Research Paper

A cellular automata modelling approach in household water use
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ABSTRACT

This paper explores the strength of simulation techniques in water conservation by employing a Cellular Automata (CA) modelling framework. The CA-based model allows the examination of various scenarios with different hypotheses in the context of water resources management in Egypt. Moreover, sensitivity analysis is applied to test the robustness of the model’s results. The empirical results show that both social media posts as well as the fear of building the Renaissance Dam in Ethiopia play a motivational role to encourage the individuals to conserve water in Egypt. This is supported by the effort of the most effective and influential categories (family, friends, and relatives, according to the results of the current study) because they are identified as the major influencers on the surrounding people in their social networks. For the results of sensitivity analysis, there is no significant difference between the results of implementing the model and the results of sensitivity analysis.

Key words | cellular automata, Egypt, Renaissance Dam, social media, water conservation

HIGHLIGHTS

- the importance of simulation models in social sciences.
- the role of CA models in water conservation problems.
- the extension of SNA into CA modeling approach.
- testing hypotheses and scenarios of reality.
- testing the robustness of model’s results.

INTRODUCTION

The strategic planning and management of water resources has become a crucial issue and a priority for policymakers on various scales, from the national scale to the global one, especially with the rapid increase in population growth which imposes great pressure on water demand. Furthermore, the nexus between water resources management and Sustainable Development Goals (SDGs) makes the concerned authorities of water resources management think creatively as to how to achieve the best allocation of water resources in various uses, either in agriculture, industry, or households. For Egypt, the situation is critical in the sense that the main source for Egyptians to get fresh water is from the Nile river with a 96% dependency ratio. Besides the high growth rates of population in Egypt, the per capita share of water decreases over time to reach 500 m³/year in 2025 which leads to increasing water scarcity in Egypt according to the Ministry of Water Resources and Irrigation of Egypt in 2014. The limited water supply with high water demand results in mismatching between them and reaching ‘water scarcity’ (Omar & Moussa 2016).
Accordingly, various approaches are proposed to manage water supply and water demand. This paper is concerned with the management of water demand. Many approaches are determined to accomplish the best allocation of water resources and to reach the optimal management of water demand. Ashour et al. (2009), Abdelgawad et al. (2010) and El Bedawy (2014) compiled these approaches as follows: 1. The transition to cultivating crops which consume less water; 2. Improvement of irrigation methods; 3. Awareness campaigns to encourage the individuals to conserve water; 4. Pricing water, polluter-pay, and user-pay principle should be applied; 5. Participatory irrigation and the shift toward privatization through enhancing farmer’s participation and reducing government intervention; and 6. Introducing a set of incentives such as land or crop taxation, and subsidies for water conservation purposes. The main focus of this paper is on the third approach to allow the individuals to be a part of the problem-solving cycle through highlighting the social influence of the surrounding networks using the Cellular Automata (CA) modelling framework.

Cellular Automata (CA) can be defined as ‘a rule-based computing machine, which was first proposed by von Neumann (1951), and the systematic studies were pioneered by Wolfram (1983, 1984)’. It is a type of dynamical system because its output is generated in discrete time. The behaviour produced by CA is updated by executing a set of very simple rules (Yackinous 2015). Many applications of CA exist for water resources planning and management. Kandiah et al. (2016) developed a CA modelling framework to simulate the consumer reclaimed water adoption, the associated demand changes, and the emergent hydraulics in both drinking and reclaimed water systems to provide insights for the planning process. Their CA-based model aimed to allow households to use reclaimed water, and these households can make decisions about the volume of reclaimed water to use in the town of Cary, North Carolina.

Both Wang et al. (2010) and Nikolopoulos et al. (2018) discussed the spatial dimension of the water resources context from different perspectives. Wang et al. (2010) deployed CA models for forest water conservation by taking the spatial heterogeneity into consideration to improve the quantitative evaluation of forest water conservation at different spatial scales, and also to provide an effective quantitative way of forest water conservation with different spatial distribution patterns of various forest types. Nikolopoulos et al. (2018) proposed a CA model to assist urban water strategic planning by focusing on external drivers and the allocation dynamics variability via stochastic internal mechanisms. Furthermore, the spatial dimension was taken into consideration in order to provide the means of its straightforward extension and reproducibility. In addition, the interaction between surface water and groundwater by the CA model was studied by Ravazzani et al. (2010) in the context of water resources planning and management. They aimed to simulate water exchange between the surface soil, the river network, and the underlying aquifer to examine the stability and convergence.

The CA model in the present study extends the study of Salman et al. (2018) in which Social Network Analysis (SNA) was used to identify the most influential actor(s) to encourage people to adopt water conservation behaviour. The extension of the present study using CA takes into account the effect of social media posts and the threat of building the Renaissance Dam in Ethiopia as external factors into the analysis. According to the report of Los Angeles Times (Islam 2019) in 2019 of ‘The Ethiopians are building a massive dam, and Egypt is worried’ and the report of Foreign Policy (Harb 2019) in 2019 of ‘River of the Dammed’, Egypt perceives building the dam as ‘looming threat’ to its water security and to its national security. So, the main objective of the present CA-based model in the current study is to identify the most effective category with the existence of these two external effects (i.e. social media posts and the threat of building the Renaissance Dam in Ethiopia). This objective cannot only be obtained by SNA as the study of Salman et al. (2018) should be repeated with the new objective which is very time-consuming and costly. Building an artificial society and simulating the new objective helps us to extend the analysis with many scenarios under various assumptions which will be demonstrated in the Methods section below in more detail.

The paper is organized as follows. A brief introduction of the CA modelling framework and how to apply it to fit the objective of the current study is elaborated in more detail in the sub-section ‘Cellular Automata (CA) model’. The extensive illustration of CA model implementation and the process overview is discussed in ‘CA model implementation and process overview’. Applying sensitivity analysis to test the
robustness of the results is shown in ‘Sensitivity analysis’. The main results and discussion of implementing the CA modelling approach on water conservation in Egypt and the results of sensitivity analysis are shown in the ‘Results and discussion’ section. The conclusions are presented in the final section.

METHODS

Cellular Automata (CA) model

Wolfram (2002) and Gilbert & Troitzsch (2005) defined CA model as a representation of the real world in a uniform grid, time passes by steps, and the ‘laws’ of the world are represented by a uniform set of rules which determine the state of every cell from its own previous state and those of its direct neighbours.

It has five main characteristics as Schiff (2011) elaborated. These characteristics are: 1. The grid consists of a number of identical cells. These cells can be either individuals, countries, firms, and universities; 2. Each cell can take one of the few possible states, for example, ‘on’ or ‘off’, ‘alive’ or ‘dead’. In addition, the cell’s state may also represent attitudes, actions, or individual’s characteristics; 3. Time passes through steps. At each time step, the cell’s state may change; 4. A set of rules is determined to specify how the state of every cell is changed and how the cells interact with each other; 5. Cellular automata are best used when the interaction is local.

In the present study, the CA model is applied using the Netlogo platform (Wilensky 1999). The cell represents the individuals from the household sector. These individuals belong to one of five possible categories (family, friends, relatives, lecturers, and religious institutions) as indicated in Table 1. The cell’s state takes the form of influencing the surrounding cells to conserve water in Egyptian society. The time is passed by ticks in Netlogo. Each cell interacts with the surrounding eight neighbours according to the Moore neighbourhood. The rule on which the cell interacts with its Moore neighbourhood is the majority voting rule such that the cell will choose and imitate the most influential category to conserve water when the majority of its neighbours also chooses and imitates this category. The majority in the present model is based on the similarity percentage inspired from the Schelling segregation model (Wilensky & Rand 2006). If the majority percentage of

| Table 1 | State variables of cells and surrounding environment |
|-----------------|-----------------------------------------------|
| **Cell variables** | **Environment variables** |
| With? | Slider: to examine the effect of the majority's opinion on changing my own |
| Vote | A random variable which takes value either 0, 1, 2, 3 or 4 to represent the category to which the individual will choose and imitate: {0: family, 1: friends, 2: relatives, 3: lecturers, and 4: religious institutions} |
| Nahda-dam | A random variable which takes value either 0 or 1 such that 0 represents the individual who is afraid of building the Renaissance Dam in Ethiopia and 1 otherwise |
| Social-media | A random variable which takes value either 0, 1 or 2 to represent the strength of social media posts on adopting water conservation behaviour, where 0 reflects the low effect, 1 reflects the medium effect, and 2 reflects the high effect of social media posts |
| Water-cutting-hours | A random variable which takes value either 0, 1 or 2, … or 24. An assumption is made to include possible regions into consideration such that 0 is used for whom the water is always available, 7 is used for whom the water cuts less than 12 hours, and 20 is used for whom the water cuts greater than 12 hours |
| %similar-wanted | Slider: the percentage of the population who chooses the family's category |
| Family-density | Slider: the percentage of the population who chooses the friends' category |
| Friends-density | Slider: the percentage of the population who chooses the relatives' category |
| Relatives-density | Slider: the percentage of the population who chooses the lecturers' category |
| Lecture-density | Slider: the percentage of the population who chooses the religious institutions' category |
similar neighbours exceeds the threshold percentage (i.e. specific majority percentage of similar neighbours determined by the author), the cell will follow the opinion of the majority to choose and imitate a specific category in the context of water conservation. In the current study, two majority percentages of similar neighbours are examined: a low majority percentage of similar neighbours (represented by 25%) and a high majority percentage of similar neighbours (represented by 90%).

**CA model implementation and process overview**

The model begins by classifying the individuals randomly into five categories with different colours; [family: pink, friends: red, relatives: blue, lecturers: yellow, and religious institutions: green] according to the procedure of ‘re-colour-patches’. Within every category, the three variables (Nahda-dam, Social-media, and water-cutting-hours) are also randomized within their associated ranges as demonstrated in Table 1.

By running the model with those who support water conservation behaviour, the update-patches procedure is activated. Every individual counts the number of surrounding neighbours who have the same colour of self and calculates its similar neighbours’ percentage from the total neighbours. If this calculated percentage exceeds the threshold percentage determined by (%-similar-wanted) slider in the interface, the individual will check the effect of the threat of building the Renaissance Dam in Ethiopia, social media posts, and the nature of water cutting hours in his/her district. This will lead us to formulate the micro-interaction rules to identify which category, mentioned above under the section ‘Cellular automata (CA) model’, has the largest proportion of influence to support water conservation behaviour in Egyptian society. Table 2 summarizes the possible combinations of configuration rules in the present model.

These combinations are tested through two hypotheses:

H₁: Only social media posts can affect the individual’s behaviour to conserve water in Egypt.

H₂: Social media posts as well as the fear of building the Renaissance Dam in Ethiopia can affect the individual’s behaviour to conserve water in Egypt.

These two hypotheses are explored when the similarity percentage is 25 and 90%, respectively, with different scenarios as follows.

1. When the majority percentage of similar neighbours determined is low: 25%

Scenario 1.1: no effect of religious institutions to adopt water conservation behaviour and other categories are ranked as follows: the influence percentages of family and friends are 36%, and the influence percentages of relatives and lecturers are 24%.

Scenario 1.2: every category mentioned above under section ‘Cellular automata (CA) model’ influences the adoption equally by 50%.

Scenario 1.3: the influence percentages are: family and friends are 36%, relatives and lecturers are 24%, and religious institutions are 4% (Salman et al. 2018).

| Table 2 | Possible combinations of configuration rules in the present model |
|---------|---------------------------------------------------------------|
| Condition | Nahda-dam | Social-media | Water-cutting-hours | Response |
| If the percentage of similar neighbours exceeds the threshold percentage determined by (%-similar-wanted slider)*. In other words, if the percentage of surrounding neighbours in the Moore neighbourhood with the same colour of myself is greater than either 25 or 90% with every value of other parameters in the second, third, and fourth columns, respectively, the response elaborated in the fifth column will be executed | 0 or 1 | 0 | 0 | Change my own colour to match the colour of the majority in the surrounding Moore neighbourhood |

*This study depends on the similarity percentage to allow the individual to take a decision for water conservation. This parameter is inspired from the Schelling segregation model.
2. When the majority percentage of similar neighbours determined is high: 90%

Scenario 2.1: no effect of religious institutions to adopt water conservation behaviour and other categories are ranked as follows: the influence percentages of family and friends are 36%, and the influence percentages of relatives and lecturers are 24%.

Scenario 2.2: every category mentioned above under ‘Cellular automata (CA) model’ influences the adoption equally by 50%.

Scenario 2.3: the influence percentages are: family and friends are 36%, relatives and lecturers are 24%, and religious institutions are 4%.

Zero-influence of religious institutions is a hypothetical ranking or a claim to see which other categories will occupy an effective position to influence water conservation in Egypt rather than the religious institutions. Even though there are many pieces of evidence of the effective role of praying institutions in water conservation programs in Egypt, the author would like to exclude the effect of these praying institutions from politics, and to examine which other categories compete for their role in this context. Concerning the influence of 4%, it is adapted from the findings of the study of Salman et al. (2018) and it is considered as a given in the present study to examine its consequences in the water conservation context using the CA-based model.

Sensitivity analysis

Sensitivity analysis, according to Chattoe et al. (1997), refers to the capability to change and vary the input values of the model for the purpose of model validation and testing the robustness of the model’s results. Chattoe et al. (1997) and Alden et al. (2014) showed three techniques for sensitivity analysis: parameter robustness which examines whether combining the set of parameters allows getting the desired model’s results, verification of the initial configurations of the simulation model are the best ones, and verification of the model’s results whether they could be obtained similarly if the model is run several times with the same parameter values. In the present study, the third technique of sensitivity analysis is followed.

To perform sensitivity analysis with the scenarios mentioned above under ‘Cellular automata (CA) model’, a set of steps are executed to see how the model responded via BehaviorSpace in Netlogo. First, the values of variables are varied as follows:

- [%-similar-wanted" 25 90]
- ['lecturer-density" 24 50]
- ['relatives-density" 24 50]
- ['friends-density" 36 50]
- ['family-density" 36 50]
- ['religion-density" 0 4 50]

Second, the model produces outputs for ten repetitions. Then, the average of these ten repetitions is taken to be compared with the previous outputs of the model. Third, the repetitions are run for 40 steps because the behaviour does not change and the model reaches its steady-state after 40 steps. Fourth, the results of these ten repetitions are exported into a csv file. The total number of runs is 960 runs to obtain the output of sensitivity analysis for the present model.

RESULTS AND DISCUSSION

Results of implementing CA-based model

By following rules and scenarios demonstrated above under ‘Cellular automata (CA) model’, the emergent pattern and the most influential category are identified. When the majority percentage of the similar surrounding neighbourhood is low (i.e. 25%), diversification of the most influential categories is observed. When the selected five categories started the simulation model with the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 0%), family, relatives, and friends are categorized as the greatest influencers when the role of religious institutions disappears. By initializing the model with equal influence percentages of the five selected categories (i.e. 50% per category), only friends can influence the individual’s
behaviour. However, when the model is initialized by the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 4%), only religious institutions can affect the water conservation behaviour of Egyptians.

When the majority percentage of the similar surrounding neighbourhood is high (i.e. 90%), the situation becomes different. When the selected five categories started the simulation model with the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 0%), relatives are categorized as the greatest influencers when the role of religious institutions disappear. By initializing the model with equal influence percentages of the five selected categories (i.e. 50% per category), only friends can influence the individual’s behaviour. However, when the model is initialized by the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 4%), family and lecturers can highly affect the water conservation behaviour of Egyptians. Figure 1 shows these results.

By combining the effect of both social media posts and building the Renaissance Dam in Ethiopia, the ordering of the most influential categories to encourage Egyptians to conserve water is changed. When the majority percentage of similar neighbours is low (i.e. 25%), family and friends are categorized as the greatest influencers when the selected five categories started the simulation model with the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 0%). Family, in addition to relatives and religious institutions, can highly influence the individual behaviour by initializing the model with equal influence percentages of the five selected categories (i.e. 50% per category). However, when the model is initialized by the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 4%), only lecturers can highly influence the individual behaviour. Figure 2 shows these results.

By increasing the majority percentage of similar neighbours to be 90%, relatives occupy the highest ranking to influence the individual’s opinion to conserve water when the selected five categories started the simulation model with the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 0%). By initializing the model with equal influence percentages of the five selected categories (i.e. 50% per category), only family and friends impose a high impact on others. However, relatives returned to the competition besides the role of family when the model is initialized by the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 4%).

Thus, not only social media posts can shed light on the importance of water conservation in Egyptian society and

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**Figure 1** | Examination of social media effect when the similarity percentage is low (a) and when the similarity percentage is high (b).
therefore can affect the individual behaviour to allocate water usage efficiently, but also the fear of building the Renaissance Dam in Ethiopia can do so. Accordingly, $H_2$ is confirmed and supported by reaching these results.

**Results of sensitivity analysis**

To check the robustness of the results of the selected parameters elaborated above under ‘Results of implementing CA-based model’, the sensitivity analysis is conducted and the average of the ten repetitions yields the following results. When the majority of the similar surrounding neighbourhood is low (i.e. 25%), friends, family and lecturers are categorized as the greatest influencers when the selected five categories started the simulation model with the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 0%). By initializing the model with equal influence percentages of the five selected categories (i.e. 50% per category), friends with relatives and religious institutions can highly influence the individual’s behaviour. When the model is initialized by the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 4%), only friends can highly affect water conservation behaviour of Egyptians.

When the majority percentage of the similar surrounding neighbourhood is high (i.e. 90%), the results can be described as follows. Only family is categorized as the greatest influencer when the selected five categories started the simulation model with the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 0%). By initializing the model with equal influence percentages of the five selected categories (i.e. 50% per category), friends with relatives and religious institutions can highly influence the individual’s behaviour. When the model is initialized by the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 4%), only friends can highly affect water conservation behaviour of Egyptians. Figure 3 shows these results.

By taking into consideration both the effect of both social media posts and building the Renaissance Dam in Ethiopia, the sensitivity analysis produced the following results. When the majority percentage of similar neighbours is low (i.e. 25%), friends and lecturers are categorized as the greatest influencers when the selected five categories started the simulation model with the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 0%). By initializing the model with equal influence percentages of the five selected categories (i.e. 50% per category), relatives in addition to the family and religious institutions can highly influence

![Figure 2](https://iwaponline.com/washdev/article-pdf/doi/10.2166/washdev.2020.035/711690/washdev2020035.pdf)
the individual's behaviour. However, relatives and lecturers can highly influence the individual's behaviour when the model is initialized by the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 4%). Figure 4 shows these results.

By increasing the majority percentage of similar neighbours to be 90%, the results are described as follows. Family with relatives occupy the highest ranking to influence the individual's opinion to conserve water when the selected five categories started the simulation model with the following influence percentages (family: 36%, friends: 56%, relatives: 24%, lecturers: 24%, and religious institutions: 0%). Friends, relatives, and lecturers impose a high impact on others by initializing the model with equal influence percentages of the five selected categories (i.e. 50% per category). Friends with family and relatives can highly influence water conservation behaviour when the model is initialized by the following influence percentages (family: 36%, friends: 36%, relatives: 24%, lecturers: 24%, and religious institutions: 4%).

Therefore, very small differences between the results of the model's implementation above under 'Results of
implementing CA-based model’ and the output of sensitivity analysis in this sub-section. Some categories maintain its influential role in water conservation behaviour, while others are altered. However, this change does not have any crucial and significant impact when policymakers are targeting them to diffuse awareness of water conservation behaviour. In other words, the sensitivity degree of the model’s results is very low. This is supported by conducting the T-test to examine whether there is a significant difference between the results of the model’s implementation and the output of sensitivity analysis. The statistical test indicates that there is no significant difference between them which implies that policymakers can depend on either the output of the model or the output of sensitivity analysis to deliver messages and to increase the awareness of how to conserve water in Egypt.

By employing a novel CA model for water conservation in Egyptian society, a number of implications and recommendations are suggested on various levels; social, educational, legal, and political levels (El Bedawy 2014) and (Abdelgawad et al. 2010). On the social level, family, friends, and relatives are considered as the largest influencers to encourage the surrounding individuals to conserve water and to contribute to efficient water usage. So, these three categories are the starting point to begin the awareness campaigns in this context. The inclusion of these categories in water resources planning and management becomes crucial to achieve the best allocation of water resources in Egypt.

On an educational level, the extensive awareness of water issues in schools and universities should be taught through comprehensive courses by specialists and experts to reinforce the role of the influential categories in society. On the legal level, the need to set a legal framework to support the effort of other institutions is necessary by imposing penalties and fines on the individuals who pollute water resources. On the political level, the possibility of public diplomacy mechanisms such as professional labour unions, student unions, parliament, and political parties should be activated. The regional and world forums, such as the World Youth Forum (WYF), also share expertise in water issues from different perspectives. Water pricing policies may support the balance between water demand and water supply depending on the principle of cost recovery. This may compensate a small part of the governmental expenditure which is directed to this kind of service for its individuals.

CONCLUSIONS

In this study, the CA-based model is applied to explore the strength of simulation techniques in the context of water conservation in Egypt, and to examine various scenarios and hypotheses in this social phenomenon. The results of the current study show that family, friends, and relatives are considered as the largest influencers to encourage the surrounding individuals to conserve water and to contribute to efficient water usage. The role of these categories is supported by the influence of the two external factors used in the current study (i.e. social media posts and the fear of building the Renaissance Dam in Ethiopia). In other words, the second hypothesis is confirmed because not only social media posts can shed light on the importance of water conservation in Egyptian society and therefore can affect the individual behaviour to allocate water usage efficiently, but also the fear of building the Renaissance Dam in Ethiopia can do so.

Moreover, the results of sensitivity analysis imply that there are very small differences between the results of the model’s implementation and the output of sensitivity analysis. Some categories maintain its influential role in water conservation behaviour, while others are altered. However, this change does not have any crucial and significant impact when policymakers are targeting them to diffuse awareness of water conservation behaviour. In other words, the sensitivity degree of the model’s results is very low. This is supported by conducting the T-test to examine whether there is a significant difference between the results of the model’s implementation and the output of sensitivity analysis. The statistical test indicates that there is no significant difference between them which implies that policymakers can depend on either the output of the model or the output of sensitivity analysis to deliver messages and to increase the awareness of how to conserve water in Egypt.

This paper is restricted to illustrate the role of simulation in the management of water demand by introducing a novel CA model in the household sector in Egyptian society. This is achieved by highlighting the effect of social media posts and the negative perception of building the Renaissance
Dam in Ethiopia. This work can be extended by taking into consideration water quality issues and other water resources such as the relationship between surface water and groundwater to obtain a comprehensive picture of water issues in Egypt.

DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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