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Agent-Based Modelling for representing water allocation methodologies in the irrigation system of the Formoso River Basin, Brazil

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Abstract. The intersection of water and social systems is strictly linked to society's adjacent political and economic contexts, which adds complexity to water-related issues, such as new demographical, market, and behavioural conditions. Traditional hydrological modelling approaches have often failed to include social aspects and their impacts on hydrological processes when representing human actions as fixed external conditions, thus, neglecting dynamic and heterogeneous behaviours that are intrinsically human. As an alternative, Agent-Based Models (ABMs) can represent the complexity of modelled water resources systems and their interchange with social contexts. The Brazilian Formoso River Basin (FRB) is a human-water system characterized by intense agricultural activity where conflicts among water users are present. Aligned with the principles of socio-hydrology, this study proposes an ABM to represent the interaction of natural and social systems in the Urubu River basin, a sub-basin of the FRB. The model considers farmers and regulatory authorities as agents who act according to the Belief-Desire-Intention (BDI) paradigm. Farmers are heterogeneous decision-makers with distinct collaborative profiles towards water management strategies. Finally, a methodology to extract information on farmers' behaviour towards cooperation from water demand data is presented, which might contribute to the conceptualization of more complex socio-hydrological models.

Keywords. Water allocation; agent-based model; socio-hydrology; conceptualization; UPH 18; SDG 6; Formoso River Basin

1 Introduction

Water is a common-pool resource whose lack of effective regulation may lead to the "tragedy of the commons" demonstrated by Hardin (1968). Thus, the adequate allocation of water among users is imperative. Water allocation has been important to support communities by ensuring water availability for essential activities, such as human consumption, sanitation, food production, and other economic activities. Consequently, changes in society have resulted in new challenges for problems related to water and its allocation (Dinar et al., 1997). In addition, the interface of water systems with political, social and economic contexts adds complexity to water allocation, especially in watersheds characterized by water use conflicts (Carraro et al., 2006).

Particularly, in Brazilian agricultural basins the decrease in water availability, whether due to fluctuations in the natural hydrological regime as a result of climate change or due to the intensification of consumption by users, may increase the frequency of water crisis episodes. Consequently, uncertainty about water supply may generate or intensify conflicts among irrigation users themselves, as well as enhance competition between this and other uses (ANA, 2021), including non-consumptive uses, such as the ecological flow.

Traditional models developed to support decision-making regarding water resources often fail to consider social aspects and their associated heterogeneities in the representation of hydrological processes by considering human actions as fixed boundary conditions (Khan et al., 2017). As an alternative, Agent-Based Models (ABMs) can represent the complexity of systems in numerous environmental applications, such as land use and cover change (Ralha et al., 2013) and urban water supply (Berglund, 2015). Such models are based on a bottom-up approach where system-level outcomes result from agent-level interactions. These agents represent autonomous entities that inhabit a shared environment and follow behavioural rules to achieve their own interests.

In the water resources domain, agent-based modelling follows the concept of the socio-hydrology (SH) discipline (Sivapalan et al., 2012). Socio-hydrology aims to explore and understand the dynamic and co-evolutionary aspects of coupled human-water systems, including the possible generation of emergent behaviours from this two-way interaction. SH is also comprised within the scientific decade 2013–2022 of the International Association of Hydrological Sciences (IAHS), entitled "Panta Rhei – Everything Flows" (Montanari et al., 2013), dedicated to research activities regarding changes in both hydrology and society.

Additionally, measuring and modelling social information from existing data in order to incorporate them into socio-hydrological analysis is still a work in progress, as expressed by the 18th Unsolved Problem in Hydrology (UPH 18): "How can we extract information from available data on human and water systems in order to inform the building process of socio-hydrological models and conceptualisations?" (Blöschl et al., 2019).

Regarding the reasoning of modelled agents, the Belief-Desire-Intention (BDI) is a paradigm based on Bratman (1987)'s human practical reasoning model. The BDI architecture has been used to formalize the behaviour of more elaborate cognitive agents, and thus represent the complexity of human decision-making, including that of farmer agents (Kock, 2008; Liang et al., 2016; Taillandier et al., 2017).

The implementation of coupled socio-hydrological models allowing the integration of water users' decisions, represented by a BDI agent model, into hydrological models may contribute to the evaluation of management strategies including the negotiable water allocation, especially during drought events or dry seasons.

In order to support the management of conflicts over water use, this work presents an agent-based model to represent the effect of the cooperative behaviour of farmers on water availability in the context of a Brazilian agricultural river basin. The model is focused on simulations during the dry season, when water diversion for irrigation is the major use and water levels are low.

2 Methodology

2.1 Case study overview

The proposed socio-hydrological framework has been developed based on the water allocation process in the Formoso River Basin (FRB), sited in the state of Tocantins, north of Brazil. The FRB is an agricultural basin and covers approximately 21 300 km^2 (Fig. 1a). The region receives an average of 1600 mm of precipitation annually. However, the monthly average precipitation ranges from 1–5 mm during the dry season (May–September), to 120–320 mm during the wet season (October–April) (Alves et al., 2016; Fragoso et al., 2021).

The Irrigation District of the Formoso river (DIRF) was established in 1980 and is now the second-largest public irrigation project in Brazil, covering an area of over 20 000 ha (ANA, 2021). Therefore, agricultural activity plays a central role in the local economy and is by far the major water user in the basin. The region's strong seasonality along with its hydrophilic soil allows double-cropping systems to be established, with alternate cultivation of two crops in the same area over an annual cycle, mainly rice and soybean seeds. Rice crops are flood-irrigated, whereas soybean crops are irrigated with subsurface irrigation through channels supplied by stationary pumps (Tocantins, 2007; Vergara et al., 2013; Silva, 2015).

There are 52 agricultural properties that operate a total of 105 active stationary hydraulic pumps in the FRB (GAN, 2022). These pumps divert water from the rivers (Formoso, Urubu, Duerê, or Xavante) for irrigation purposes in the basin, each with a daily average demand of 1620 $L\,s^{-1}$ (IAC, 2018). Some of the properties withdraw water from more than one river.

The cultivation of soybean seeds in the FRB during the dry season represents the critical period concerning water availability in the basin (Silva, 2015). Consequently, the reduction of water availability along with high levels of irrigation water consumption led to streamflow depletion in some stretches of the Formoso and Urubu rivers in June–July 2016, jeopardizing the water security in the region. Judicial interventions were introduced, including the temporary suspension of water use permits and associated pumps operation, resulting in the increase of conflicts among water users (IAC, 2018).

Technical measures were requested by the State to the Federal University of Tocantins (UFT). The GAN (High-Level Management) project is an initiative of several specialists from the Institute of Attention to Cities (IAC), linked to the UFT. The GAN project resulted in the proposal of a series of water management rules and strategies in the 2018–2019 Biennium Plan (IAC, 2018). One of these strategies involved installing, operating, and transmitting water consumption data from irrigation pumps in real-time and continuously every 15 min (https://gan.iacuft.org.br/, last access: 23 January 2023).

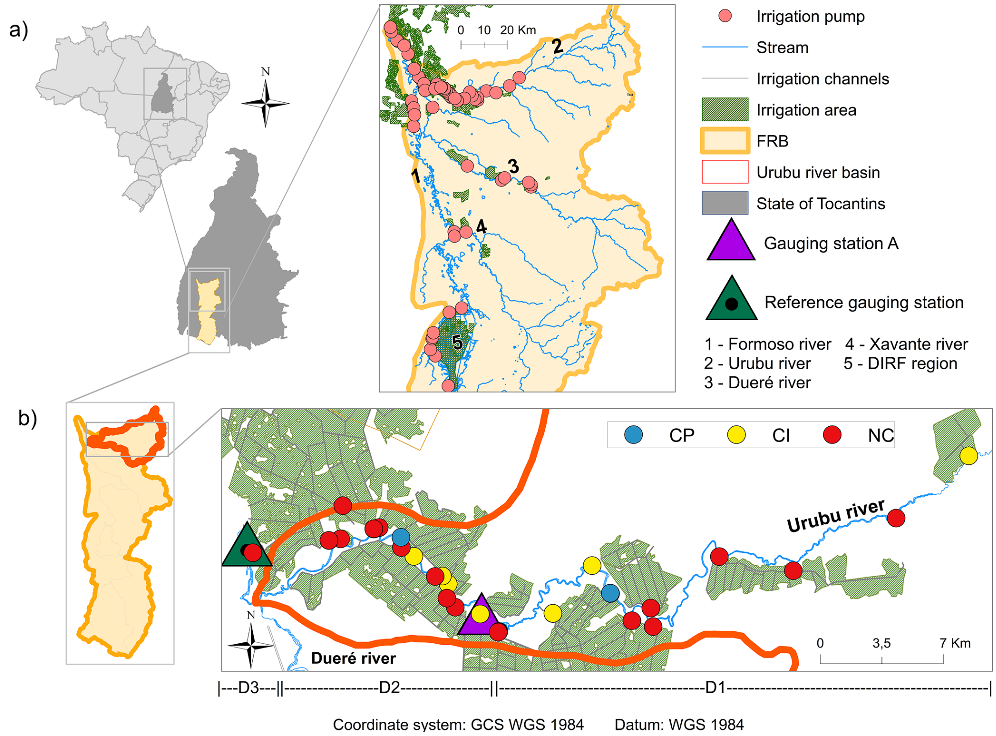

Figure 1. Map and overview of the irrigation network and irrigation area in **(a)** the Formoso River Basin (FRB), and **(b)** the Urubu river basin. Data source: GAN (2022).

2.2 Modelling proposal

Based on the Formoso River basin case, the model presented in this study provides a framework to represent farmers' decisions in agricultural basins towards water use during the dry season. It builds the representation of a socio-hydrological system in order to assess the economic, social, and environmental performance of different configurations of water allocation and management strategies.

Heterogeneity of the decision-making of farmer agents was introduced in the model. Based on reports and interviews with local experts carried out in February 2022, each irrigation pump operation was categorized as collaborative/non-collaborative according to its owner's engagement in the technical recommendations and maintenance indicated by the GAN project. Furthermore, the results of the interviews were confronted with the GAN database of water withdrawals during 2019–2021 describing the farmers' commitment to providing automatic water withdrawal information during soybean season (May–August).

These analyses resulted in the definition of three behaviour profiles towards water use (Table 1). Cooperative-Proactive (CP) behaviour is related to those farmers who agree with the GAN project and also cooperate with frequent data transmission within the GAN system for a certain pump ($\leq 25\,\%$ data transmission failure). Conversely, if a farmer consents to the project, but does not collaborate with consistent data transmission ($> 25\,\%$ transmission failure), their operational behaviour was classified as Cooperative-Ideological (CI). Finally, if a farmer does not collaborate with the project itself nor with the data transmission, they were classified as Non-Cooperative (NC).

An Agent-Based Model (ABM) is proposed to represent the social behaviour and interaction among actors in the basin. The initial conceptualization was outlined using the Tropos methodology for agent-oriented software development (Bresciani et al., 2004).

3 Proposed Agent-Based Model

The proposed ABM was based on the fundamental interrelation between two higher-level entities: Water Users and Water Regulatory entities. Water users' main goal was considered as achieving a welfare state, which is an abstract concept that may have different meanings depending on the user type, e.g. industry users aim to maximize their profit, whereas household water consumption users desire to have their basic sanitary and domestic necessities fulfilled. The present ABM considers water use for agricultural purposes, so the water user agents are farmers.

In general, the main role played by agricultural agents in ABMs is the consumption of water for irrigation purposes. Their attributes may include their geographic location, the size of their property, as well as demographic and socioe-

Table 1. Classification and Distribution of farmer agents' behaviour in the Urubu River basin. Data source: GAN (2022).

Behaviour profile	Agrees with project	Data transmission >75 %	Farmer agents in each category (%) ($n=24$)
CP[a]	Yes	Yes	17 %
CI[b]	Yes	No	29 %
NC[c]	No	No	54 %

[a] Cooperative-Practical. [b] Cooperative-Ideological. [c] Non-Cooperative.

conomic aspects (Kaiser et al., 2020). Since farmer agents are instances of water users, they also aim to reach welfare, which is represented here by fulfilling the objective of generating income through crop production. Each property and associated irrigation pumps were considered as being operated by a single farmer agent.

Regulatory agents, who may be national or local authorities, have as their main objective to provide sustainable water resources to water users through regulatory instruments. In Brazil, ANA (National Water and Sanitation Agency) is the national regulatory entity for water resources that cross more than one state, whereas water resources located within the boundaries of a single state are operated by local regulators. In the specific case of the Formoso river basin, the local regulatory agency is represented by Naturatins, which provides regulatory services for all the state of Tocantins.

Regulatory entities may issue water permits to water users, according to water availability, economic objectives, and environmental protection. Their ability to communicate with other agents is a very relevant attribute. In general, the reasoning of regulatory agents may include knowledge bases on water use permits, previous allocation rules, and historical records of hydrological conditions (Kaiser et al., 2020).

3.1 Results for the Urubu River basin

Following the methodology presented in Sect. 2.2, the cooperative behaviour of the 24 farmer agents whose pumps are located in the Urubu River basin (Fig. 1b) was characterized as: most of them act as Non-Cooperative (54 %), followed by Cooperative-Ideological (29 %) and Cooperative-Proactive (17 %). A summary of this analysis can be seen in Table 1. The Urubu River basin is modeled as representative of the FRB social-hydrological interaction since all three behaviour profiles could be identified there.

Based on the work of Volken (2022), irrigation pumps were gathered in three different demand groups according to their location in the basin: (i) D1, before gauging station A; (ii) D2, after gauging station A and before the Dueré river confluence; (iii) D3, after the Dueré confluence and before the reference gauging station (Fig. 1b).

Table 2. Water use rules for the Urubu River basin. Source: IAC, IAC (2018).

Stream	Gauging Station	Yellow stage[a]	Red stage[b]
Urubu	Reference	3.98 m (1 July)	2.20 m (1 August)

In our model, levels below the ones described, or starting from the date in parentheses, induce the following rules: [a] Water demand decrease. [b] Water withdrawal interruption.

3.2 Agent decision-making process

In the present agent-based modelling exercise, both farmers and the regulatory entity are decision-makers who act according to the Belief-Desire-Intention paradigm (BDI).

The Biennium Plan (IAC, 2018) is a drought mitigation plan developed for the FRB, which contains management measures (water use rules) triggered by predefined dates and water levels in specific sites along the main channels of the basin. According to historical data identified in reference gauging stations, the Biennium Plan issued two different water use rules: (i) Yellow stage is established when water levels go down below the attention threshold level, or on the 1st of July, whichever happens first, initiating a slot rotation in the irrigation network; (ii) red stage is defined when levels go down below the critical threshold level, or on the 1st of August, whichever happens first, inducing the interruption of water withdrawals. The Yellow stage was implemented in the model reducing the original water withdrawal. The rules defined for the Urubu river are provided in Table 2. These rules apply to the pumps (water demand sites) located upstream of the stream's respective reference gauging station.

The local water regulator agent for the Urubu River basin case was modelled as having the single "Regulate" capability, that is, issuing and communicating the Biennium Plan rules to farmers according to the current date and/or observed streamflow levels.

Farmer agents were defined with two capabilities: (i) Irrigate, and (ii) Generate Income, the former being a necessary condition for the latter. The most important decision of the farmer agent is defined at the beginning of the simulation when they decide the total land area they will reserve to grow soybean seeds and consequently sell as crop production at the end of the crop cycle.

In order to accomplish the "Irrigate" desire, farmers take into consideration the following factors: their perception of water supply quantity in the previous wet season, the neighbourhood effect within their demand group (D1, D2 or D3), the Biennium Plan rules on the Urubu river, the current date and stream level, and their potential irrigable area. These are the farmer's beliefs which are applied to their decision of expected irrigated area (EIA) by introducing multiplicative factors (α and β, dimensionless) that either reduce or maintain their total potential irrigable area (PIA) (Eq. 1).

Table 3. Multiplicative factors' definitions and potential values for each behaviour profile.

Factor	Definition	Behaviour profile	Range
α	Previous wet season perception	CP	[0.89–0.95] ∪1.0[a]
		NC	1.0
		CI	[0.92–1.0]
β	Influence of neighbours profile	CP	[0.89–0.95]
		NC	[0.9–1.0]
		CI	[0.92–1.0]

[a] First condition of Rule 1.

CP and CI profiles are assumed to have an inclination to reduce their areas more than NC agents. Thus, by combining α and β values (Table 3), CP farmers were considered to reduce up to 20 % (minimum of 11 %), whereas that percentage was defined as 15 % and 10 % for CI and NC farmers, respectively.

$$\mathrm{EIA} = \mathrm{PIA} \times \alpha \times \beta \quad (1)$$

Moreover, a set of behavioural rules were defined (Rules 1–6):

- Rule 1: IF previous wet season $\geq$ average THEN $\alpha = 1$ ELSE $\alpha \leq 1$ (see Table 3).
- Rule 2: IF current day = 1 July OR water level $\leq$ attention level THEN reduce water withdrawal
- Rule 3: IF current day = 1 August OR water level $\leq$ critical level THEN interrupt water withdrawal
- Rule 4: IF current day = 1 July AND water level $\leq$ attention level THEN reduce water withdrawal
- Rule 5: IF current day = 1 August AND water level $\leq$ critical level THEN suspend water withdrawal
- Rule 6: IF nNC / (nT) > 0.75 THEN max(β) ELSE IF nCP / (nT) > 0.75 THEN min(β) ELSE β = rnd().

For all three profiles, if their perception of the previous wet season is that it was greater than or equal to the average, then there is no reduction on their expected irrigation area (first condition of Rule 1). On the contrary, a reduction factor is considered for cooperative farmers (Table 3).

The Biennium Plan regulation, as seen from Table 2, depends on the current date and/or observed stream level. CP farmers were considered to entirely comply to this regulation (Rules 2 and 3), whereas CI farmers were assumed as being more resistant to them, needing both level and date criteria to be true (Rules 4 and 5) to collaborate. NC farmers were considered as maintaining their water consumption regardless of the Biennium Plan commands.

Neighbourhood effect was considered based on the overall predominant profile within the respective demand group D_i ($i = 1, 2, 3$) of farmers (Rule 6). If the number of NC farmers (nNC) in the D_i group is greater than 75 % of the total number of farmers in that group (nT), farmers are influenced by non-collaborative attitudes. Thus, for all categories of farmer agents in that group, β is assumed as their respective maximum value for that factor (upper bound values for β from Table 3). On the contrary, if the number of CP farmers (nCP) is greater than 75 %, farmers are stimulated to act cooperatively, and thus β is given by the lower bound values. For other conditions, β is assumed as a random value within the intervals presented in Table 3 according to a uniform distribution.

Finally, in order to achieve the desire of Generating income, at the end of the simulation, the actual Total Irrigated Area (TIA) (Eq. 2) is calculated from the Total Consumed Water (TCW, [volume]) multiplied by a factor that correlates TIA to TCW (AVf, [area volume^{-1}]). Consequently, the total revenue (Rev) is calculated as the TIA ([area]) multiplied by the productivity (p, [mass area^{-1}]) and the soybean market price (smp, [price mass^{-1}]) (Eq. 3).

$$\mathrm{TIA} = \mathrm{TCW} \times \mathrm{AVf} \quad (2)$$

$$\mathrm{Rev} = \mathrm{TIA} \times p \times \mathrm{smp} \quad (3)$$

The neighbourhood influence is being considered in order to evaluate the joint effect of a collective water permit which is a command and control management tool being evaluated by the National Water Agency in Brazil. Enacting new regulations, issuing penalties or incentives, and introducing educational measures may influence users' behaviours (Akhbari and Grigg, 2013). All of these management measures may interfere in the current distribution of behaviours presented in Table 1.

Thus, the introduction of new factors on the conceptualization of farmers' BDI, or the simulation of scenarios with farmers assuming different configurations might help assess the effect of social behaviours of farmers on total water withdrawals and the basin's economy, and, accordingly the importance of initiatives that enhance collaboration among users. Additionally, the integration of the presented ABM into a hydrological model resent might contribute to visualizing the impact of farmers' decisions on the streamflow availability.

4 Conclusions

This paper proposes an Agent-Based Model to represent the decision of farmers toward water use and regulatory rules. The model encompasses the profiles of farmers in the Formoso River basin, an agricultural basin where drought events jeopardized economic activities in the last few years. A framework considering the interaction between a simple regulatory agent and farmers is presented. Based on the BDI architecture, agents act according to specific intentions aligned with their beliefs in order to achieve distinct desires, namely, income generation, and sustainable water resources, in the case of farmers and water regulators, respectively. The update of the presented framework by considering other behaviour configurations for farmers, as well as other profiles for the regulatory agent, may help elucidate important aspects of both regulation and cooperation mechanisms within the basin. Finally, the development of a methodology that evaluates both quantitative and qualitative data to extract information on farmers' behaviour adds to the conceptualization of socio-hydrological models.

Data availability. Some data can be provided by the corresponding authors upon request.

Author contributions. Conceptualization: All authors. Data curation: DS, CA, FV. Formal analysis: DS, CA. Methodology: All authors. Project administration and Resources: FV. Supervision: CA, FV. Validation: FV. Writing – original draft preparation: DS, CA. Writing – review and editing: All authors.

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