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Impact of water allocation oversight in irrigation systems: an agent-based model approach

Impacto da fiscalização na alocação de águas em sistemas de irrigação: uma abordagem a partir de modelo baseado em agentes

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Abstract

As access to water is a right of all people, government agents are responsible to allocate water to guarantee its sustainable use for multiple users. However, deciding the best allocation strategy is not a straightforward task. In complex systems, which depend on a collection of individual decisions by people, water policies may have unpredictable impacts. Considering the water allocation in a water canal, we present an agent-based model that allocates water and incorporates an agents' adaptability behaviour strategy of overriding the manager's decision when water right is denied. We compared scenarios of farmers' override susceptibility and of water availability on the Canal do Sertão in the state of Alagoas, northeastern Brazil. In the scenario of reduced water capacity, agents with water rights in the last segments of the canal were unable to withdraw water due to agents who withdrew illegally. The sustainability of the system proved to be sensitive to the level of susceptibility of capturing water illegally, deserving attention and investments in the oversight sector. Besides this effect, the model can be applied to assess and compare advantages and impacts on the water levels for different water policies such as financial subsidies or different water allocation strategies.

Keywords: Hydrocomplexity; Sociohydrology; Mesa.

Resumo

O acesso à água é um direito de todas as pessoas, e agências governamentais são responsáveis por alocar a água para garantir seu uso sustentável para múltiplos usuários. No entanto, decidir a melhor estratégia de alocação não é uma tarefa simples, pois em sistemas complexos, que dependem de uma série de decisões individuais por parte das pessoas, as políticas de água podem ter impactos imprevisíveis. Considerando a alocação de água em um corpo hídrico, apresentamos um modelo baseado em agentes que aloca água e possui uma estratégia de comportamento adaptável dos agentes de sobrepor a decisão do gestor quando os direitos de água são negados. Realizamos uma comparação de cenários da susceptibilidade dos agricultores em sobrepor e da disponibilidade de água no Canal do Sertão, no estado de Alagoas, nordeste do Brasil. No cenário de capacidade reduzida de água, os agentes com direitos de água nos últimos segmentos do canal foram incapazes de retirar água devido a agentes que a retiraram ilegalmente. A sustentabilidade do sistema mostrou-se sensível ao nível de susceptibilidade de captura de água ilegal, merecendo atenção e investimentos no setor de fiscalização. Além do efeito estudado, o modelo pode ser aplicado para avaliar e comparar vantagens e impactos nos níveis de água para diferentes políticas de água, como subsídios financeiros e créditos, ou diferentes estratégias de alocação de água.

Palavras-chave: Hidro-complexidade; Socio-hidrologia; Mesa.

INTRODUCTION

The increasing competition for water to meet future food and energy needs is a great challenge in the 21st century, as we must deal with changes in water availability and pressure for its rational use (D'Odorico et al., 2018). As water is a right of all people, in Brazil, water withdrawals and uses are managed by government agencies (Brasil, 1997). The agencies' main role concerning water allocation is to guarantee the sustainable use of water for multiple purposes. However, in complex systems, which depend on a collection of individual decisions by people, achieving such sustainable use of water is not a straightforward task (Kanta & Zechman, 2014).

Interactions and feedback between individuals must be considered as equally important as environmental variables when studying human-water interactions and understanding their respective impacts (Sivapalan et al., 2012). For instance, in the context of irrigation, environmental conditions such as soil, climate, and irrigation technology must be considered, along with the social relationships that farmers have with management authorities and their neighbors. These interactions serve as means for resolving conflicts through negotiation, coordination, cooperation, or competition. The inclusion of these interactions introduces an additional layer of complexity when modeling human-water systems, this is known as "hydrocomplexity" (Kumar, 2015).

The unpredictability of impacts in hydrocomplex systems increases the difficulty for the manager to propose water public policies to ensure effective access to water rights. Policymakers and stakeholders need to evaluate trade-offs between socioeconomic benefits to decide whom to prioritize when allocating the often-limited water resources. Farmers make decisions based on external stimuli (*e.g.*, social, political, and economic conditions), and their own previous experience (Meempatta et al., 2019). To consider this heterogeneity of stakeholders in modelling, it requires validation data not easily available (Crooks et al., 2008) and a pan-disciplinary approach (Blair & Buytaert, 2016), adding even more challenges to efficient water allocation.

Despite the considerable advances in understanding the impacts of water policies in complex systems (Al-Amin et al., 2018; Kanta & Zechman, 2014; Khan et al., 2017; Wens et al., 2019), limited studies have considered human-agriculture systems (O'Keeffe et al., 2018; Pande & Savenije, 2016; Tamburino et al., 2020). In semi-arid regions, conflicts for water are aggravated due to the below-average rainfall and severe droughts. In some of these areas, water canals play an essential role, and, in many places, they are the main water source in the area. One such case is the Canal do Sertão, a water canal that withdraws water from the São Francisco River in northeastern Brazil and delivers it to the semi-arid region in Alagoas, Brazil. Water users in the region have the Canal do Sertão as their main water supply source for their activities.

In every water body, water users will have conflicts in water scarcity scenarios. In this matter, oversight is a mechanism to guarantee the rational use of water. Therefore, this study aims to assess the joint impacts of water allocation in an irrigation context and explore the impact of oversight in a canal system. Considering the non-linear interactions between people and water we develop an agent-based model (ABM) that incorporates: 1) a water allocation module for modelling water rights among farmers in a water canal; and 2) an adaptability behaviour we call "override" (Bouziotas & Ertsen, 2017), which consists of farmers withdrawing water from the canal even when their request is denied by the manager. We apply the model to the Canal do Sertão, a water canal that withdraws water from the São Francisco River in northeastern Brazil and delivers water to the semi-arid region in Alagoas, Brazil. We consider varying levels of susceptibility to oversight severity and different water availability scenarios.

MATERIAL AND METHODS

In the methodology section we first describe the study site, which focuses on the Canal do Sertão in Brazil. Then, we describe the agent-based model designed to capture the dynamics of water management through water rights and other important factors such as hydrological processes and socio-economic aspects. Finally, we present the scenario simulation to assess oversight impacts.

Study case

The Canal do Sertão is a water canal that aims to promote socioeconomic development in the semi-arid region of Alagoas State, northeastern, Brazil (Figure 1). The water pumping system is located on the shore of Lake Apolônio Sales and the canal was designed to conduct water by gravity throughout 250 km. The pumping flow is determined by the variation in demand and managed by the Secretary of State for the Environment and Water Resources of the state of Alagoas (SEMARH/AL). At its full capacity, the canal would have a discharge of 32 m^3/s, using 12 water pumps (Alagoas, 2003). Currently, such water flow is not demanded and only one water pump is being used. Besides irrigation, the canal was projected to supply cities, industry usages, livestock feed, among other purposes.

The water canal is divided into 15 segments for operational purposes of the already constructed canal length. Some segments have their own manual water gates to divide themselves from their upstream segment. The planned water available for each segment for one water pump (Table 1; Alagoas, 2021) considers segment's length and the maximum evaporation rate (m^3/day). To allocate water, the manager calculates a simple water balance by considering the water pumped to the canal and the amount of water used. The water balance is calculated separately for each segment. The calculated water availability is hereafter called virtual water. The term "virtual" is applied here because there is no guarantee that the virtual water is the one in the canal. This discrepancy arises from the fact that water users have the flexibility to withdraw quantities equal to or less than their authorized allocation from the canal. In some cases, users may even exceed their permitted water rights through unauthorized means.

The Canal do Sertão, as most of the water bodies, suffers from illegal water withdrawal. Due to its length, it is difficult to oversight all segments. By 2019, SEMARH/AL had identified over 1000 illegal water users and started a campaign to regulate all users. As this is a continuous action, illegal withdraws are likely still occurring in the Canal.

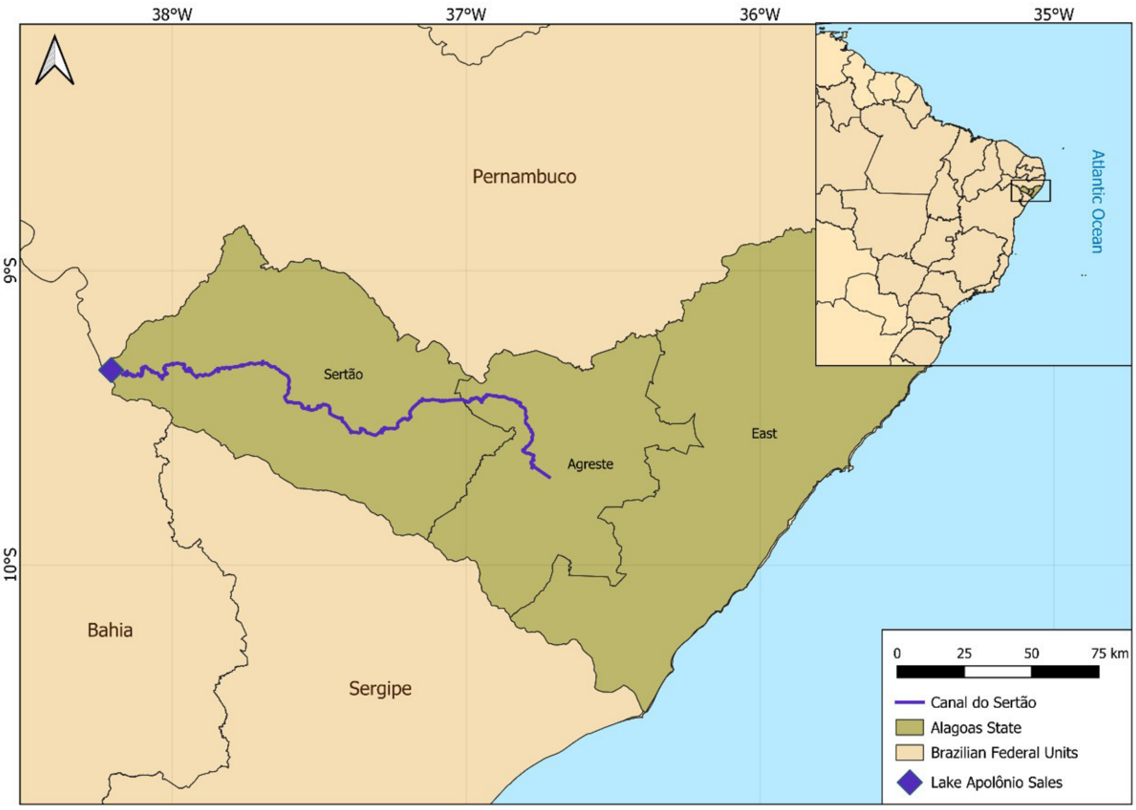


Figure 1. Study location.

Table 1. Planned water available per segment.

Segment	Length (m)	Maximum evaporation (m^3/day)	Planned water available to conceive water rights (m^3/h)
CP00-CP01	8122	716.9	764.5
CP01-CP02	8585	757.8	808.1
CP02-CP03	7993	705.6	752.4
CP03-CP04	8765	773.7	825.1
CP04-CP05	8331	735.4	784.2
CP05-CP06	7858	693.6	680.0
CP06-CP07	7953	702.0	646.7
CP07-CP08	7316	645.8	569.9
CP08-CP09	9553	843.3	518.3
CP09-CP10	8034	709.2	435.9
CP10-CP11	6964	614.7	377.8
CP11-CP12	7921	699.2	344.2
CP12-CP13	7645	674.8	265.9
CP13-CP14	7528	664.5	261.8
CP14-CP15	8768	774.0	305.0

Model description

The agent-based-model (ABM) was designed to explicitly represent the water withdrawal process in the canal. As most of the water volume is designated for irrigation purposes, we decided to only include farmers and the manager as agents in the model following the principle of parsimony. Two types of agents interact with each other and the environment: Farmer Agent and Manager Agent. The relationship between these agents is summarized in Figure 2. First, a farmer decides to ask for water rights to the manager. The amount of water to ask is based on farm characteristics, such as area of irrigation. The manager decides to conceive the water right based on the water use policy at play and the water available in the canal. In case the water right is conceived, the farmer withdraws water up to the permitted amount. Farmers are only interested in their own profit and can

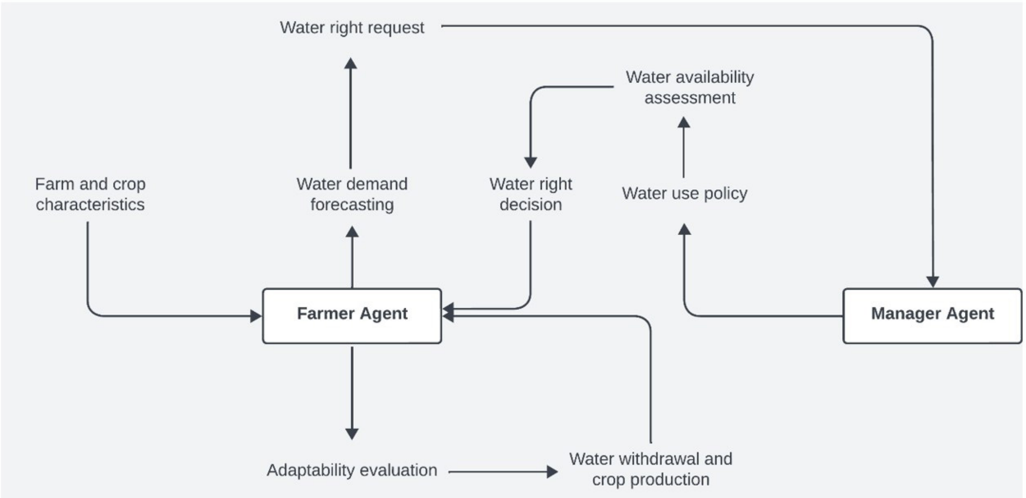


Figure 2. ABM diagram of interactions.

withdraw more or less than permitted based on their own sense of adaptability behaviour.

Following the Canal do Sertão management configuration, the modelled Canal is divided into 15 management segments. Agents are randomly located in one of the segments. The water balance calculated by the manager (virtual water) considers each segment independent of the others. This means that water users compete for water rights only with other users in the same Canal segment. Naturally, the virtual water is only for management purposes. Water withdrawal from upstream users can still affect downstream users in downstream segments.

We considered one year as the computational time step. This allowed us to assess a multi-annual evolution of the system while simplifying the water balance model. This time frame respects the season to harvest crops and the canal configuration, as a fixed water volume is pumped to the Canal. Currently, at the canal, the water pump works 12 hours/day. Therefore, simple units' transformation was used to calculate water volume in m^3/year from Table 1. To represent the Canal do Sertão, the spatial world in the model is a network represented by a Line Graph. This permitted the investigation of upstream-downstream relationships. The graph is divided into 15 segments which are represented as an attribute for each position in the model. They correspond to the actual segments in the Canal do Sertão. Segments are numbered 1 to 15 upstream to downstream. At initialization, 10,000 graph nodes were created. Each node is a possible position a Farmer Agent to allocate itself. The segment attribute is uniformly assigned to all nodes. This means that we have approximately 667 nodes for each Canal segment, as there are 15 segments in total. Later, we discuss how the water balance is calculated for each segment to conceive water rights. Note that the decision to create 10,000 nodes limits the model to have the same number of simultaneous agents. Therefore, we previously ran the model multiple times to get sensibility on how many simultaneous agents are necessary to use all water from the canal and decided on a reasonable number of nodes.

Each step begins with the creation of new agents. The water rights data from 2014 to 2021 (Alagoas, 2021) showed no reasons to believe there is a trend in new water users per year. Therefore, we decided to create a fixed number of agents per year solely based on the mean value of the whole time series (101 users/year).

Farmer Agent

The main objective of the Farmer Agent is to maximize their income. In the presented model, each farmer is represented by single agents, and not clustered. Clustered farmers, with the same homogeneous properties, although would decrease computation time, should be taken carefully, as the loss of micro-scale features that influence the macro-scale system behavior could be lost in the process.

Attributes related to the farmer's water right request

The amount of water each Farmer Agent asks the Manager is defined stochastically. Each farmer has two main attributes to define the amount of water to request: crop type and farm area.

Farmers can decide among a subset of crop types. Considering empirical knowledge of SEMARH/AL officers about the main crops in the Canal do Sertão area and at-hand data, we selected a subset of three possible crops: maize, passion fruit and cassava (Table 2). Crop yield, revenue and production cost were calculated based on the Brazilian Institute of Geography and Statistics (IBGE) data on temporary (Instituto Brasileiro de Geografia e Estatística, 2018a) and permanent (Instituto Brasileiro de Geografia e Estatística, 2018b) crop production for the year 2018 in the state of Alagoas. We extrapolated the state average for the Canal do Sertão.

To represent market fluctuations in the revenue and cost variables, we randomly drew a new value from a normal distribution centered on the values from 2018 data and a standard deviation coefficient of 5% of the 2018 data. Mathematically, for

Table 2. Crop characteristics.

	Maize	Passion Fruit	Cassava
Yield (ton/ha)	0.724	14.428	11.392
Revenue (R$/ton)	664	1845	440
Cost (R$/ton)	448	1351	333

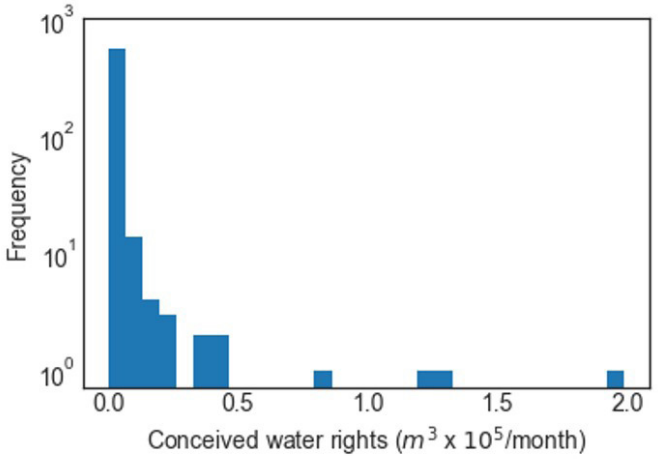


Figure 3. Water rights histogram.

the year t in the ABM, $Yield_t \sim Normal\left(Yield_{2018}, 0.05 \times Yield_{2018}\right)$ and $Cost_t \sim Normal\left(Cost_{2018}, 0.05 \times Cost_{2018}\right)$.

As mentioned, farmers act at their own interests. To choose a crop type to plant each year, farmers take into consideration the profit for planting each crop in the respective year. In the model, farmers randomly select among the three available crops. The probability to choose each crop is weighted on the crop profits. Therefore, farmers are biased to choose the most advantageous crop considering only economic aspects.

To calculate farm area, we considered a directly proportional relationship between farm area and water irrigation amount. Also, water irrigation amount is equal to the water right (all water requested is used for irrigation).

We used actual water rights data from the Canal do Sertão (Alagoas, 2021; Figure 3) to fit the distribution model from which we randomly selected the water demand forecast. We filtered only water rights for irrigation purposes from the dataset and we calculated water withdrawal in $m^3 / month$.

To convert water rights data into irrigation areas, we divided the amount of water in water rights by $40 m^3 / day / ha$, which approximates general crop water needs in the region. This value of water is taken empirically from an ad hoc consultation with SEMARH/AL officers and represents the maximum irrigation coefficient that is considered when conceiving water rights. Values above this threshold are usually denied in water rights analysis because of physical characteristics and water needs for every crop type.

For each created farmer agent, the farmer sends a signal to the manager to request the water right. In the presented model, there is no water rights revision every four years as is usual in many water rights policies in Brazil. If the farmer agent already has water right conceived, this process to calculate the water demand is skipped. This means that the farmer does not increase or decrease the size of the farm and consequently, the area of irrigation throughout the years.

To fit a distribution model to the data, we considered that the water asked by the farmer is affected by a combination of several economic factors that we are unaware of or are not estimated in the model (irrigation technology, market values, farmer experience, etc.). The Power Law fits a large number of empirical regularities in economics and finance (Gabaix, 2009) and was used to fit conceived water rights data. To fit parameters we chose the Maximum Likelihood Estimator.

Attributes related to the manager decision

The objective of the manager is to assure the rational and integrated use of the water resource. In our model, the manager adopts the policy of "first come first served". The manager always conceives water to farmers if there is water available in the respective canal segment. The manager calculates the water balance in the segment and deducts the value from virtual water availability whether the water right is conceived. At the end of this process, the manager sends a signal to the farmer agent indicating whether the water right is conceived or not.

Attributes related to farmer's adaptability

If water right is conceived, farmers will try to withdraw water from the canal. They will succeed based on the actual water availability (hereafter, real water) at the farmer's site. The water availability is a result of the water balance from all farmers upstream. If the water right is denied farmers may or may not withdraw water from the canal, based on their sense of adaptability. In the model, farmers can override the manager decision and ignore its water right denial.

Each farmer has its own probability to override $\left(P_{over}\right)$ which is an adaptability behaviour that, even though it is illegal, it occurs in real life. This situation will cause conflict because some other downstream farmer agents will not withdraw water from the canal as they expected. The quantity of overrides is a combined effect of the manager's capacity to oversee whether the water rights conditions are being respected and the inherent water user characteristics. For these effects, we established a threshold to override (T_{over}).

When created, farmers are given a random probability to override (from zero to one). This value does not change over time and is compared to T_{over} if a water request is denied. Farmers override if P_{over} falls below T_{over}.

Scenario simulation

We chose to assess two types of scenarios, including the implementation of a management policy (scenarios 1 and 2) and a farmer adaptability action (scenarios A and B). In scenario 1 the canal is at its current water availability $WA = 1$. Scenario 2 corresponds to a water shortage scenario considering only 60% of current water capacity $WA = 0.6$. For the farmer adaptability action, scenario A considers an override threshold $T_{over} = 0.3$, and in scenario B a $T_{over} = 0.1$. More intense oversights (in frequency of campaigns or severity of restrictions) have effect on farmer susceptibility to override, i.e., decrease T_{over}.

Water shortage from scenario 2 could be a result of climate change or issues with the main water pump (currently, the Canal do Sertão operate with one water pump that supplies the canal). Scenario B correspond to a farmer's response to a more severe oversight due to possible investments in this management sector. We chose to compose all the scenarios according to Table 3.

For ease of reference, we will call scenarios based on their characteristics: 1A will be the base scenario, 1B will be the oversight scenario, 2A will be the water scarcity scenario, 2B will be the water scarcity+oversight scenario.

To assess the results, we ran the model with a time frame of 20 years. There were two reasons for choosing this period: i) watershed's management plans, which contain strategies and guidelines to achieve beneficial goals for a geographically defined watershed, are designed to be implemented in 20 years in Brazil; ii) we considered this period at the verge of reasonable extrapolation, as data may not still represent farmers and environment characteristics in longer time frames. Therefore, we performed 20 model steps, each step corresponding to one year.

Development framework

In this study, we explore the potential use of ABM under the agricultural scenario, using the Mesa Python package (Kazil et al., 2020). It is an open-source programming package for ABM design and evaluation that supports simultaneous activities and allows the possibility of creating different kinds of behavioral models by inheriting classes from the framework. The entire model is programmed in Python.

RESULTS

In this section we introduce results comparing the effects of different thresholds with canal at full water availability (base and oversight scenarios). Then, we present the results for the scenarios under water shortage conditions (water scarcity and water scarcity+oversight scenarios).

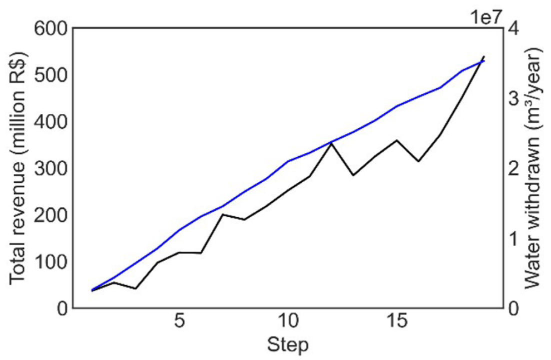
Effects from investing in water management oversight (base and oversight scenarios)

By the end of the 20 years, total farmers' revenue for the base scenario (Figure 4a) was 47% higher compared to the oversight scenario (Figure 4b) in Brazilian Reais (R$) as more agents were producing in the base scenario. We did not consider inflation for the simulated period. Therefore, values are based on the Brazilian Real currency from the year 2018, which correspond to our cost and production source data.

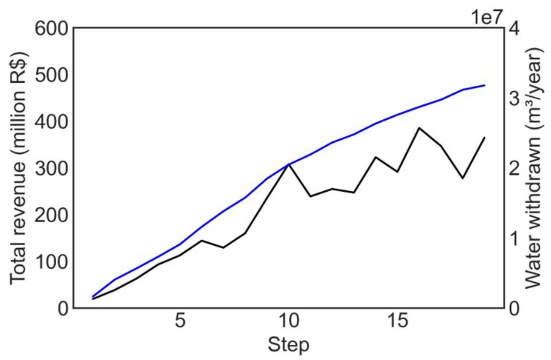
In the base scenario, farmers began to override from year 6 (Figure 5a) as virtual water reached zero in segment 14 at year 5 (Figure 6). When virtual water ends in any segment, the following

Table 3. Scenarios assessed.

	Scenario 1	Scenario 2
Scenario A	1A: $WA = 1$; $T_{over} = 0.3$	2A: $WA = 0.6$; $T_{over} = 0.3$
Scenario B	1B: $WA = 1$; $T_{over} = 0.1$	2B: $WA = 0.6$; $T_{over} = 0.1$.

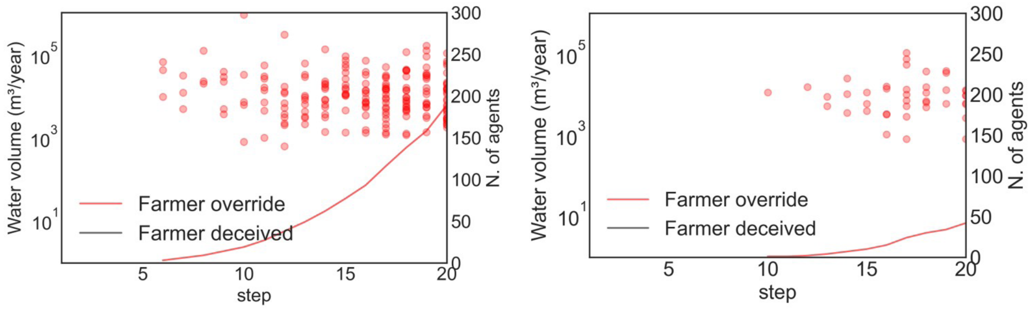


(a) base scenario



(b) oversight scenario

Figure 4. Total farmers revenue over the modelling years. The blue line corresponds to the water withdrawal, and the black line to the total revenue.



(a) base scenario

(b) oversight scenario

Figure 5. Agents that overrode and deceived agents over the modelling years. The scatter plot shows new overrides and deceived agents. The secondary axis shows cumulative number of agents over the years.

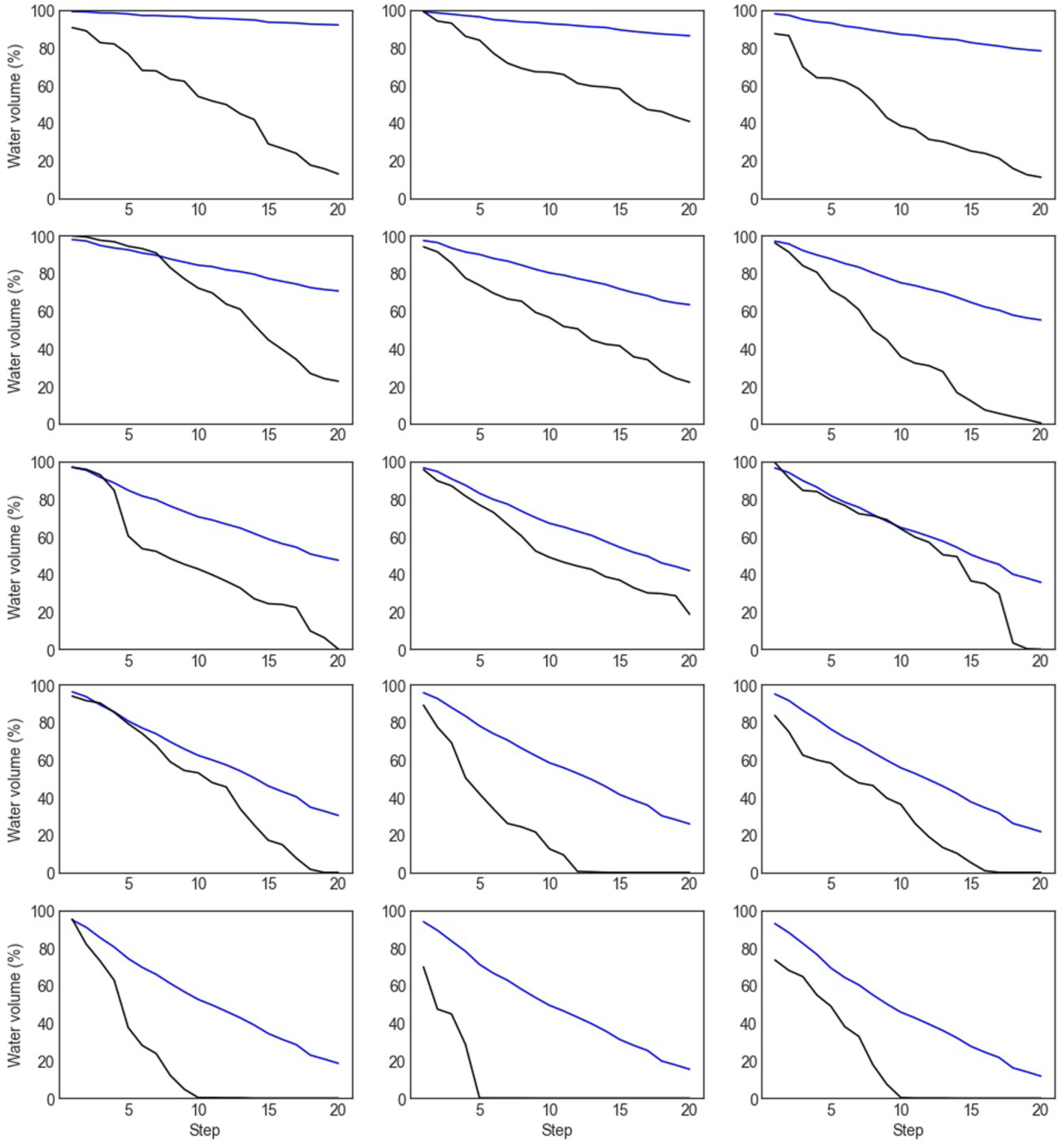


Figure 6. Virtual water volume at each segment. Plots correspond to segments numbers 1 to 15 - from top to bottom, then left to right at each line (base scenario). The blue line corresponds to the real water, and the black line to virtual water.

water rights are denied to users. This means they have two options: do not withdraw or start to override depending on their inherent characteristics, summarized on the probability to override (P_{over}).

By year 20 in the base scenario, 189 agents had overridden the manager's decisions. Over time, more agents followed suit, creating an exponential trend as the number of segments with no virtual water increased. We called deceived agents, farmers who had their water right, but could not withdraw because there was no real water available. Despite the growing number of farmers who overrode for the base scenario, by the end of 20 years, all agents could withdraw water because the canal did not dry out (Figure 6). Virtual water for segments 13 to 15 ended sooner than other segments, as less water was allocated to these segments, and agents were randomly allocated in any segment.

For the oversight scenario, as expected, fewer agents overrode (Figure 5b). However, even with the difference of over 100 agents overriding when comparing the base to the oversight scenario, the difference in real water volume between both scenarios was close (11.72% for the base scenario, compared to 11.85% for the oversight scenario). This is explained by the combined effect of crop choices and farmland areas of production, as the number of agents in both scenarios is the same. This compensated the inactive agents that did not withdraw in the oversight scenario because of the lower override threshold. As in both base and oversight scenarios the canal did not dry out, and the current pumping water schedule was sufficient to supply the water users. As virtual water serves only for management purposes, it can be virtually reallocated to other segments if it is needed to avoid conflicts.

Effects from water shortage and investing in water management oversight (water scarcity and water scarcity+oversight scenarios)

Figure 7 shows agents that overrode and deceived agents at each year for the water scarcity and water scarcity+oversight scenarios. As both scenarios consider water shortage conditions, the canal dried out and deceived agents started to appear in the latest segments. In the water scarcity scenario at the 20th year, 197 have overridden, while 248 were deceived. In the water scarcity+oversight scenario, where agents had lower probability to override, 67 have overridden and 110 were deceived.

In both scenarios, there was a lower number of agents that overrode compared to deceived agents. As the manager denies water considering virtual water by segment, overrides started to be performed well before the appearance of deceived farmers.

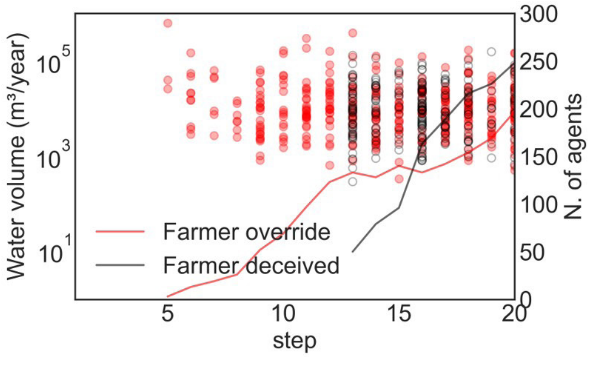
Even though the same distribution draws all agents, deceived agents ascend at a much more rapid rate than agents who overrode. This behaviour may be explained by the cumulative previous effect of overrides.

It is expected that when performing more steps in the model, every new agent that has its water right denied and override the manager decision will result in one or more deceived agents downstream. This is a result of the model structure, as no farmer stops withdrawing. In other words, farmers who overrode are not "caught" by the oversight officials or stop withdrawing for any other reasons.

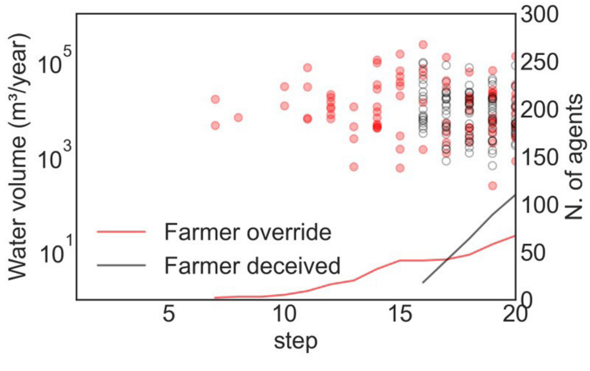
DISCUSSION

Model impacts on water management

The model can greatly influence public management strategies within the Canal do Sertão. Recently, the water management authority (SEMARH/AL) commissioned a study to develop a water charging methodology for the canal (HidroBr, 2022). The study recommends pricing water based on volume units while considering the cost sustainability of the canal. However, the study solely focuses on the direct economic effects of implementing this policy. In this context, a comprehensive model that evaluates the broader socioeconomic impacts of the proposed water prices and their long-term consequences becomes indispensable. The implementation of water charging entails dealing with bureaucratic procedures and negotiating agreements with interested municipalities and stakeholders. Hence, gaining a deep comprehension of the socioeconomic consequences tied to each charging scenario is essential. This understanding would form the basis for informed discussions and the effective implementation of these policies.



(a) water scarcity scenario



(b) water scarcity+oversight scenario

Figure 7. Agents that overrode and deceived agents over modelling years. The scatter plot shows new overrides or deceived agents. The secondary axis shows cumulative n. of agents over the years.

The studied model has various potential applications in the Canal do Sertão. For instance, it could be utilized to assess the influence of deploying type-C hydrometers, capable of transmitting real-time measurements via cellphone signals, having an effect on the susceptibility to override; it could analyze the financial incentives associated with cultivating low water-demanding crops, thereby impacting the probabilities associated with crop selection; determine the optimal timing for the introduction of a new water pump increasing water availability, which will affect potential new water users and revenue generated from water charging; estimate government income for water charging; or evaluate the anticipated effects resulting from the implementation of planned irrigated perimeters within the Agreste region once the Canal construction reach this region.

The model framework presented in this study offers a valuable tool for testing the implications of various water policies, with room for adaptation to different contexts. While specific water policies were outlined for the Canal do Sertão, the framework can also be applied to explore alternative scenarios, as demonstrated in the existing literature. These include investigating different water rights criteria in response to water scarcity (Yang et al., 2020), assessing the impact of agricultural education programs (Eanes et al., 2019), or exploring the effects of implementing pricing charges on water withdrawal (Dono et al., 2010). By employing this framework, policymakers and stakeholders can gain valuable insights into the potential outcomes of different water management strategies and make informed decisions to ensure sustainable water allocation and maximize socioeconomic benefits.

Model limitations and future work

Our model introduced a series of innovations incorporating empirical data into the ABM. Although we provide a bottom-up approach for decision-making of water allocation, we discuss the remaining challenges addressed to future research to assist model reproducibility and replicability. The main limitations in the model rely on data availability and water users' decision mechanisms.

This study explores the concept of agent adaptation known as "override" and examines its implications. The sensitivity analysis performed on this parameter (with thresholds of 0.3 and 0.1) presents a paradox, as obtaining an empirical value for it proves challenging. Even direct interviews with farmers would not provide reliable information, as they are unlikely to openly admit whether they would override if their water rights were denied. Conversely, they would readily disclose their non-override intentions. Given farmers' self-interest behaviour, it is reasonable to assume that the dominant strategy would be to override rather than adopt an altruistic approach. However, instances where farmers choose not to override, may be influenced by two factors. Firstly, concerns about potential fines or legal consequences might deter them from overriding. Secondly, intrinsic characteristics such as a sense of community, religious beliefs, or normative values, where the approval of important individuals in the farmers' lives plays a role, could also influence their decision-making. While the latter aspect is not currently incorporated into the model, it could be addressed by adopting the Theory of Planned Behaviour (Ajzen, 1991). T_{over} could also be affected by several oversight strategies such as the number of oversight campaigns, fines, and the number of confiscated water pumps or withdrawing systems due to illegal withdrawals. The model can also be modified to account for different T_{over} ranges for some segments and change over time. Segments that are approaching their maximum virtual water capacity would require more stringent oversight measures, which would ultimately affect the value of T_{over}.

One of the modeling assumptions made in our study is that farmers' allocation is random. However, this assumption may not accurately reflect reality, as there are inherent inequalities in goods and productive lands, such as variations in soil quality or easier access to water sources (e.g., gravity-fed systems). While dividing the canal into segments is an initial step toward incorporating spatial features into a more robust model, it is not a straightforward task. To model such non-random behavior, it would be necessary to utilize microeconomic datasets, including information on labor, cost constraints, and satellite imagery for land-use mapping.

In addition to agent allocation, the determination of the number of new agents was based on the water rights time series. However, it is impossible to accurately determine the number of illegal users not accounted for in the water agency's database. While oversight efforts aim to address this problem by acting against illegal users, the actual number of new agents can vary based on the local context. In the region, when public policies are implemented to encourage regularization, there is typically an increase in the issuance of new water rights. Examples of time-bound regulations include incentives for farmers tied to the issuance of water rights and tax exemptions for new users.

Our findings highlight the significant impact of crop choice on the total revenue of the Canal do Sertão. However, due to limited available data on crop types specifically for the canal, we had to rely on secondary data from similar regions to estimate the costs of crop production. Additionally, in the absence of comprehensive data, we made an *ad hoc* decision to select the main crops commonly planted in the area. It is important to acknowledge that our assumption of homogeneous decision behavior among all farmers may not hold true in a real-world scenario (Sanga et al., 2021). Conducting interviews and behavioral modeling, such as discrete choice experiments (Burton et al., 2020), would be valuable for future improvements, allowing for a better understanding of crop choice dynamics and farming area preferences. However, it is essential to consider that interviews provide a snapshot of the current situation, and we must assume that future farmers will behave in a similar manner.

Dealing with uncertainty is important when we use models to forecast or predict. In this paper, we chose to validate the model ensuring it represents the real-world system. However, we acknowledge various sources of uncertainty that we did not consider for further investigation in data (e.g., crop subset choice, cost and revenue values) and in the model itself (e.g., parameters estimation, model complexity). It is important to determine the appropriate level of abstraction, as the trade-off between model complexity and uncertainty is essential for a more effective modelling (Blair & Buytaert, 2016). We leave uncertainty analysis for future investigations.

The scope of this study was limited to only farmer agents. Future research could include multiple agent types (Al-Amin et al., 2018) and that agents communicate with each other increasing model complexity. The impact of climate variability could be explored to evaluate associated impacts in long-term planning.

CONCLUSIONS

This study explores the water allocation in canals focusing on irrigation purposes. We propose an agent-based modelling framework that incorporates: i) a water allocation module that distribute water rights; ii) an adaptability behaviour strategy of overriding the manager's decision. We performed a double scenario comparison of the override susceptibility from farmers. We applied the model to the Canal do Sertão, a water canal in the Brazilian Northeast semi-arid region.

We found some benefits of using an ABM to assess the impacts on water systems. For the studied case, in the base and oversight scenarios, the canal did not dry out for the current water pumping schedule. In water scarcity and water scarcity+oversight scenarios, the oversight threshold showed its impact on deceived agents. The oversight threshold proved to be sensitive to maintaining the sustainability of the system, praising the attention and investments in the oversight sector.

The modelling framework can be applied to assess and compare advantages and impacts on the water levels for different water policies. This study still has some limitations that need to be addressed. We recommend future works include a more robust decision process of crop choices such as discrete choice modelling to account for agents' heterogeneity. We reiterate that such improvement in farmers' behaviour would provide more useful modelling results to shape policies towards better water allocation strategies.

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Authors contributions

Yan Ranny Machado Gomes: Conceived of the presented idea, built model and performed computations, analyzed and discussed the results, wrote the manuscript, wrote the final draft of the manuscript.

Christopher Freire Souza: Conceived of the presented idea, analyzed and discussed the results, reviewed the draft.

Augusto Hugo Farias da Cunha: Analyzed and discussed the results, reviewed the draft.

Suzana Maria Gico Lima Montenegro: Analyzed and discussed the results, reviewed the draft.

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