Agent-based Modeling as a Decision Support Tool for Water Conservation Planning

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ABSTRACT

The paper presents a simulation approach to model water conservation campaigns by coupling agent-based and hydraulic models. The approach is unique as it incorporates modeling the communication strategies that can be used to promote water reduction measures. An illustrative case study is developed where households, represented as agents, are targeted through a mail-in and social media campaign that prompts them to consider adopting rain barrels. The water demands before and after the rain barrel campaign are evaluated through the EPANET2.0 hydraulic network solver in order to calculate the change in energy use stemming from the measures. The study found that 1.51 ML of water a day could be saved through the campaign however it would take 18 years to reach the adoption target using the proposed communication strategy.

Keywords: Decision Support; Water Distribution; Energy Reduction.

1 AGENT-BASED MODELING FOR DECISION SUPPORT

The following work proposes a systematic framework to evaluate water conservation measures through the use of simulation. The paper begins by discussing how the use of simulation, particularly agent-based models, can be used as a decision support tool for conservation planning. An illustrative case study is then developed in order to demonstrate how these principles can be applied. Undertaking socio-technical models that couple social behaviour and technical systems can help develop a better understanding of the consequences that human behaviour can have on infrastructure design and operations. These types of models are useful because they account for the complexity that arises when multiple stakeholders are involved in making decisions. The agent-based framework is also well suited to model complex systems [1] in which cumulative interactions can create feedback loops and emergent behaviour. The effect of policy decisions for example, water restrictions due to droughts or conservation campaigns can be modeled by representing the various stakeholders as agents. Agents are software entities that represent live or inanimate objects and are the fundamental building blocks in the agent-based modeling methodology (ABM). The agents are autonomous and are assigned a set of attributes and behaviours that describe their individual state. They are situated within an environment in which they can perceive, and from which they can receive signals that can trigger them to update their behaviour [2]. Two fundamental types of agents exist: active or reactive. Reactive agents do not update their behaviour, they only respond to their environment and events, while active agents can update their behaviours through interactions [2]. Active agents can also be goal-seekers which solve problems in order to attain their objectives [3] and can mimic human decision making processes using a variety of sub-models including econometric, social, cognitive, experience-based or threshold rules [4]. This study incorporates active agents that modify their behaviour based on peer pressure and through the influence of a conservation agent.

1.1 Evaluating Conservation Campaigns Through Simulation

This work develops a systemic approach meant to evaluate conservation strategies. Although the scope of this paper is limited to exploring a subset of residential conservation strategies, the framework could easily be extended to include a broader range of water users. The simple framework consists of undertaking a series of steps that are meant to establish conservation targets, test communication strategies and evaluate the effect of the program on infrastructure performance. The schematic presented in Figure 1 provides an overview of the framework. The first step consists of choosing the appropriate metrics in which the reductions are to be measured, water use, energy or greenhouse gas reductions. A number of conservation measures exist to achieve these reductions and can consist of technological solutions such as efficient fixtures, water recycling schemes or seek to modify individual behaviours such as turning the tap off when brushing your teeth, taking shorter showers, etc. Choosing a communication strategy is the next step within the framework. The communication strategy refers to how the information will be conveyed to the water users. There are a number of different strategies that conservation planners can utilize in order to communicate their message. A few examples that are popular among municipalities include radio and television advertisement, school education programs and offering rebates to residents for water efficient fixtures. The communication strategy plays a crucial role and often determines the success of a campaign. A successful communication strategy will result in a higher participation rate and increase the chances of attaining the reduction target. For this work, simulations are performed in order to model a particular communication strategy to promote the use of rain barrels in order to reduce outdoor water use. ABMs are ideal tools to create these simulations because agents can be imbedded with the ability to communicate with each other and change their behaviour once they have received information. A range of scenarios can be tested for different communication strategies in order to estimate reasonable timelines for a conservation target to be reached. Finally, the change in water use can be evaluated through the use of hydraulic models.

The following work seeks to demonstrate the use of a simulation framework used to systematically evaluate water conservation campaigns by coupling agent based and hydraulic models. The framework is then used to answer the following research questions:

1. What level of energy savings can be achieved at the network level through the widespread adoption of rain barrels within Kingston?
2. How long is it likely to take to reach the objective given a specific communication strategy?

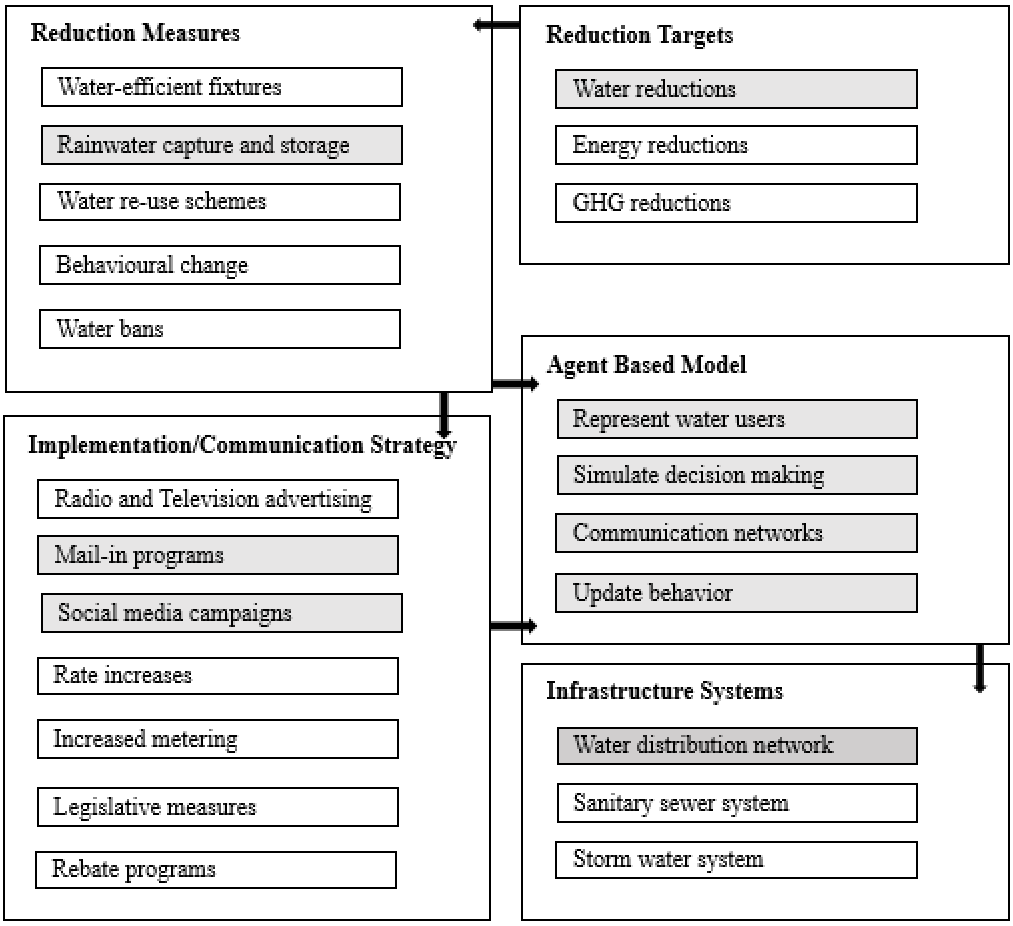

Figure 1: Framework to Evaluate Conservation Campaigns (grey shading indicates the strategies modeled for this paper)

2 METHODS

This illustrative case study presents a theoretical conservation campaign where residents from the City of Kingston were represented as household agents that were encouraged to purchase rain barrels. A conservation agent communicated with the household agents to inform them of the program. The communication strategy simulated two different approaches undertaken to promote the use of rain barrels. The first was to simulate the use of print-media. Every year the household agents were sent a message from the conservation officer prompting them to consider equipping their homes with a rain barrel. In addition to the print media campaign, a social media approach was modeled. The conservation agent communicated with a sub-set of household agents through social media. If the household agents purchased a rain barrel, they would share with two of their neighbors which would prompt them to consider purchasing their own rain barrel.

2.1 Agent-based Model

For this study, a community was simulated in which household agents were assigned a water end-use and a social model to simulate the change in water consumption over time. A previously developed ABM [5] was modified in order to incorporate outdoor water use to account for lawn watering. The Tourigny & Filion (2016) model uses an end-use model developed by Blokker et al. (2010) [6], although with some modifications, to calculate water use for each individual household. The end use model was modified in that flow rates for the given fixtures were deterministic rather than probabilistic and that diurnal patterns were excluded. The flow rates were based on typical values for both low-flow and regular fixtures and are explained in greater detail in Tourigny & Filion (2016) [5]. The model used in this work separates household water use into seven different end uses that represent common household fixtures: toilets, bathtubs, washing machines, dishwashers, taps and outdoor tap use. The daily frequencies in which the fixtures were used were dependent on the number of people residing in each household for all fixtures with the exception of the outdoor tap which was a function of lot area. The distribution of household occupancy was initialized to match the population of the case study. The household agents were connected to two other agents and a conservation agent. The connected agents could pass information to each-other and modify their behaviour upon receiving new information. In this case, the household agents considered equipping their households with rain barrels.

2.2 Outdoor Water Use

Average monthly daily demand for the month of July for outdoor water use was added to the Tourigny & Filion (2016) model. The month of July was taken because, historically, it has been the hottest temperature and the lowest precipitation amounts for the study area [7] leading to the highest outdoor water use. The outdoor use accounted for lawn maintenance and was calculated by assuming that 60% of residents water their lawn [8] and use 2.5 cm of water per week [9]. Lot sizes were determined using geographic information system (GIS) maps and were calculated by subtracting roof and driveways footprints from the total lot areas for each residential lot. The GIS maps contained zoning information and therefore only land parcels which contained residential dwellings were taken into account. Outdoor water use was also limited to single detached, semi-detached and row houses. Multi-residential complexes and apartment buildings were not accounted for in the model. Watering restrictions are imposed on Kingston residents whereas household may only water on every second days. The days on which the residents can water are determined by their civic addresses and thus lawn-watering customers were assumed to water every second day (3.5 times/week).

Table 1. Outdoor Water Use Parameters

Parameter	Value	Source
Population	32,000	[10]
Fraction of households that water lawns	0.6	[8]
Number of days per week for lawn watering[1]	3.5	
Average water amount per week	2.5 cm	[9]
Rain barrel capacity	210 L	[14]
Average lot area[2]	130 m²	
Average precipitation in July	64.3 mm	[7]

[1] Based on watering restrictions for the area
[2] Derived from GIS maps

2.3 Communication Strategy

The communication strategy was modeled using the ABM for a theoretical rain barrel program. Household agents were contacted directly by a conservation agent once a year with a message that prompted them to buy a rain barrel to save water designated for outdoor use. The fraction of agents that became aware of the leaflet campaign was based on a study undertaken by Howarth & Butler

(2004) [11]. In this study, the researchers found that when residents received a leaflet at their homes promoting water conservation behaviour only 17% of respondents remembered the campaign one month after they received it. A social media strategy was adopted in addition to the leaflet campaign that consisted of a conservation agent that communicated with a randomized subset of household agents directly to simulate communication through social media. The message prompted the recipient household agents to consider adopting a rain barrel. If the household agents adopted the new fixture when prompted through the social media message, they would communicate with two of their connections and try to convince them to do the same. The social media messages were sent four times every season from the conservation agent to 6,684 randomized household agents. The number of randomized agents that received the social media messages was chosen to match the number of Twitter followers held in the Utilities Kingston account. The likelihood that a particular household agent would adopt the barrel when prompted was probabilistic. The agents bought a rain barrel with a probability of 0.62 when prompted through the printed material and 0.02 when contacted through social media. In the absence of local data, the probablistic parameters were chosen based on results from a study undertaken by Silva et al. (2010) [12] which surveyed a number of water users from six American cities on a variety of topics relevant to communication strategies for water conservation campaigns. Results from the Silva et al. (2010) survey indicated that 62% of respondents would participate in a rebate program if given the option. 18% of respondents indicated having engaged in conservation behaviour after receiving promotional material through a mail-in program and 2% did so as a result of peer pressure. Ten iterations were performed for each experiment with different seed values to randomize results.

3 EXPERIMENTAL DESIGN

Four scenarios were tested to simulate different levels of adoption throughout the population of eligible households where an eligible household represented a household that engages in lawn watering. The change in demands were calculated using the ABM and the demands were modified from total water use demands provided by the city. The results were used to determine the total pumping requirements through the EPANET2.0 hydraulic solver [13] (Rossman, 2000).

3.1 Case Study: Kingston, ON

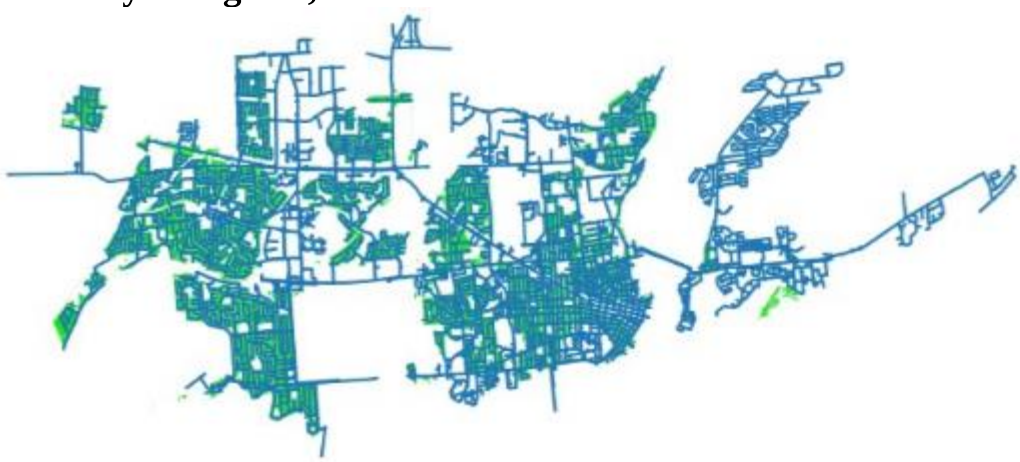

Figure 2. City of Kingston Water Distribution system

A case study was performed using the city of Kingston, Ontario, a mid-sized Canadian city located on the edge of Lake Ontario and the St-Lawrence River. The city's population was 123,363 in 2011 [10] , the last census year. The area is served by two water treatment plants that draw their water from Lake Ontario. The water and waste water services for the city are owned by the City of Kingston but privately operated by Utilities Kingston. The city's facilities also include five booster stations, 561 km of water main and eleven storage facilities [15]. The land area is approximately 450 km^2 with 53,838 private dwellings in 2006 [15].

4 RESULTS

4.1 Adoption Timelines

The number of rain barrels adopted based on the percentage of eligible household is shown in Table 2 along with the potential water reductions and the associated timelines. The results indicate that, based on the chosen strategy and the assumed effectiveness of the measures, it would take 18 years for 75 percent of the eligible households to purchase rain barrels. The adoption of 14,400 rain barrels could reduce average water use by 1.51 mega litres (ML) per day. Conversely, 1,920 rain barrels which would represent a 10 percent adoption rate would save 0.2 ML of water every day and could be achieved within two years.

Table 2. Adoption timelines and Water savings for the Rain Barrel campaign

Percentage of Eligible households	Total Barrels	(ML/day)	Associated Timelines
75	14400	1.51	18 years
50	9600	1.01	9 years
25	4800	0.50	4 years
10	1920	0.20	2 years

4.2 Energy Reductions

The water savings from the use of rain barrels generated different levels of energy savings which are shown on Table 3. The number of barrels that are used per day is half of the total rain barrels because only half of the population is assumed to water their lawn on any given day (due to the existing by-law in Kingston). When 10% of the population adopted the rain barrels (923 rain barrels), 0.22% of the daily energy use from pumping was saved. The amount increased to 1.6% or 315 kWh when 7,209 rain barrels were used.

Table 3. Water and Energy Use reductions

		Energy Savings	
Percentage of Eligible households	**Barrels in use/day**	**kWh-day**	**Percentage**
75	7209	319	1.60%
50	4806	222	1.11%
25	2403	124	0.62%

10	962	44	0.22%

5 CONCLUSION

The case study demonstrated the utility and functionality of an ABM to estimate adoption timelines for a conservation strategy that involved equipping homes with rain barrels. The communication strategy developed for this work was theoretical but was based on strategies that are widely used in municipal government. With the growth in data collection, an opportunity presents itself to monitor the effectiveness of conservation campaigns particularly through the use of social media. Data could be gathered which could then further inform assumptions about social behaviour. The framework presented in this paper could be used to test a variety of scenarios for different conservation campaigns to evaluate their effectiveness at reducing water and energy use.

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