 1996; Nowak and Lewenstein, 1996), agent based models (Holyst et al., 2000; Kacperski and Holyst, 2000) and complex network theory (Aleksiejuk et al., 2002; Sobkowizc, 2003a and 2003b) for a variety of social simulation purposes. Statistical mechanic have been used so far to analyse existing models (Castellano et al., 2009) while in this research we use them to develop more general behaviour rules of domestic water demand. The combination of Complex Network Theory, Social Impact Theory, Theory of Planned Behaviour and Statistical Mechanics within an agent based modelling framework (UWAB) is a key innovation in the work presented in this paper.

Results on behavioural changes due to demand management policies and environmental pressures are simulated within the UWAB model and are then translated into specific domestic water demands through micro-simulation of in-house water appliances using the Urban Water Optioneering Tool (UWOT) (Makropoulos et al., 2008). This approach exploits the potential of already mature, proven simulation models for urban water modelling while enhancing their remit by developing the functionality required to directly take into account the social component of water demand. The proposed model and approach is also applicable for use with other urban water system models to investigate the impact of behavioural change of domestic water users to the water cycle — allowing for example a much more thorough assessment of the urban water system's response to alternative water demand management strategies. The methodology and models are demonstrated using the 1988–1994 drought in Athens, recreating the response of city's water demand to the water demand management efforts of that period.

2. Material and methods

2.1. The Urban Water Agent Behaviour (UWAB) model

2.1.1. Purpose

The Urban Water Agent Behaviour (UWAB) model was created, using the NetLogo agent programming language (Wilensky, 1999), to simulate the effects of environmental pressures and water demand management policies on water demand behaviour of households focusing specifically on water conservation. There is a wide variety of available ABM toolkits, with *NetLogo*, *Swarm* and *Repast* being the three platforms that are most commonly used as identified in an analysis of 53 different ABM platforms by Nikolai and Madey (2009). In this research, NetLogo was selected for reasons related to (i) ease of use, (ii) available support documentation, (iii) the existence of an active support community and (iv) the availability of a significant number of freely available models to learn and get inspired from (Thielle and Grimm, 2010; Voinov and Bousquet, 2010). Unlike other agent based models that deal with domestic water demand (e.g. Athanasiadis et al., 2005 or Galan et al., 2009a, b) this model does not include a statistical or econometric model of consumption and focuses only on the household's water demand *behaviour*. Water *consumption* is then estimated using a model specifically developed to simulate demand from the appliance level all the way to the water source (UWOT — presented in the following section). In this section the variables, processes and design concepts of the UWAB model are presented using the ODD protocol (Grimm et al., 2006) in the form of a roadmap, following recommendations by Polhill et al. (2008).

2.1.2. Design concepts

Using the ODD terminology, UWAB's design concepts can be defined as follows:

- Emergence: Emergence in UWAB relates to the fact that the micro behaviour of each household agent results in the estimation of the macro behaviour of the community. This behaviour is then converted into water demand through UWOT.
- Adaptation: Household agents adapt their behaviour firstly by changing their attitude on water conservation due to the social impact exerted on them. Then, household agents review their decision regarding water demand behaviour based on the effect of their behaviour on their water bills.
- Fitness: At an individual agent level, households measure the fitness of their decision by assessing their goal of reducing their water bills. Global 'fitness' is measured after integrating with UWOT and producing results of mean monthly domestic water demand.
- Prediction: Household agents anticipate the reduction of their water bill. They have however no memory or learning mechanisms.
- Interaction: Household agents interact with each other forming social networks and influencing each other's water conservation attitude. Through the social impact parameter (see below), household agents interact with their social network and are affected by policy measures.

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