Computational Water, Energy, and Environmental Engineering, 2021, 10, 140-154
https://www.scirp.org/journal/cweee
ISSN Online: 2168-1570
ISSN Print: 2168-1562

On the Use of Agent Based Modelling for Addressing the Social Component of Urban Water Management in Europe

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How to cite this paper: Koutiva, I. and Makropoulos, C. (2021) On the Use of Agent Based Modelling for Addressing the Social Component of Urban Water Management in Europe. *Computational Water, Energy, and Environmental Engineering*, **10**, 140-154.
https://doi.org/10.4236/cweee.2021.104011

Received: July 22, 2021
Accepted: August 20, 2021
Published: August 23, 2021

Abstract

The paper aimed to provide a review of different tools that estimate how human behavior changes by water management strategies and quantify this change to support the decisions of urban water managers. To support decision makers, it is essential to be able to model the urban water system's human part explicitly and link it to the hydro system's response, rather than only explore the reaction of the system based on scenarios. To do so, tools are needed that can model the human part of the system, explore its reaction to potential changes and dynamically link back this to the techno-environmental model of the water system. This work reviews state-of-the-art ABMs that are publicly available focusing on the human part of the urban water system in Europe. The review leads to the proposals of three pillars for future development of ABMs for urban water management in Europe: end-user enablement; Machine Learning and Artificial Intelligence integration and adversaries modelling.

Keywords

Agent-Based Modeling, Urban Water Management

1. Introduction

Climate change, population change, resource limitations, ageing infrastructure, pollution, recent terrorist attacks and extreme sanitary needs—due to COVID-19 pandemic—put ever increasing pressures on urban water systems. While integrated urban water management requires the coordination of all the urban water system's parameters, decision makers have at their disposal tools primarily for the technical-environmental part of the urban system. Society is usually dealt with by exploring different scenarios [1].

So how can water managers decide what measures they should apply and how can they adapt their decisions to the changing urban water system? The answer could be an adaptive, integrative management of the total urban water cycle which may potentially secure resilience to future uncertainties arising from both climatic, infrastructure and social changes, thus increasing cities' livability [2]. To do so, urban water managers need methods and tools that will enable them to understand society's behavior and the way policy measures affect it [3].

The scientific community has developed hydro-informatic tools capable of addressing the technical-environmental side of the urban water system as realistically as possible [4]. To this end, the following presents a non-exhaustive list of tools that have been developed to:

- **Explore the water demand and supply balance** by assessing the metabolism of the urban water system [5], assisting long-term planning and policy assessment and development [6], supporting integrated urban water management [7], and modeling the entire urban water cycle from source to tap [8] [9];
- **Assess flood risk management in different levels of detail**, such as using a higher resolution model to support rapid flood analysis [10] or combine tools of 1D and 2D flood simulation engines that are able to address any flood problem [11]; and
- **Simulate the water network and management** by assessing the hydraulic and water quality behavior of pressurized pipe networks [12], or combining this with urban water planning engines to support urban water decision makers [13].

However, even these approaches fail to integrate into a model—and a simulation thereof—the dynamic behavior of humans making them unable to incorporate the effect of externalities, such as climatic, economic, and management conditions [14]. To be more precise, what is missing is the closing part of a loop process that links the social component behavior back to the technical-environmental components allowing water resources management to shift from integrated to adaptive by including all the dimensions of the urban water cycle under one overarching management regime [2] [15]. This enablement of bidirectional feedbacks between the social and the technical-environmental components is also examined by socio-hydrology which aims to understand the emergent dynamics of the complete socio-technical water system [1].

The difficulties of modelling the social component of the urban water system are unavoidable due to the "complex, nonlinear, path dependent and self-organizing" nature of human processes [16]. This complex adaptive nature of the human dimension of the urban water system is better modelled using Agent Based Modelling (ABM) which is capable to capture complex system characteristics and has been used to do so in many instances [17]-[22]. This is consistent with the growing realization that decision support systems for water resources management need to move into linking the socio-economic environment with both the engineering/technical infrastructure and the natural resources [4].

ABM core competency is that it can model bottom-up behaviors, simulating the microscale to derive the dynamic interaction between the social component and the urban water system and therefore, could become the link in the simulation process of the complete socio-technical system [17]. ABMs are made up of agents, defined as "computer systems located in an environment capable of acting autonomously within that environment to achieve all their objectives" [23]. Simply put, an agent has a set of characteristics as well as a set of rules that define its behavior so that it can respond to its environment and interact with other agents.

In more detail, the main attributes of ABMs [24] are:

- **Heterogeneity**: agents with different roles and different sets of behavioral rules.
- **Behavioral rules**: complex and random.
- **Learning and adaptation**: about their environment and the presence of other agents.
- **Interaction topology**: determining the influence between the agents.
- **Non-Agent Environment**: including initial conditions, background procedures, and communication to external to the ABM processes.

Furthermore, different types of agents can be used to model different types of human and societal groups. For instance, moving agents, with rules of movement or random movement, can be used to simulate humans trying to escape something or simulate randomness in the agents' interactions. These attributes allow ABMs to model human behavior through the simulation of micro-behavior and interaction. A recent review [25] identified ABM challenges as: standardization issues, with the ODD protocol [26] being used by many but not all ABM developers, model verification with different approaches being used to validate ABMs, and issues in identifying the outliers in model outputs.

This work aims to suggest ways forward for using ABM tools in urban water management. To do so, a bibliometric analysis of scientific literature has been employed to identify the state-of-the-art of ABM tools that have been developed and used for urban water management in Europe. Europe has been set as a boundary of this work due to the overarching legal and policy agenda of water resources management within the European countries. The main aim is to identify how these state-of-the-art ABMs pave the way towards modelling the complete socio-technical system simulation to assess the effects of policy and end-user driven interventions, such as water demand management, water markets, innovation uptake, etc. [4].

The following sections present: 1) the method used for the setup of the boundaries of the state-of-the-art and the selection and collection of the literature review, 2) the results of the review that produced a classification of the studied ABMs into different subject categories and 3) the discussion of the results that led to the proposal of the three pillars for future development of ABMs for urban water management in Europe.

2. Method

To define the use of ABM in addressing the human side of urban water management a thorough literature and ABM simulation models review was undertaken.

Initially a Scopus search, available in its entirety through the authors' institution, in Article Title, Abstract or Keywords was performed, and the resulting list of publications was downloaded. The query used when searching in Scopus is:

TITLE-ABS-KEY ("Agent Based Modelling") AND TITLE-ABS-KEY (water)

This search resulted in 1180 documents. The results were first assessed using spreadsheet data analysis functions and then were processed manually by the authors. This was possible due to the low number of the resulting list. The aim was to produce a list free of entries not relevant to the topic at hand. After cleaning the list and removing articles about land use (~10%), agricultural irrigation (~6%), serious games (~0.1%), review or discussion papers regarding the use of ABMs (~10%) and other outliers (~45%), the final list of documents consisted of 313 articles relevant to urban water and ABMs. This list was further cleaned by including only once articles of the same tool—presented in different stages of maturity or for different case studies. Additionally, from this list case studies outside Europe were identified, and removed from the final review list but were taken into consideration in the assessment, as a matter of completeness of ABMs addressing the social component of the urban water cycle. The final list consists of 21 publications (~2% of the initial results).

3. Results

The publications included in the resulting list were classified in two large hyper-components: water balance (76%); and flood risk (24%). These were then classified based on the social component modelled, and the specific subject matter they are dealing with. Three different subject matters were identified during the analysis: 1) water demand and supply management strategies; 2) diffusion of water saving or water reuse technologies; and 3) flood management strategies.

Figure 1 presents the classification of the results into these three different subject matters per social component modelled. As seen in **Figure 1** users of the water system are simulated in about 90% of all assessed ABMs that address water balance issues while flood relevant ABMs simulate both decision makers and users.

To assess the influence of the results, a ranking criterion was developed dividing the number of citations of a paper with the number of the maximum citations of the assessed publications. **Figure 2** presents the cumulative summation of the above scores per subject matter.

There are several ABM platforms that are being used by the scientific community. A search in the OpenABM database [27] showed that Netlogo [28] is the most used ABM platform, followed by Repast [29] or other Java based development platforms for ABM, Anylogic [30] and some other programming languages (C++, Python etc.) at the end of the curve.

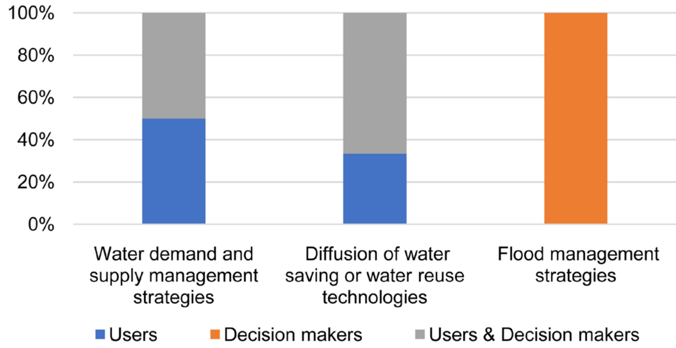

Figure 1. Classification of ABMs used for urban water management based on the specific subject matter and the society part modelled.

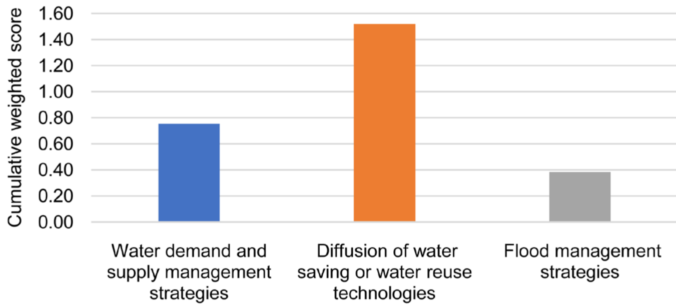

Figure 2. Ranking of different subject matters per cumulative weighted score.

Figure 3 presents the increasing trend of the annual occurrence of novel ABM models in publications counting only once publications of the same ABM even if the different steps of the ABM design and development process from conceptualization to application have been published.

Table 1 presents information on the assessed ABMs per subject matter providing: the rank of the model (as it was earlier estimated); the social component that the ABM models; the ABM platform used; and the water system model used. It is also worth mentioning that all models included in Table 1 had information relevant to the validation and verification process of the tool. Those works that did not include information relevant to the modelling framework are not included in the table but were included in the state-of-the-art assessment. It is worth noticing that most of the ABMs follow the ODD protocol [26] and include sensitivity analysis of their parameters, validation of results and even metrics of their efficiency (MAPE% etc.).

Water users are modelled using ABM to analyze and forecast household water demand [31] and to explore the effect of water demand management strategies on household water consumption [32]. Furthermore, [33], which is focused on an area outside Europe, developed an ABM simulating the users' behavior and how it affects energy and water consumption.

The combined behavior of water users and decision makers have been included in ABM to explore social learning [34]; implement econometric models of water behavior in the micro-scale [35]; estimate reservoir storage changes

Table 1. Indicative list of ABMs assessed relevant to urban water management in Europe.

Rank	Social parts	ABM platform	Water system model	Authors	Year
			Water demand and supply management strategies		
0.25	U & D	JADE	Integrated within the ABM	Athanasiadis I. N., Mentes A. K., Mitkas P. A., Mylopoulos Y. A.	2005
0.12	U & D	MASON	Integrated within the ABM	Mashhadi Ali A., Shafiee M.E., Berglund E. Z.	2017
0.11	U	Netlogo	UWOT	Koutiva I., Makropoulos C.	2016
0.09	U & D	Cormas	Integrated within the ABM	Moglia M., Perez P., Burn S.	2010
0.03	U & D	Unknown	MATLAB®-based HMETS hydrological (rainfall-runoff) model, MODFLOW, Climatic Scenarios	Bakhtiari P. H., Nikoo M.R., Izady A., Talebbeydokhti N.	2020
0.01	U	Anylogic	Integrated within the ABM	Alvi M. S. Q., Mahmood I., Javed F., Malik A.W., Sarjoughian H.	2019
			Diffusion of water saving or water reuse technologies		
0.90	U	Netlogo	Integrated within the ABM	Schwarz N., Ernst A.	2009
0.28	U & D	Repast	Integrated within the ABM	Galán J. M., López-Paredes A., Del Olmo R.	2009
0.06	U & D	MASON	Integrated within the ABM	Giacomoni M.H., Berglund E.Z.	2015
0.00	U	MASON	EPANET	Ramsey E., Pesantez J., Fasaee M. A. K., Dicarlo M., Monroe J., Berglund E. Z.	2020
			Flood management strategies		
0.14	D	Logo	TUFLOW	Jenkins K., Surminski S., Hall J., Crick F.	2017
0.00	D	Netlogo	Integrated within the ABM	Koutiva I., Lykou A., Pantazis C., Makropoulos C.	2020

U: Users; D: Decision makers; U & D: Users and Decision Makers.

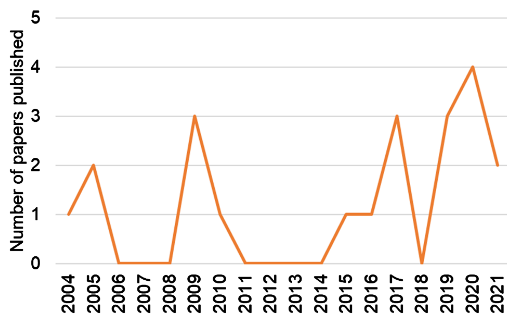

Figure 3. Annual occurrence of novel ABM publications relevant to urban water resources management.

using scenarios of water demand and supply [36]; explore the effects of urban water system changes to water availability [37]; select management strategies, compatible with society, to alleviate water deficit in a long-term horizon [38].

It is evident from **Table 1** that for this subject matter only in recent years, ABMs have started being coupled with specialized water management tools. This can be mainly attributed to the advancement of software applications, such as Docker, that enable the integration of different tools or the diffusion of programming languages that could be used as interfaces between the ABM and the water management tool. A special mention here is required to two ABMs that have been developed for urban water management experiments but are designed for areas outside Europe. In [39], Netlogo was coupled with QGIS and R to explore different water consumption behaviors in Amman, Jordan. Furthermore, in [40], Netlogo was coupled with a regional hydrologic model for Cape Town, South Africa to explore spatio-temporal scenarios for the Food-Energy-Water nexus.

Moreover, ABM is used to explore the diffusion of technologies for water reuse [41] [42] [43], rainwater harvesting [44] or water saving appliances [45]. To be more specific, in [45] scenario analysis of urban development is integrated with the diffusion of water saving technologies and the conservation behavior of urban households to assess scenarios of water consumption in Valladolid, Spain. Furthermore, in [44] an ABM was created to explore how a smart water grid would enable the sharing of rainwater resources in a distributed neighborhood system. Finally, an urban water management ABM has been developed that explores spatiotemporal patterns of domestic water use based on water demand management policies and the diffusion of water saving technologies [43].

ABMs in this subject matter use different ABM platforms and integrate into their majority, the environmental-technical component of the water system within the ABM. However, more recent ABMs integrate water specific tools, for instance EPANET [46] to link dynamically water demand behavior with network operation. These developments can be attributed as well to the developments of EPANET that allows the tool to exchange information with external software [47]. An ABM relevant to the diffusion of water saving technologies but outside the geographical scope of this work is that of [48] which integrated the SWARM platform with Matlab and VB to analyze the effects of the diffusion of water saving appliances and water reuse technologies to urban water consumption in Beijing, China.

In flood risk, ABM is used to explore the decision-making mechanisms of flood risk management [49] [50]. In this subject matter, it is more common to link specialized flood modelling tools with ABM (see **Table 1** flood management section). In [49], an ABM was integrated with a surface water flood risk model (TUFLOW) of London, to assess different adaptation options of both homeowners and decision makers and the role of flood insurance in the context of climate change. In [50] an ABM was created together with a user interface, to enable authorities to explore the effects of their decision making and their cooperation to their city's flood risk management.

A special mention must be made to the DAnCE4Water agent-based urban development tool created by the Cooperative Research Centre for Water Sensitive Cities (CRCWSC) of Monash University, Australia, linked to a 1D - 2D MIKE FLOOD hydrodynamic simulation to understand the effectiveness of adaptation strategies of water drainage system and urban planning policies [51]. Another recently developed model, with a case study outside Europe, coupled flood modelling with an ABM, using Repast for the ABM and MIKE Flood, to evaluate the effects of long-term flood risk management policies in Sint-Maarten [52].

4. Discussion

ABMs have been in a trajectory of development in recent years, although issues of quality, standardization and uniformity are still valid [25]. ABMs are used to address mainly urban water balance and innovation take-up and less flood management. The review about the state-of-the-art ABMs in addressing the human component of the urban water management identified that recently models tend to integrate with existing tools for the techno-environmental component of the system.

As a next step, it is proposed to move forward into making scientifically valid tools with measurable uncertainty and quantifiable efficiency, user-friendly enough for the common urban water manager. To do so, it is suggested to enable the decision-maker by either creating user-friendly interfaces or gamifying the ABMs to allow immersive learning. Adding to this, the ongoing development of the AI field should be taken into consideration when designing and developing new ABMs, with the aim to include these efforts and strengthen the abilities of the agents per se or the efficiency of the ABM. Finally, together with the digitalization progress of the urban water systems new challenges arise and these could also be explored by using ABMs to address issues of human threats in urban water systems. It is anticipated that even more ABMs will come of age in the next few years and the next step should be to become utilizable by the decision makers as well. The following paragraphs analyze, the above three main pillars that were identified as a way forward for ABM tools in terms of urban water management in Europe.

4.1. End-User Enablement and Gamification

Further to the strong research activity in establishing adequate tools for the simulation of the urban water system, it has been deemed necessary to create tools for the transfer of the generated knowledge [34]. The traditional educational tools, such as textbooks, are difficult to provide the required level of knowledge, due to their descriptive nature [53]. It is worth noting here that ICT tools play a key role in promoting new practices, enabling collaborative learning among different users through different practices. Social psychologists aim at explaining human behavior and social cognition, identity, attitudes, stereotypes, attributions, cognitive errors, decision making, conflict and navigation in the social world [54]. In accordance with social psychology, in decision analysis it is assumed that decisions are based on two pillars: beliefs and values. And while values reflect personal attitudes towards what is worth fighting for, beliefs can be greatly affected by expert and scientific knowledge. The rational person has been assumed to make decisions by weighing pros and cons. However, it is unrealistic for the social perceiver to use exhaustive strategies for making "scientific" and "logical" judgments. Instead, people (even scientists) often use heuristics or shortcuts that reduce to complex problem solving to simpler judgmental operations, to meet the pressing demands of the environment [55].

The emergence of new methodologies and educational tools and their combination with simulation tools, such as digital serious games offer a higher level of complexity in knowledge transfer [56]. These new developments may support water managers, who usually follow legislative instruments and their current approaches often are "trial and error" implementations that require new decisions every time a review point is reached and without a formalized plan for knowledge transfer and learning from current practices [57]. Serious games have been developed in the past to assist water management decision makers, mainly in their effort to raise awareness and educate water users on the value of water and the need to safeguard water resources.

The most known water game is, the Aqua Republica, developed by DHI and UNEP-DHI [58], which is an online serious game that has been mainly used to promote awareness and build capacity regarding water scarcity and water saving options in Universities and schools [59]. A review of serious games focusing on water resources management [60] showed that water games are gaining ground with most gaming applications dealing with river basin management, being highly simplified and requiring major facilitation by technical experts. Additionally, most user interfaces are often simple and do not take advantage of the sophisticated technologies available in the video games industry [60].

4.2. Coupling with ML Techniques

As the field of AI progresses, through the digitization of processes, the development of cloud services and the automation of data collection, it is anticipated that opportunities will arise for the progression of the application of ABM to urban water management.

In terms of data collection, the Internet of Things revolution brought data capture systems to production by improvements over their autonomy, reliability, connectivity, security, and interoperability. Smart meters and surrounding infrastructure will enable the processing of real time data sets to explore system operation and real-time water consumption [4]. Evidently, to enable IoT in urban water management ICT infrastructure is needed to develop, produce, and deploy AI and ML solutions. Furthermore, this infrastructure will require highly trained personnel in DevOps, data science and software development teams that can design, develop, and deploy high quality AI solutions and can also create dashboards and visualizations to communicate the results to the end-users. These IoT developments in urban water systems have already enabled researchers to predict water demand or create stochastic time series of water consumption [61] [62] [63] [64] [65].

The diffusion of smart meters and the collection of different spatio-temporal data sets of urban water demand and supply will enable the use of ML techniques in urban water management issues and enhance the projection quality of ABM tools. Existing applications of ML in ABM tools are applied to equip adaptive agents with experience learning or to analyze the outcomes produced by a given ABM [66].

4.3. Modelling of Adversaries

A preliminary literature review identified that there are ABM tools [67] [68] [69] [70] [71] that explore: the likelihood of an attack to a network; the strategies of attackers and how security may control them; cross sectoral cascading effects etc. These tools are focused mainly on the telecommunication sector. Future ABMs could explore another social component of the urban water system, that of the adversaries of the system, indicating people that either intentionally or not, create problems to the water system. The diffusion of IoT and the connection of critical assets to the network increase the vulnerability of the urban water system to cyber-attacks. While security protocols have been improved, it is crucial to identify vulnerable points of urban water systems to cyber-attacks. ABMs can be used to address this issue, by providing an experimentation platform to explore the bidirectional feedbacks between adversaries and the urban water system [72] and potentially linked to water management tools that model cyber-physical security resilience [73].

5. Conclusion

The performed state-of-the-art review regarding the use of ABM to address the human component of the urban water management identified that ABM is used primarily in urban water balance, innovation take-up and lees in flood management. ABMs tend to integrate water system processes with a few—and more recent—being integrated with existing tools. Three areas of development were proposed to support the decision-maker, which are: ways to support immersive learning, use of other AI techniques to improve the agents' cognition or the efficiency of the ABM, and to explore using ABM human threats in urban water systems. While more ABMs come of age, they could potentially play an important role in a decision-making support process, by being used to explore what-if scenarios to acquire knowledge regarding all the available decision options.

Acknowledgements

This research is co-financed by Greece and the European Union (European Social Fund—ESF) through the Operational Programme "Human Resources Development, Education and Lifelong Learning" in the context of the project "Reinforcement of Postdoctoral Researchers—2nd Cycle" (MIS-5033021), implemented by the State Scholarships Foundation (IKY).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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