Agent-Based Modeling and Simulation for Integrating Social and Natural Dynamics in Water Resources Management

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Abstract. *Water resources modelling based solely in natural dynamics may presented limitations due to neglection of social factors. This article presents an exploratory study of agent-based modeling and simulation for managing water use conflicts between farmers and regulators and among farmers. Water users' behavior is guided by the Belief, Desire, and Intention (BDI) reasoning model, aiming at welfare, often through crop sales and income generation. Heterogeneous behavior is captured through diverse cooperation profiles linked to different compliance levels with water use rules set by the regulatory agent. The resulting framework offers insights into environmental flows and water consumption equity among users, testing opportunities for new water policies.*

1. Introduction

The allocation of water resources has evolved toward sustaining communities by ensuring the water availability for human-related uses (e.g., drinking water for human consumption, navigation, irrigation, industrial processes), as well as for natural purposes (e.g., environmental flow, biodiversity preservation, nutrients, and hydrological cycle).

Thus, the management of water resources shall involve methodologies for comprehending the hydrology cycle and its interaction with society. Modeling is one of those methodologies applied to support decision-making on water allocation. In particular, it enables assessments under broad spatial and temporal scales of particularly complex systems, such as the hydrologic, social, and economic systems.

Therefore, using models for water resource investigations and social systems has become increasingly relevant [Blair and Buytaert 2016]. As a result, incorporating sociological aspects into water systems modeling has been the subject of an increasing number of scientific investigations, aligned with the emergence of transdisciplinary fields such as socio-hydrology [Sivapalan et al. 2012] and socio-hydrogeology [Re 2015].

Agent-Based Modeling and Simulation (ABMS) is a commonly used approach to represent human behavior in water-related contexts, and in particular, in applications grounded in the socio-hydrological concept [Al-Amin et al. 2018, Pouladi et al. 2019, Du et al. 2023, Sousa et al. 2024]. Moreover, the repercussion of the agent-based approach is partly due to the development of increasingly resourceful and user-friendly ABMS implementation and simulation platforms, which enables the development of ABMS by users who are not necessarily specialized in computer science [Taillandier et al. 2019]. In the context of environmental applications, the use of free ABMS platforms such as NetLogo [Tisue and Wilensky 2004], CORMAS [Le Page et al. 2000], and GAMA [Taillandier et al. 2019] have been extensively used.

The use of the Belief-Desire-Intention (BDI) agent reasoning model [Bratman 1987] has been widely used in ABMS representations [Kock 2008, Taillandier et al. 2012, Liang et al. 2016]. In particular, the BDI model can be advantageous for water resources-related applications. The complexity of decision-making processes similar to human decision-making can be represented in a more computationally tractable structure [Kock 2008].

In this context, this work presents an exploratory study on the role of ABMS in advancing the management of water resources, particularly through the explicit representation of decisions of water users and regulators toward conflict resolution. The rest of the paper is organized as follows. Section 2 presents the applied methodology, Section 3 the applied model results, and Section 4 the conclusion with future work.

2. Methodology

The conception of the agent-based model was outlined using the TROPOS methodology from the agent-oriented software engineering area, developed by [Bresciani et al. 2004]. The TROPOS diagrams were delineated using the piStar tool [Pimentel and Castro 2018]. A legend for the basic elements used is provided in Figure 1. More methodology details can be found in [Sousa 2023] and in the GitHub project's repository[1].

Figure 1 presents the agent-based model, including the main actors of the problem in the Early Requirements stage of TROPOS, along with their objectives, resources, and basic tasks. Two agent types represent the dynamic of water management: water users and a regulatory entity. A local regulatory authority agent and a farmer agent are instances of these agent types, illustrating the water use for irrigated crop production.

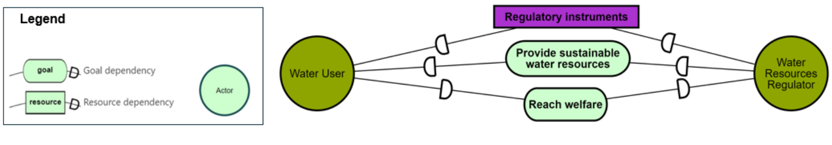

Figura 1. TROPOS early requirements diagram.

Farmer agents are human-based decision-makers according to the BDI paradigm. Water users' main goal is to reach welfare, which in the case of the instantiated farmer agent, may be achieved by selling their crop production and generating income. Heterogeneous behavior is taken into account, considering that each farmer agent acts according

[1] https://github.com/deborahsousa/Coupled-ABM-Hydrol-Formoso

to a profile related to compliance with water use rules issued by the local regulatory agent, whose goal is to provide sustainable water resources to users.

The present framework assumption is that a farmer's water withdrawal decision may be influenced by four beliefs: cooperation profile, water use rules, water available for use, and neighborhood effect. Each belief leads to the desire to comply or not with any restriction or attention rule that has entered into force and culminates in the intention (or not) of consuming water through the activation of their irrigation pumps. The local water regulator defines their management strategies based on a set of rules to be issued according to the season and the water availability in the region.

Regarding the implementation perspective, the GAMA Platform (version 1.8.2) and its built-in BDI plugin (*simple_bdi*) were used to develop the agent-based model since the geographic location of water users plays a crucial role, with upstream and downstream users having different impacts on the model. Moreover, GAMA was chosen due to its diverse and extensive applications, including decision support systems, urban systems, urban mobility, epidemiology, adaptation to climate change, and disaster management. GAMA uses its own high-level, agent-oriented language, the GAma Modeling Language (GAML).

3. Results and Discussion

The model is applied to the Formoso river basin situated in the state of Tocantins in the north of Brazil (Figure 2). The basin is characterized by intensive agriculture and water scarcity, with drought events in recent years. As a result, a drought mitigation regulatory plan was established through restriction and attention rules applied to farmers' irrigation pumps [IAC 2018]. As part of this mitigation plan, an online dataset was launched. The GAN Platform[2] is a pioneer online water management tool in Brazil as it displays both water availability and demand data for each pump in the Formoso river basin.

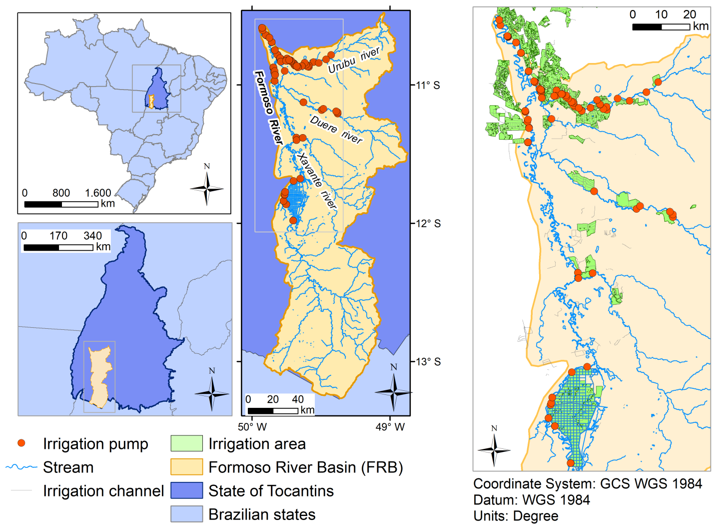

Figura 2. Geographical context of the Formoso river basin.

The application of agent-based models in the Formoso river basin has been explored in other works [da Silva et al. 2023, Sousa et al. 2024]. As presented in

[2]https://gan.iacuft.org.br/monitoramento-mapa

[Sousa et al. 2024], we consider heterogeneous behavior for farmer agents categorized according to three profiles: Cooperative (CP), Intermediate (CI), and Non-Cooperative (NC). This categorization focuses on the willingness to cooperate on the water consumption data transmission to the GAN platform. Each profile is linked to a compliance level about water usage rules issued by the regulatory agent.

The geographical set in GAMA of the irrigation pumps, water network, and irrigable lands are presented in Figure 3, as well as the results of the total daily water volume consumed by all farmers and in each profile (CP, CI, and NC). Note the pattern of water consumption is higher for NC farmers than for CP farmers. These results implications can be evaluated according to diverse metrics such as economic (overall basin income), ecologic (environmental flows), and social (income equity) variables.

A proposal for advancing water resources management toward conflict resolution is to integrate the ABMS results of water withdrawal into a hydrological model as presented in Figure 4.Additionally, the integration of role-playing games (RPG) and ABMS may enhance conflicts resolution of natural resources management [Adamatti et al. 2005].

Finally, we conclude that this agent-based framework advances water resources management by enabling the simulation of scenarios of different water policies and water use rules and including the explicit representation of water user decisions, as well as the compliance evaluation, surveillance, and application of financial penalties.

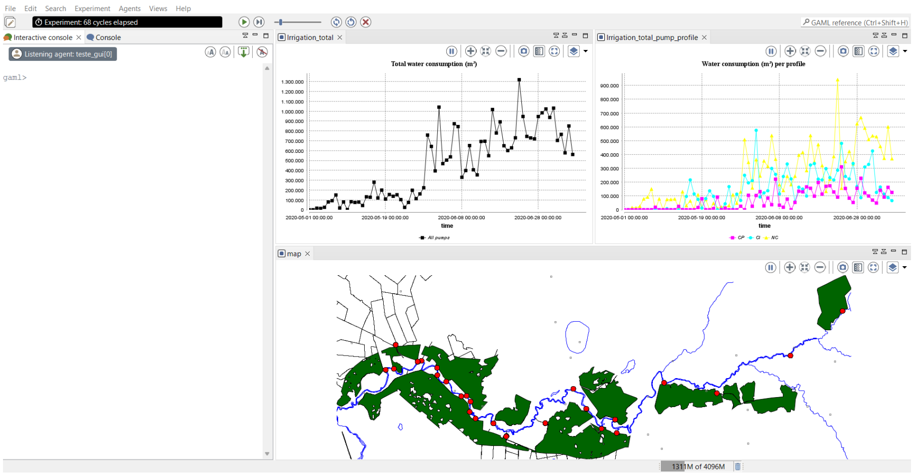

Figura 3. Graphical user interface visualization of the model in GAMA platform.

4. Conclusion

This work presents an exploratory study for advancing water resources management based on an increasingly trend observed in the literature of integrating social beahviour into natural dynamics. The presented approach uses ABMS to represent the behavior of actors of relevance in water-related issues. The main contribution of this work is providing a framework of agent-based coupled with hydrological modeling, which enables the evaluation of the importance of practical cooperativeness among users through collective compliance with usage rules. Additionally, the framework can be used by policy-makers when making decisions to safeguard sufficient water for farmers and other instances of users. The extension of the presented framework may happen through the simulation of additional scenarios, such as with an active and proactive role by the regulatory entity.

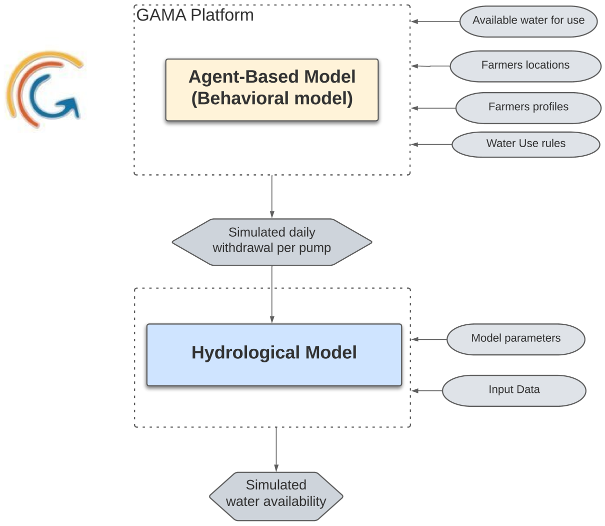

Figura 4. Proposal of coupling ABMS and hydrological models.

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