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Agent-based models as a strategy for water resources management with sustainable development perspective

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ABSTRACT

Regarding the increase in water extraction from limited sources and future generations' demands, the importance of sustainable development is significantly increasing. Moreover, growing competitions over these limited sources have caused major conflicts. In the present study, agent-based models alongside other approaches such as economic issues have been presented as an efficient strategy and complementary instrument in order to solve water resource management crises with a sustainable development perspective. In the following sections, the general structure of these models, their importance in managing water resources, their application, restrictions and advantages will be discussed. **KEYWORDS**: agent-based models, conflict, sustainable development, water resource management.

1. INTRODUCTION

Heterogeneous distribution of water resources in terms of location and time, and human's inappropriate exploitation of these resources have caused a variety of issues for managing these valuable resources. Water has been used to supply different ranges of needs and objectives, such as power generation, entertainment, environmental preservation and etc. in fact, this multipurpose nature of water exploitation has led to conflicts among its different users. Consequently, a professional socio-systematic analysis seems to be necessary to manage and overcome these conflicts.

Agent-based models can efficiently operate as a solution through stimulation of different aspects of all the usages [1]. Although these models are relatively modern, they have become an efficient tool for analyzing, modeling and stimulating complicated systems recently [1]. These models function as basis for modeling the social interactions among users which are affecting each other [2]. An agent-based model provides a tool to express social decision making processes [3] and to stimulate users' actual behavior by specifying their relationship.

In the current water resources management models to deal with water allocation issues, all the areas are considered one system, and the amount of allocated water is considered a decision variable in a mathematical optimization model which functions as an optimizer. However, in the reality, each user can decide only based on his personal interest and not necessarily the whole system. If a number of decision variables increases, issues get even more complicated; specifically when the objective function is non-linear. Therefore, considering an accurate universal representation, as to reduce complex calculations, multi-agent based models have been taken into account.

The agent based model theory originated from computer science and artificial intelligence [4]. An agent is considered an independent unit in a system, which can interact with others under a set of behaviors. In this system, agents can exploit water resources only in their own interests [5]. The consumers' decisions which are restricted by regulation of management and environmental limitations can be affected by others' decisions.

1.1. REVIEW OF LITERATURE

The first agent-based modeling was developed by Thomas Schelling in 1978 as a segregation model. In this stimulation, people can be defined as agents able to interact with each other.

Izquerdo et *al* developed an agent-based model, named FERLUS-W for prioritizing the beneficiaries [6]. This model is the extended version of Polhill *et al* FEARLUS model [7]. Edwards *et al* evaluated the interactions of an integrated water consumption model against an agent based model, according to available information sources [8].

Galán *et al*, developed an agent-based model for managing Spain water resources [9] and Zachman proposed a multi agent based model which was a combination of agent based, mechanical and dynamic procedures for simulating pollution events [10]. Kock used an agent based model in a socio-hydrology system in his study [11], he developed two social – hydrological agent based systems in Spain and the U.S to evaluate the social effects of adding another organization to other water management organizations. Soman *et al* also developed several models for identifying

farmers' behavior in selecting their agricultural products [3]. Kennedy *et al* developed an agent based model for stimulating the conflicts between pastoralists in North Africa [12].

Joe *et al* developed a domestic water use model as the domestic water managing instrument to evaluate and water consumption policies and expanding the future infrastructures [13]. Bettle *et al* used agent based model concept to develop a multi-actor based model in order to stimulate water supply decision making processes; they applied this model to specify the critical areas to assess the needs for water supply, regarding the climatic effects. Nikolick *et al* stimulated a dynamic system and an agent based model through temporal and spatial analysis, in order to integrate the water resources [14]. Other examples of applications of agent based models in water resources are that Hare employed an agent based model to control agricultural water pollution [15], Berger used this model for the farm lands and water resource management [16], Tillman used it for extending a water supply system [17] and Bars used it for the basin management and water resource allocation [18]

2. MATERIALS AND METHODS

2.1. Sustainable development and the dynamic system in managing water resources

The concept of sustainable was introduced by Thomas Robert Malthus in 1798. The unjust and unequal exploitation of natural resources between two generations (current and future) makes it difficult to achieve an ideal society [19]. In 1987, *World Commission of Environment and* Development announced that in a comprehensive perspective, the purpose of sustainable development strategy is to create a compatibility between human and nature. According to the *World Commission of Environment and* Development, human has the ability to manage sustainable development to supply the current demands without neglecting the future generation needs. Thus, sustainable development requires [20]:

- A political system which efficiently supports citizens' decision making security.
- An economic system able to provide extra sources in a context with sustainability attitude.
- A social system which supplies tensions arising from the uncoordinated development.
- A consumption system which protects ecological context relying on regulations.
- A flexible management system with auto correction ability.

The notion of sustainable development and its application in water resource management is an issue which has been over emphasized during the recent years. Therefore, receiving feedbacks related to water resources which are established by indicators and criteria development seems to be necessary. In fact, sustainable development is a program of actions, a set of principles and thinking methods related to human activities' patterns, which deals with the world mechanism using different approaches and the current knowledge. Although all the dynamic elements are in contradiction, they adapt to each other in a way that preserves sustainability of system. According to the presented theories, sustainable development refers to a kind of development which does not interrupt future generation requirements while supplying the current generation's demand. This theory emphasize on the negative and unpredictable social and environmental consequences on sustainable economic development.

A lot of efforts have been made in order to organize the sustainable development principals in different sections including eater resource management. Although these efforts are undeniable to reach sustainable developments in a long term, constant improvement of the human's activities in accordance with environmental changes and strengthening the capacities are also necessary. In this regard, using trial and error would be required to achieve a sustainable development. Effective feedbacks and the ability to response to the suitable changes in economic activities and human societies play crucial role in sustainable human activities with other involved elements, which is in fact the key solution. Specifically, feedbacks are very important elements in environment sustainability. Sustainable access to healthy water is one of the primary basis for the next generation's welfare. The world water cycle and effecting factors on the flowing waters and earth's crust, create natural capacity for water resources.

Water accessibility changes during time and in different locations. In many places, water resources are at a premium, resulting in a low performance of soil and water ecosystems. On the other hand, there are plenty of water resources in some places in which meeting humans' need on one side and the industrial water consumption on the other side cause challenges for water managers. During the centuries, the water resource management has been trying to find a way to use water resources to benefit human societies. However, a lot of actions taken to control water have brought about undesirable and unexpected consequences in long term [22].

2.2. The structure of agent based models

All of the agents are independent in these models and consist of a set of specific knowledge and information, while they can interact with other agents and their shared context. The agents are purposeful, as they can operate in the environment and react to policies and economic situations of the surrounding area [22]. They are specified by the characteristics, behavioral rules, their resources and experiences. An agent can be any independent sector such as a group, an organization and etc. [23]. People or groups of people are considered agents in the agent based models with social processes and their relationships are considered social processes of interactions [24].

An environment which interacts with agents contains simulated elements which are not covered by agents' groups and determine the overall dynamicity of the system and factors affecting the agents [1].

The essential steps to create an agent based model is as follows:

- 1. Identifying agents
- 2. Specifying their distinct behavior

- 3. Specifying the living environment of the agents and has interact with
- 4. Specifying the agents' relations and developing a theory related to their interactions with their context and with each other
- 5. Developing essential users' information
- 6. Proper expression of agents' interaction with other agents or agent with the environment
- 7. Validate the agent's behavioral model

2.3. Categorizing the agents' behavior and their interactions

Bandini divided the agents' behavior into reactive and deliberative. Reactive behaviors are those in response to the context behaviors with agents; and the deliberative behaviors which are more complicated than the other group, are based on each agents' knowledge from the context and its previous experiences. There is also a third group, hybrid group, which is a combination of these two groups.

Agents' behavior can be also divided into direct and indirect, that is in contrary to the direct behavior, an intermediary institution causes the behavior.

Fig 1 shows a schematic of an agent based model. Here the relations among components are connected by lines in a way that each arrow indicated the impacts on each agents. Regarding this figure, there is a direct relation between users 1 and 3 and an indirect relation resulting from the context exists between users 1 and 2.



Fig. 1. The relations among agents

2.4. The importance of agent based models in water resources management

Regarding the water resources limitations, for the purpose of the better management of these resources, the economic values and social issues as well as the users' relations should be considered. The importance of this issue is to the extent that sometimes the results are significantly affected by these relations and the managers are not able to manage the area properly.

In fact, these models create an instrument to pursue the system thinking theory's objectives. In this theory, the system perspective is distanced from a correlational perspective among agents and tends to consider a cause and effect relations. The agent based models provide an accurate insight for water resource management through achieving a cause and effect behavioral pattern and thus the issues can be resolved more seriously.

Furthermore, scarcity has caused many conflicts among different sections of different areas. This models via applying psychological and social approaches motivates all the agents to cooperate for the best water resource management strategy. These behavioral characteristics, playing a crucial role in these models, can combine with the economic perspective for a better management of water basins.

2.5. Water resources management applications

Although these models are a new trend in water resource management, yet many studies having conducted on them during the recent years. One of their applications is to create a stimulation (modeling) of the reactive process of a user to the supplied water; so that this instrument can supply agents' water demands by predicting their probable behavior, in a way that all of them would be satisfied. These social behaviors have tuned into mathematical equations so at all the phases would tend to approach to the possible satisfying amount of water for each user. Masih Ekhbari *et al* have presented an agent-based structure from this application [28]. The present study has proposed a structure that reallocate the satisfying amount of water to users, based on the social interaction and finally resolve the conflicts among users.

Another application is RL (reinforcement learning) model which is modeling the behavior of users learned by observing others' behavior and experience [29]. In fact, this instrument estimate the probable possible decision-making changes of an agent in compare with what the agent has been already done. A good example can be decisions of farmers to change the cultivation product with regard to other experienced farmers of economic benefits. Eftekhar *et al* have developed a model to redeem water from agricultural sites, based in the RL model's application [30]. They tried to assess the users' competition on their proposed price to redeem water by creating a water market. The users' behavior evaluation at each time step is based on the RL model, thus the competition effects the environmental water demands can be assessed through an agent based model.

2.6. Limitations

Despite the efficiency of these models in water resource management, they still encounter some restrictions. One of them is the nature of these models since in order that a model reaches its main objective, it needs to be created on the correct level of details about all the phenomenon related to its objective, which is a very difficult matter regarding the complexity of social behaviors. For instance, a system based on human must include agents such as rational behaviors and individual and psychological complicated objectives. Measuring and calibrating these features and even interpreting the outcomes is usually very hard [31].

Based on agent based models definition, a system is not considered a cumulative level. These details consist of features and definitions of characteristics, potential behaviors and their interactions with the surrounding context and other agents; and the only solution for these problems is multi-stage implementation to obtain acceptable answers [32]. Therefore, the huge volume of parameters to be checked can be very time consuming and include complicated calculations.

Another drawback of this models is the surprising behaviors obtained from mathematical equations which can rarely happen in the real world. These model are actually very sensitive to the primary conditions and even small changes in the interactions [33].

2.7. Advantages

Three main advantages can be mentioned for these models:

- 1. Controlling the little-known phenomena
- 2. Providing a suitable environment to study systems
- 3. Their flexibility due to spatial development of models

The little-known phenomena, such as compatibility and chaos, are unexpected behaviors that are unfamiliar with the classic systems [33]. These phenomena provide clearer view of these of impacts of phenomena, considering the equation of social behaviors.

On the other hand, agents' behavior can be predicted by stimulating these models in a way that finally would result to a proper behavioral pattern which can be a base for better management. Moreover, regarding the new achievements in spatial models, the agent-based models enjoy more flexibility.

Finally, through applying these models and considering the Game theory, all the players can cooperate so that satisfy all of them and also move toward sustainable development. This matter is expressed in a way that by reallocating water in several steps, we can properly approach each agent's satisfaction.

3. Conclusion

Most of the water resource managements steam from the water shortage, and meanwhile lack of clear vision of the surrounding environment has caused numerous problems for sustainable development process. The interactions of sections are not usually considered for water system modeling and their management, and possible social reactions to decision are normally neglected. Thus in order to have a perfect management, we need to look for an integrated management through considering all of the aspects.

Despite the relatively long background of these models in computer science, they are recently applied in water resource management and have caused to significant progresses. These models provide a clearer vision about agents and predicting their behavior through behavioral patterns can equip managers and decision makers with better strategies, considering the systematic thinking theory.

Finally, these models are providing appropriate instruments to support negotiations among different sections and to avoid conflicts.

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