International Environmental Modelling and Software Society (iEMSs)
2012 International Congress on Environmental Modelling and Software
Managing Resources of a Limited Planet, Sixth Biennial Meeting, Leipzig, Germany
R. Seppelt, A.A. Voinov, S. Lange, D. Bankamp (Eds.)
http://www.iemss.org/society/index.php/iemss-2012-proceedings

A hybrid artificial intelligence modelling framework for the simulation of the complete, socio-technical, urban water system

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Abstract: A (truly) integrated approach to the management of urban water should take into account, further to the characteristics of the technical system, a range of socio-economic processes and interactions – combined into what has been termed the "socio-technical system". This is by no means an easy endeavour: conventional simulation tools often fail to capture socio-economic processes and their interactions with the technical urban water system. Variables depicting the socio-economic environment are usually static and estimated from literature and/or expert opinion. To address this issue, new socio-technical modelling approaches are emerging aiming to explicitly account for the feedback loops between the socio-economic environment and the urban water system. In this paper we develop a hybrid artificial intelligence (AI) conceptual model using System Dynamics (SD), Agent Based Modelling (ABM) and urban water modelling tools to investigate the urban water system's response to different policies. The SD model simulates the broader socio-economic, natural and technical context and links to more specialised tools for the social and technical sub-systems: For the social sub-system, ABM is used to model preferences and decisions of water users, whereas for the technical system, the Urban Water Optioneering Tool (UWOT) is used to provide a detailed representation of the urban water cycle, affected by the end-users' decisions. The proposed modelling framework allows for the dynamic nature of the socio-economic variables to be explicitly included in the assessment in order to test the effectiveness of different policies, such as awareness raising campaigns, and dynamically simulate the subsequent response of the urban water system in time. The paper discusses the integration of urban water and social simulation models at a higher modelling level via a System Dynamics platform and the suitability of such a framework for the assessment of the performance and pressures on urban water systems under varying conditions and scenarios.

***Keywords**:* system dynamics; agent based modelling; urban water system; socio-technical system; integrated modelling

1 INTRODUCTION

The urban water system is a complex socio-technical system, including interdependent human and non-human elements bound together in networks (Kaghan and Bowker 2001, Sofoulis 2005). Water supply is closely linked to the availability of water resources, thus linked with the uncertainty related to hydroclimatic conditions and variability. On the other hand urban water demand is mainly driven by socio-economic factors and the associated uncertainty is related to anthropogenic change. Hence, an interdisciplinary approach is required that takes into account the water system's socio-economic drivers besides merely its technical components. It is now widely acknowledged that to achieve sustainable urban water management an integrated, adaptive, coordinated and participatory approach needs to be adopted that challenges conventional technocratic urban water management practices (Brown and Farrelly 2009).

This integrated analysis needs to move beyond the static representation of the socio-economic variables and deal with the system's dynamic complexity by enabling the study of dynamic interrelationships and feedback loops between these distinct aspects of the urban water system. There is a need for decision making tools that will be able to simulate the urban water system's response to different policies assisting policy makers to take more informed decisions. Recent developments in integrated modelling tools, and more specifically, component-based approaches can facilitate Integrated Water Resources Management (IWRM) and deal with the interdisciplinary nature of complex water management issues (Safiolea et al. 2011).

An example of such integrated tools are system dynamics (SD), an approach able to describe complex dynamic systems governed by feedback relationships, whose response we want to monitor over time. The system dynamics methodology has been used in a wide range of water resources management problems (Winz et al. 2009) and SD models are often used as decision support systems, facilitating the assessment of various policy effects. Another key strength of SD models is their ability to help with the visualisation and communication of management decisions to stakeholders and the general public, assisting meaningful participation (Stave 2003). SD models are well suited for aiding the analysis of complex interdisciplinary problems as they provide a unique modelling framework for integrating physical and social processes associated with water resource management problems (Tidwell 2004; Winz et al. 2009). Examples of SD models used for policy analysis and evaluation for urban water management include among many others the assessment of conservation alternatives in the Middle Rio Grande (Tidwell 2004), policy evaluation for municipal water conservation (Ahmad and Prashar 2010) and strategy formulation for mitigating water shortages in Taiwan (Yang et al. 2008).

In this research we investigate the use of the SD methodology as a flexible interdisciplinary and transparent platform that will be used for integrating more specialised models with greater level of detail for specific sub-sections of the urban water system. Agent based modelling (ABM) has been identified as an appropriate tool in terms of addressing socio-economic elements of the water system (Koutiva and Makropoulos 2011). The proposed modelling framework links social simulation agent based models and urban water models via an SD integrating platform. We discuss the use of the proposed framework as a tool for decision making in urban water management.

2 PROPOSED METHODOLOGY

Our work focuses on domestic water demand and the effectiveness of associated policies for demand management. To facilitate this study a hybrid artificial intelligence conceptual model was developed: this approach enables the developer to benefit from the strengths of different methods by using the appropriate method to simulate different parts of the overall model. For example, the SD top-down modelling approach is considered useful when system behaviour is known and can be reproduced by the system's structure as a series of feedback loops. On the other hand ABM assumes no fixed system structure and the overall system behaviour emerges from individual agent rules, making it thus a bottom-up modelling approach (Borshchev and Filippov 2004). Hybrid SD and ABM models have been used in social studies; in the work presented by Marquez et al. [2011] social dynamics at the macro level are described by SD, while the low-level interactions are captured by distributed agents. Other hybrid modelling examples include the simulation of the supply chain (Schieritz and GroBler 2003) and the design and operation of renewable energy systems (Mazhari et al. 2011).

In the work discussed here, system dynamics have been selected to represent the broader socio-economic, technical and natural environment in an aggregate manner and the associated variables, population, available water and policy, are modelled in a top-down manner. The agent based model carries out social simulation by modelling the preferences and decisions of water users. Their environmental behaviour is influenced by their own intrinsic social characteristics, but also by the broader environment in which they operate - which is modelled by the SD. The emerging water use behaviour and patterns from the ABM then affects the broader environment by feeding back into the SD model's domestic demand. The urban water cycle at the household level is simulated by the Urban Water Optioneering Tool UWOT (Makropoulos et al. 2008), which provides to both the agents and the SD model, household water demands for different household types and technical configurations. In the current conceptual model the SD component using available hydroclimatic information assesses whether there is a need to trigger a particular policy related to demand management and then provides this information to domestic water users. The system's water supply configuration is described in the SD model section, whereas water demand is modelled in more detail through ABM and UWOT. Figure 1 presents the schematic of the hybrid conceptual model developed, which comprises of three sections (SD, ABM and UWOT) with their main interconnections. The performance of the urban water system is evaluated at each time step.

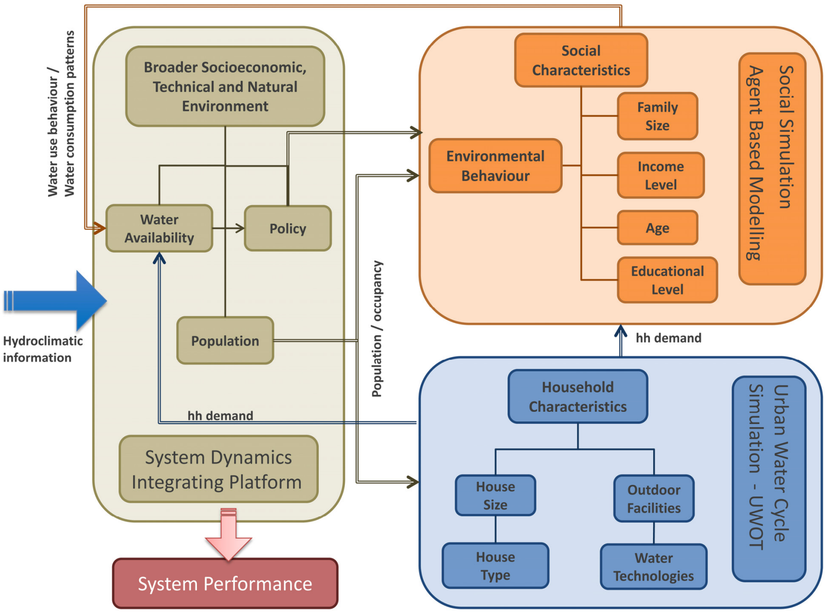

Figure 1. Hybrid conceptual model schematic

2.1 Hybrid Model Description

The causal loop diagram used for the development of the system dynamics model along with the indirect causal links through the agent based model and UWOT is shown in Figure 2. This specific causal loop diagram has been developed for testing environmental awareness campaigns as a policy for demand management. The simplified representation of *urban population* change takes into account only a net growth rate, while population increase is limited by a negative density dependant feedback as it approaches a specified population capacity. The model variable *availability index (AI)* has been introduced as an indicator of how much water is available in the system and is defined as:

$$AI = \frac{S(t-1) + I(t) - C(t)}{C(t)} \quad (1)$$

Where *S* is the available water in the system, i.e. the water stored in the surface water reservoirs, *I* the net inflows and *C* the total consumption including losses. Essentially this indicator represents how many additional monthly “consumptions” could be covered by the available water supply after having satisfied the various demands and losses. The variable *risk index* counts the times within a year when the *availability index* falls below a certain user-defined threshold. When the value of the *risk index* exceeds a set target an environmental awareness campaign is triggered. Both thresholds are subjects of water company policy and are considered in this work as external inputs. The agent based model receives from the SD model the information on water availability and the existence or not of an environmental awareness campaign.

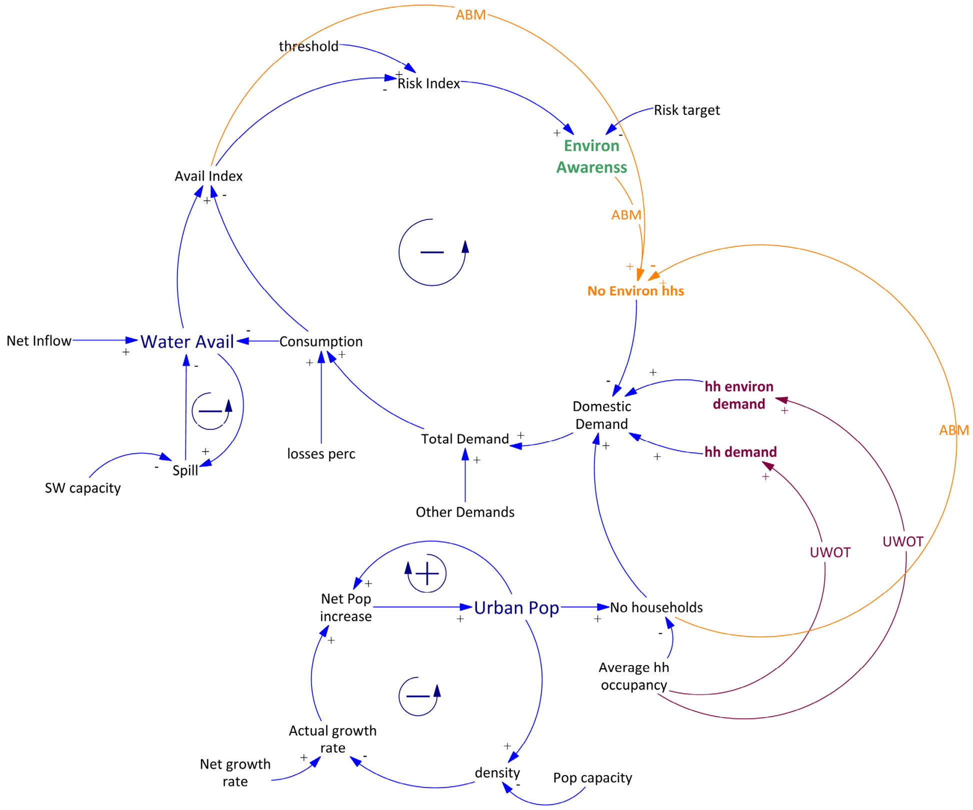

Figure 2. Hybrid model causal loop diagram

In turn, the ABM investigates the decision of the urban population to decrease water demand based on subjective attitudes triggered by their individual environmental behaviour. This simulation is based on the assumption that people with a strong environmental behaviour tend to conserve more water (Gilg et al. 2006). In principle, individual environmental behaviour is affected by households' age, income level, educational level and other social characteristics (Gilg et al. 2006, Gregory et al. 2003, Jones et al. 2011). Households’ environmental behaviour is assigned to the case study population using sampling from a normal distribution. Four types of environmental behaviour are identified based on the cumulative probability to the given population (namely committed, mainstream, occasional and non environmentalist). These different types are assigned different probabilities to decrease water demand ranging from 0.05 for non-environmentalists to 0.5 for committed environmentalist. It is assumed that households' environmental behaviour is uniformly affected by the existence of an environmental awareness campaign, when such a campaign is initiated by the SD model. Highly environmentally aware households are also given additional information regarding actual water availability from the SD model, which increases their probability to decrease water demand. The final outcome of the ABM is the total number of households per month that have decided to decrease water demand. This output feeds back into the SD so that it calculates total domestic demand based on values of conventional and reduced household water demand provided by UWOT. Figure 3 presents the decision process of the agent based model.

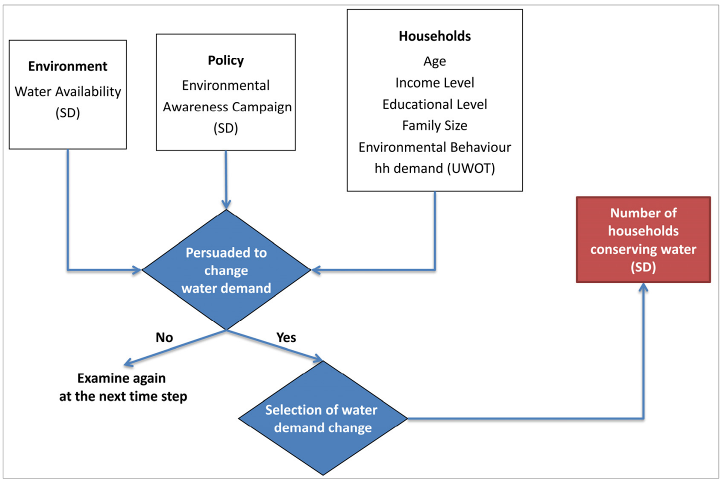

Figure 3. Agent based model simulation process

The aim of this modelling experiment is to assess the effectiveness of a particular demand management policy by estimating the risk of failure of the water system for different water availability thresholds.

3 PROOF OF CONCEPT

3.1 Model description and assumptions

The representation of a simplified version of the Greater Athens water supply system has been selected as a proof of concept for the proposed conceptual hybrid model. The modelling experiment presented in this paper aims to investigate the interactions between the natural and socio-economic environment under varying conditions and simulate the response of the urban water system. The model was developed in the Netlogo modelling environment, an agent based simulation platform and programming language that also facilitates system dynamics modelling.

In our case domestic demand is the main driver of total water abstraction and as such only domestic demand management measures are examined. Non-domestic water demand has been taken into account only as a mean annual value based on Efstratiadis et al. [2009]. The seasonal variability of demand has not been taken into account for this application. The simplified version of the Athens water system was tested against varying climatic conditions and for this purpose 100-year synthetic timeseries statistically consistent with historical data (Koutsoyiannis et al. 2003) were used for the inflows to the four reservoirs comprising the actual Athens water supply system. At the beginning of the simulation the total surface water storage was assumed to be at 50% of its capacity and the model was setup with a monthly time step. For the calculation of net inflows to the water supply system mean monthly evaporation estimates have been used, as well as average values for all other reservoir losses. The values used for the losses from the external aqueduct and the internal distribution system are in line with the ones estimated from field measurements in the study of Mamassis et al. [2011]. Current population values for the area serviced by the Athens Water Supply and Sewerage Company (EYDAP SA) were taken from Efstratiadis et al. [2009]. Besides the main model output variables, the model also estimates the number of times the water system fails during the length of the simulation, i.e. the number of time steps when the available water cannot meet total demand.

3.2 Baseline and policy scenarios

Initially the model was run without introducing any demand management policy. Under this baseline scenario the agents are not influenced by the additional effects stemming from the activation of a policy. The choice on whether to conserve or not is based for the majority of the agents solely on their social characteristics and for a small percentage of the households also on environmental conditions and specifically the system's water availability. The performance of the water system was evaluated assuming a constant population under varying climatic conditions, using 100-year synthetic timeseries for the reservoirs' inflows. For this purpose the population capacity in the SD model was set equal to the initial urban population at the beginning of the simulation for both baseline and policy scenarios. The population was set at the current levels of the population serviced by the water company as defined in Efstratiadis et al. [2009]. It should be noted that the 100-year simulation does not represent a forecast, but rather a risk assessment in the short-medium term (1-5 years) against different hydroclimatic input.

The policy is assumed to be activated when the availability index falls below a set threshold. The environmental awareness campaign, initiated by the SD model, targets every household and may enhance temporarily the household's environmental behaviour, thus increasing the household's probability to decrease its water demand. The agents, who ultimately decide to conserve water after being influenced by the campaign and/or the environmental conditions, are assumed to reduce their initial household water demand by 10%. This lower household water demand is a result of reduced use for showers and garden watering as calculated by UWOT. The policy scenario was simulated under various availability thresholds, and various levels of assumed effect of the policy on environmental behaviour, and the number of the water system's failures has been estimated for each configuration. The simulation results for the example of the Athens simplified water system are presented in Figure 4.

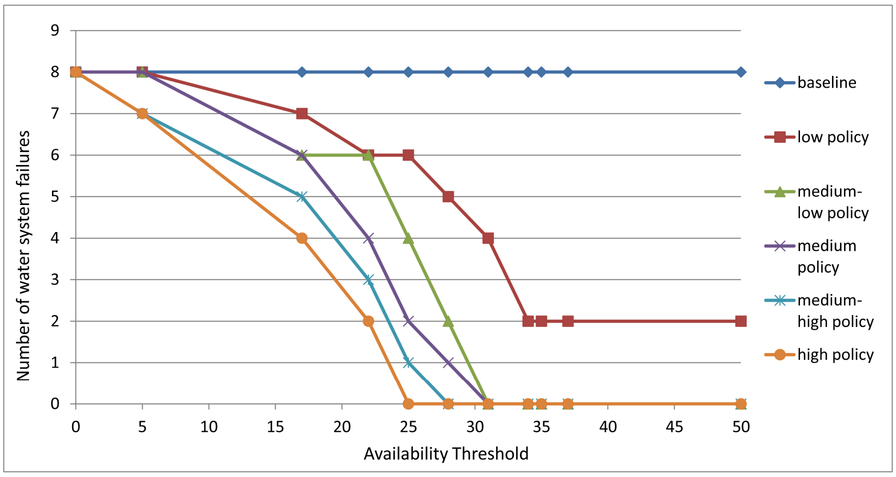

Figure 4. Water system failures vs. water availability threshold under varying policy effects

In Figure 4, it can be observed that as the threshold that triggers the launch of the policy increases (in other words, as risk aversion rises) and awareness campaigns are hence launched sooner rather than later, their effectiveness rises: demand reductions resulting from these campaigns are incurred early enough to significantly decrease system failures. Although several parameters in this analysis need to be carefully calibrated to provide added value (e.g. seasonal variability), it is evident that such an approach can assist in setting, case specific, hydrological, technically and sociologically sound, thresholds for water scarcity and drought management corresponding to, for example, acceptable levels of risk. Although not presented here, the same analysis framework can also identify critical leverage points in the process of launching customized campaigns, to improve their effectiveness as part of a broader intervention strategy.

4 DISCUSSION AND CONCLUSIONS

The preliminary results of this work suggest that the proposed modelling framework can provide useful information on the effectiveness of urban water management policies. The proposed analysis can assist in identifying the type of policies that would be most effective under varying environmental and socio-economic conditions and indicate how far in advance decision makers would need to implement them in order to minimise the risk of system failure. Further relevant aspects could be explored in the proposed integrated modelling tool, such as economic and urban development scenarios by further expanding the SD model to include these interrelationships and feedbacks and possibly by creating additional links with urban growth models (Rozos et al. 2011). Of particular research interest would also be the investigation of the effect on the urban water system of additional policies targeting urban water demand, such as water pricing and the penetration of decentralised and more flexible smaller scale water technologies (Baki and Makropoulos 2011).

At a more general level, what is proposed in this work is an integrated modelling platform that links urban water and social simulation models at a higher modelling level via System Dynamics. In this approach the SD model represents the broader socio-economic, technical and natural environment, by capturing the main feedbacks that drive the system, and functions as a flexible modelling platform that links with more specialised tools for the estimation of domestic water demand. Water use behaviour and patterns of domestic water users emerge in a bottom-up manner from the agent based model that explicitly deals with the social simulation component. UWOT simulates the urban water cycle at a household level and links to both SD and ABM by providing household water demand values according to end-users' decisions. It is suggested that this modelling approach allows for the dynamic representation of the complete urban water system taking into account feedback loops between social, technical and natural components of the system. This in turn allows for a more explicit representation and investigation of decision making under uncertainty within continually changing environmental and anthropogenic conditions (Koutsoyiannis et al. 2009). An important additional benefit of this modelling tool is its ability to facilitate communication with and participation of stakeholders in urban water management. The modelling experiment presented in this paper indicates that the approach has significant potential as a policy testing and decision making "thinking platform" explicitly simulating the dynamic response of complex urban water systems under varying conditions and scenarios.

ACKNOWLEDGMENTS

The research has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Programme ”Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) - Research Funding Programme: Heracleitus II. Investing in knowledge society through the European Social Fund.

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