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Linking social simulation and urban water modelling tools to support adaptive urban water management

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Abstract: The sustainable evolution of urban areas requires the assessment of the imposed pressures and the estimation of the effect of alternative responses to the urban water resources system. Such estimation entails, to a large extent, uncertainties mainly due to the complex nature of the system and its interaction with society's subjective beliefs and (rational or otherwise) decisions. These uncertainties may be better handled by employing an adaptive approach towards integrated urban water resources management but this approach necessitates the development of more sophisticated decision support tools able to simulate both the technical and social components of the complete socio-technical system. This research focuses on the later and proposes a conceptual framework for investigating the choices of actors in response to policy interventions. The framework is implemented through a modelling "experiment" integrating an Agent Based Model (ABM), with information from the Urban Water Optioneering Tool (UWOT). The model is used for investigating the adoption of alternative domestic water technologies in an urban population under different technology subsidising policies. Agents (households) are presented with information regarding the available domestic water technology configurations through a link to the UWOT model. The agents then use this information in combination with personal (environmental behaviour, innovation acceptance type) and public (current use of technologies within the household's social network, marketing campaigns) social parameters in order to choose their preferred configuration. The paper presents the design and evaluation of the proposed conceptual framework.

Keywords: integrated modelling; agent based modelling; social simulation; adaptive management; integrated water resources management

1   INTRODUCTION

Urban areas impose pressures on the water resources system through the interaction between the main urban water flows (water supply, waste water production, drainage) and the environment (Rozos et al., 2011). These pressures are influenced by the households' water demand, which is linked to the configuration of domestic water technologies as well as to the occupants' attitude towards water consumption (and conservation). Essentially it is a combination of which water related technologies are installed and how the user decides to operate them: The development of low water using domestic water appliances does not guarantee their uptake by the urban population, nor does it guarantee their correct use. The acceptance and adoption of such technologies within the urban population is related to the user's beliefs and attitudes as well as to investment costs for implementing such technologies (Menegaki et al., 2007, Domenech, L. and Sauria,

D., 2010). The user's beliefs and attitudes are, in turn, related to the available information regarding any given technology and to the social characteristics of the household (Dolnicar et al., 2011).

The acceptance and diffusion of technologies, within a population, has been studied extensively (Rogers, 1995, Bass, 1986, van der Bulte C. and Lilien, G., 1999, Young, 2007, Burt, 1987, van den Bulte, C., and Stremersch, S.,2004). Rogers [1995] grouped people into five categories depending on their acceptance of new technologies and suggested that the cumulative adoption of a technology follows an S-curved model. Based on Roger's [1995] research there are several distinct stages that people engage to in order to gather information and decide whether or not to adopt a new technology.

The purpose of this paper is to present the design of a conceptual framework of the combined socio-technical water system and its evaluation by creating a modelling experiment able to explore the diffusion of alternative domestic water technologies in the urban water system. The modelling experiment links an Agent Based Model (ABM), simulating the decisions of an urban population and the Urban Water Optioneering Tool (UWOT), providing information on the characteristics of domestic water technologies configurations.


2   CONCEPTUAL FRAMEWORK

A conceptual framework of key elements that are assumed to shape water demand behaviour in this work is presented in Figure 1. The framework is hierarchically divided into two levels. The first level consists of the private socio-economic processes of water users. Several researchers have identified that household water demand behaviour is affected by numerous social and psychological factors, which include: residents' age, income level, family size, education level, household characteristics (size, age, type of domestic water technologies configuration) as well as other factors related to their environmental behaviour (Arbués et al., 2003, Barrett, 2004, Beal et al., 2010, Campbell et al., 2004, Fontdecaba et al., 2011, Harlan et al., 2009, Jones et al., 2011, Mondejar-Jimenez et al., 2011, Randolph B. and Troy P., 2008, Willis et al., 2011).

The selection of domestic water technologies is affected by the user's beliefs, attitudes and social characteristics (Menegaki et al., 2007, Domenech, L. and Sauria, D., 2010, Dolnicar et al., 2011). In addition, the introduction of advanced domestic water technologies is related to the innovation acceptance type of the household, which is a function of age, income level, social class, willingness to take risks, social network and others (Rogers, 1995). Moreover, water demand behaviour is related to the user's overall behaviour towards environmental protection (Gilg, A. and Barr, S. 2006). Environmental behaviour is a function of age, income level, educational level and other social characteristics (Gilg, A. and Barr, S., 2006, Gregory G. and di Leo M., 2003, Jones et al., 2011). In particular, committed environmentalists are in general older with small sized families, a high education level and owners of their house. On the other hand, non-environmentalists are in general younger, with large sized families that mainly rent their house and have both low income and educational level Gilg, A. and Barr, S., 2006).

The second level represents the public interactions between the water users and the environment, divided into the interactions with the water environment and with the social environment. The first one is represented by the links between water demand behaviour and state of water resources, including the imposed pressures, whereas the latter by the links between social influence and water demand behaviour.

Figure 1 also identifies the type of tools that may be used for creating an integrated model of the different factors that shape water demand behaviour, including urban water management models, econometric models and social simulation models.

This work focuses on the integration of a social simulation model (ABM) with an urban water resources management model (UWOT).
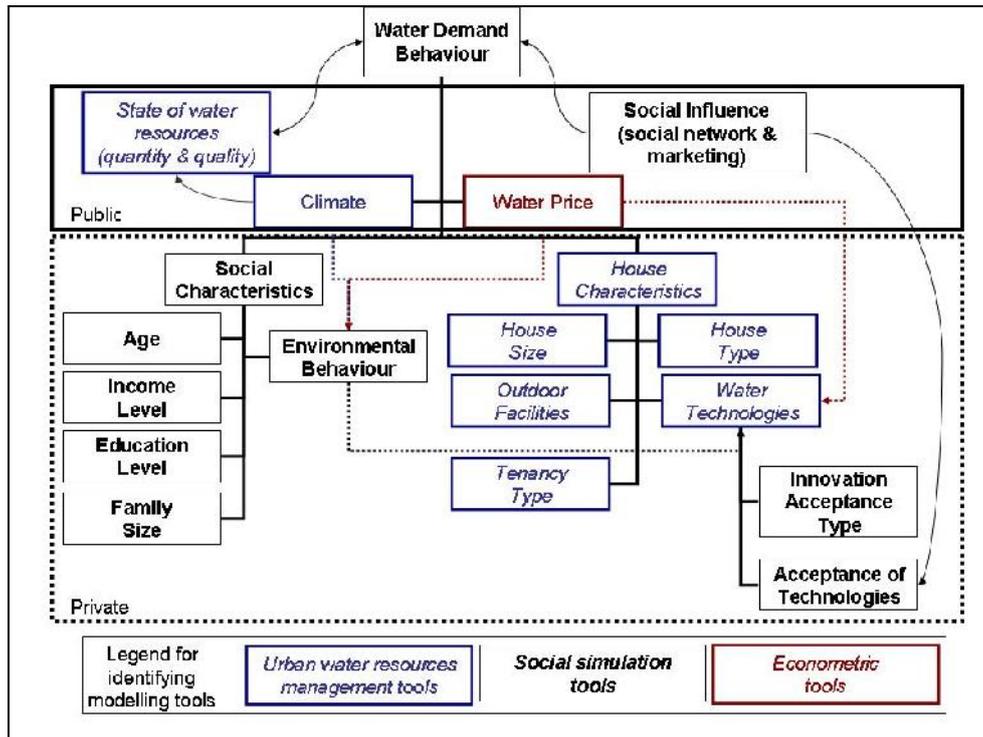
Figure 1 Conceptual model of the key elements shaping water demand behaviour and tools that may be integrated to model the combined socio-technical urban water resources system (black bold: social simulation tools, blue: urban water resources management tools, brown: econometric tools)

3 MODELLING EXPERIMENT

A modelling experiment, simulating the water demand behaviour of a number of hypothetical households, is implemented through agent based modelling using NetLogo, an agent based simulation platform and programming language. For the purposes of this modelling, information regarding technical and economic characteristics of alternative domestic water technologies configurations was provided by the Urban Water Optioneering Tool (UWOT) (Makropoulos et al., 2008b).

As depicted in Figure 1, water demand behaviour is a function of different interlinked parameters creating a complex system. The experiment presented in this paper, focuses on the investigation of the diffusion of domestic water saving technologies in an hypothetical urban population. Two different technologies are investigated: rainwater harvesting and grey water recycling. Non potable water from these technologies, is then used for toilet flushing, clothes washing and garden irrigation. In addition, the model investigates the effects of water conservation attitudes and subsidising policies to the diffusion of these alternative technologies.

Agent based modelling is used to simulate the decisions of each household towards decreasing water demand and changing domestic water technology configurations. Each agent represents one household of an average of three occupants and each household is characterised by innovation acceptance type, environmental behaviour type and social network structure. The households are also presented with information regarding their water demand and the investment cost for each alternative configuration, calculated by the UWOT. The model has a monthly time step and each month all households decide whether to (a) decrease

their domestic water demand and (b) whether to change their domestic water technologies configuration. The households' decision process is presented in Figure 2.
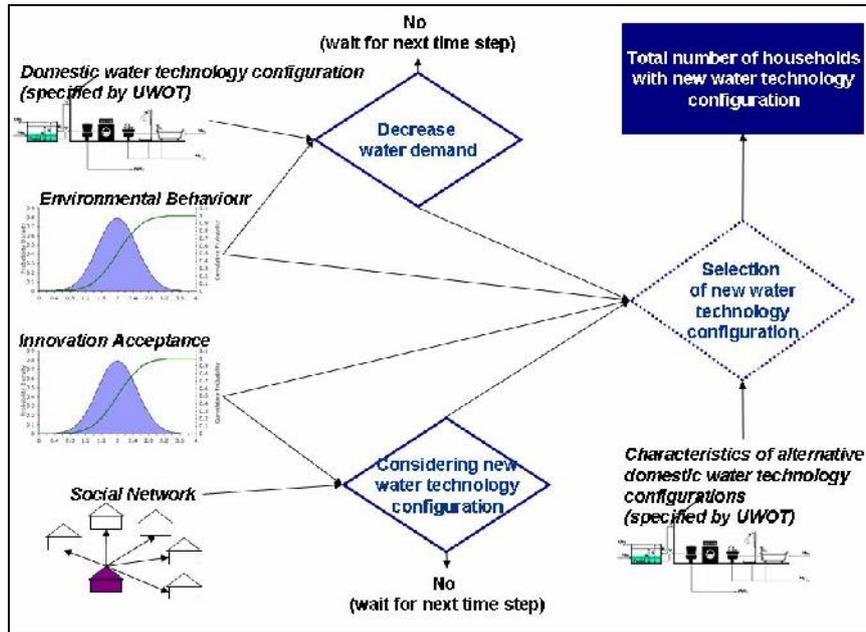

Figure 2 Households' decision process

The household's acceptance of the technologies is calculated as a function of the household's innovation acceptance and the environmental behaviour type. Both these characteristics are assigned to the hypothetical population (in the absence of more specific data), using random sampling from a normal distribution and are independent of each other. Innovation acceptance type is distributed in the population, following Rogers' adopter categorisation within a population (innovator (2.5%), early adopter (13.5%), early majority (34%), late majority (34%) and laggards (16%)) (Rogers, 1995). Furthermore, environmental behaviour type follows a normal distribution within the experimental population, committed environmentalists and non-environmentalists each occupy 5% of the experimental population, while medium-high, medium-low and occasional environmentalists each occupy a 30% of the experimental population.

The diffusion of technologies is assumed to follow the principles of social contagion (Young, 2007, Burt, 1987, van den Bulte, C., and Stremersch, S.,2004) and is regarded as a two-stage process, separating the effect of causal variables on awareness and evaluation (van den Bulte C. and Lilien G.,1999). During the first stage, households decide, based on (a) their innovation acceptance type, (b) the diffusion of the technologies in their social network and (c) the external marketing of the alternative technologies, whether they are open to consider a new configuration of domestic water technology. If a household is indeed open to consider new technologies, a stochastic sampling (roulette wheel selection) approach is used to decide whether or not, the household will in fact change. The roulette is set based on environmental behaviour and innovation acceptance type. A separate, independent decision that households take at the end of stage one, is whether or not to decrease their water demand by 5% (irrespective of technologies), by decreasing for example, shower and garden irrigation use. This decision is taken based on their specific environmental behaviour type.

During the second stage, households that have decided to change, decide which alternative technology they prefer. This decision is the result of individual preferences, selected by each agent based on their beliefs (Table 1). The agents rank the importance of water saving and social influence and the importance of cost is calculated using equation (1).

$$Cost\ Preference\ _{Agent_i} = 1 - Water\ Saving\ Preference\ _{Agent_i} + Social\ Influence\ Preference\ _{Agent_i} \quad (1)$$

Table 1 Preferences based on each household's subjective beliefs.

Environmental Behaviour Type	Water Saving Preference	Innovation Acceptance Type	Social Influence Preference
Committed	1	Innovator	0
Mainstream-high	0.75	Early adopter	0.25
Mainstream-low	0.5	Early Majority	0.5
Occasional	0.25	Late Majority	0.75
Non-environmentalist	0	Laggard	1

UWOT provides information regarding water demand and investment costs for the alternative domestic water technology configuration. Households use their subjective preferences to calculate the utility of each alternative domestic water technology configuration based on equation (2). Subsidising policies are added at this stage, decreasing the investment cost needed for alternative configurations. The households choose the configuration that maximises the utility of the configuration (or minimises the difference between the utility of the conventional domestic water technology configuration and one of the alternatives). Figure 3 is a representation of the decision process of each household. Their final decision is again determined using a stochastic sampling (roulette wheel selection) based on different probabilities for each environmental behaviour type.

$$(2)$$

$$U_{TECHNOLOGY_i} = Water\ Saving\ Preference\ _{Agent_i} \times Water\ Demand\ _{TECHNOLOGY_i} +$$

$$+ Social\ Influence\ Preference\ _{Agent_i} \times (\%\ friends\ _{TECHNOLOGY_i} + Marketing\ Effect\ _{TECHNOLOGY_i}) -$$

$$- Cost\ Preference\ _{Agent_i} \times (Water\ Demand\ _{TECHNOLOGY_i} \times Water\ Price) -$$

$$- Cost\ Preference\ _{Agent_i} \times (Investment\ Cost\ _{TECHNOLOGY_i} \times (1 - Subsidies\ _{TECHNOLOGY_i}))$$
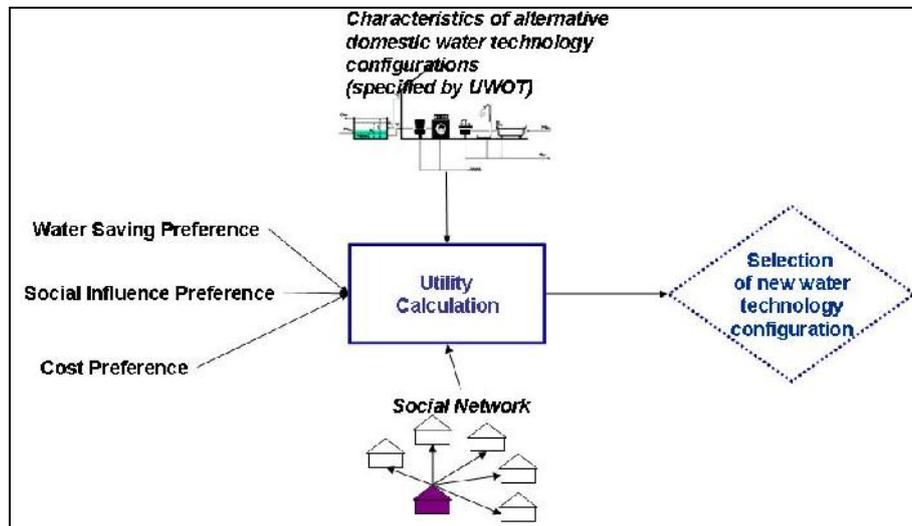

Figure 3 Household decision process of alternative domestic water technology configuration

The final outcome of this modelling experiment is the number of households that have decided to change their domestic water technology configuration. This modelling experiment was implemented by running scenarios of different subsidising policies for the alternative domestic water technologies (Table 2).

Table 2 Characteristics of the experimental model for a selection of scenarios for different subsidising policies.

Constant parameters of the modelling experiment	
Simulated number of households	100
Initial introduction of the two alternative domestic water technologies (% of total households)	3%
% of friends for each household	10%
Marketing effect	0
Water price change	0

Scenarios of subsidising policies		
Scenario number	Subsidies for Rainwater Harvesting Technologies	Subsidies for Grey Water Recycling Technologies
Baseline	0%	0%
1	30%	0%
2	40%	0%
3	30%	10%
4	0%	40%
5	10%	40%

Figures 4 and 5 present the temporal evolution of the population's cumulative percentage that adopts rainwater harvesting and grey water recycling, for the scenarios presented in Table 2.
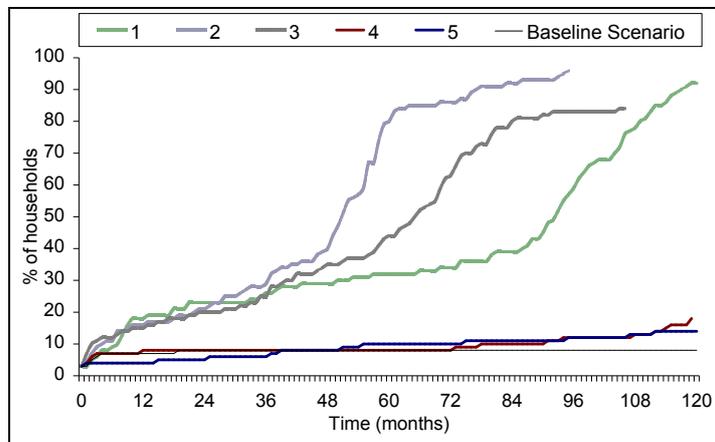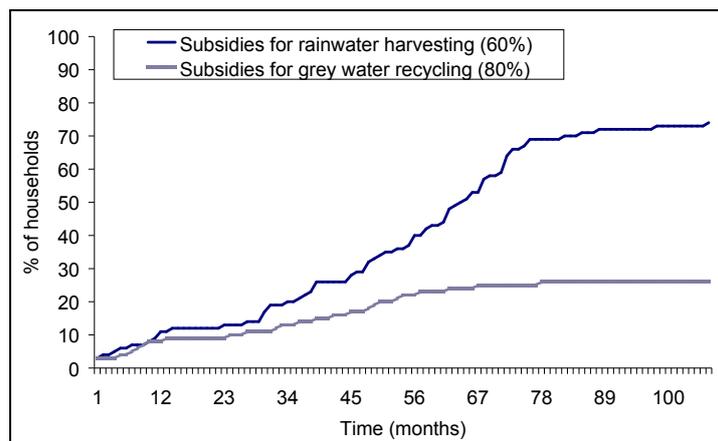

Figure 4 Cumulative adoption of rainwater harvesting technology for different subsidising policies (numbers 1-5 refer to the Scenario Numbers of Table 2).
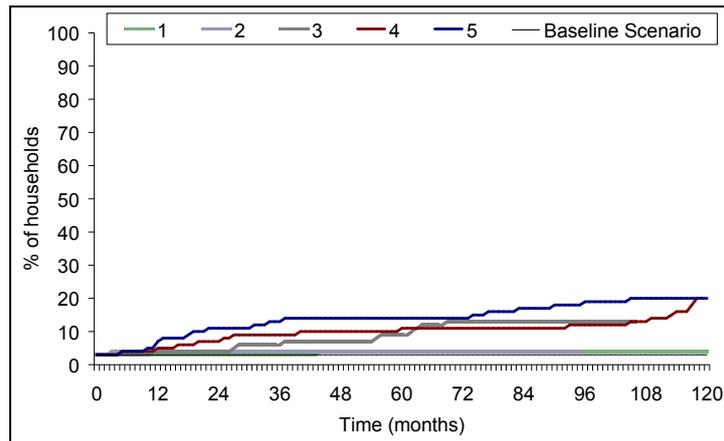
Figure 5 Cumulative adoption of grey water recycling technology for different subsidising policies (numbers 1-5 refer to the Scenario Numbers of Table 2).

From Figure 4 and 5 it is evident that adoption of alternative technologies follows an S-curve in time which fits the theoretical S-curve of the cumulative adoption of new technologies suggested in the literature (Rogers, 1995, Bass, 1986, Young, 2007). This can be attributed to the fact that innovation acceptance type, which is normally distributed in the experimental population and follows technology diffusion theory (Rogers, 1995) is one of the main components of the household's decision making process, and its s-shaped cumulative distribution clearly influences the form of the adoption process.

Figure 6 shows a comparison between the adoption of the two alternative technologies with the effect of two subsidising policies of 80% for grey water recycling and 60% for rainwater harvesting. These policies decrease investment costs, almost equalising them. However, still the majority of the population appears in this simulation to show a preference towards the rainwater harvesting technologies. This result can be attributed to the fact that households with low water saving preference and high cost preference increase the initial adoption of rainwater harvesting thus increasing the social influence on this specific technology, helping it spread in the population. What this simulation reveals is the sensitivity of the success of a given measure to initial conditions which are at the social rather than the technology domain, and the need to be able to consider such conditions when designing subsidies within a formal simulation process to support decision making.

Figure 6 Cumulative adoption of rainwater harvesting and grey water recycling technologies for a subsidising policy of 60% and 80% respectively.

The proposed methodology can be used to examine the effect of alternative subsidies and investigate the trade-off between increased subsidies, costs of implementation, adoption of the alternative technologies and water savings.

3 CONCLUSIONS

Designing adaptive water management strategies requires "thinking environments" which are able to investigate a variety of alternatives across the socio-economic and natural water system boundaries (Makropoulos et al., 2008a). Agent Based Modelling has been identified as a very promising tool for simulating the socio-economic environment and thus provides the missing link to the modelling of the complete socio-technical water system (Koutiva and Makropoulos, 2011).

An experiment was set up to test this approach based on the simulation of a hypothetical population whose subjective characteristics were assumed to follow a normal distribution. Preliminary results of the modelling experiment are promising since simulated results are consistent with theoretical principles in terms of technology adoption rates.

The next step of this research is to design and implement an extended modelling platform and use it to investigate water demand behaviour under different scenarios and drivers, tightly coupled with UWOT to consistently simulate the urban water cycle. It is suggested that such a platform will be a powerful tool to examine, design and support adaptive demand management strategies as well as to communicate results to stakeholders.

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