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YAN RANNY MACHADO GOMES

MODELLING HYDROCOMPLEX PROCESSES FOR WATER ALLOCATION MANAGEMENT

Recife
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Pre-thesis presented to the Post-graduation Program in Civil Engineering of the Universidade Federal de Pernambuco as a partial requirement for obtaining the title of Doctor in Civil Engineering.

Area of concentration: Environmental Technology and Water Resources, with an emphasis on Water Resources.

Supervisor: Prof. Suzana Montenegro, phD

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RESUMO

Como o acesso à água é um direito de todos, agências governamentais são responsáveis por alocar a água para garantir seu uso sustentável para seus múltiplos usos. No entanto, decidir a melhor estratégia de alocação não é uma tarefa simples, pois em sistemas complexos, que dependem de um conjunto de decisões individuais das pessoas, políticas hídricas podem ter impactos imprevisíveis. Considerando a alocação de água em um corpo hídrico, este estudo explora a realidade de usuários de água modelados individualmente para otimizar a alocação de água e garantir a disponibilidade para os usos múltiplos do canal. Inicialmente, dado ao sistema complexo, propomos o desenvolvimento de um modelo baseado em agentes (ABM) que leva em consideração o comportamento individual de decisão dos agricultores com base em modelagem de escolha em um canal. Como demonstração de viabilidade técnica, construímos um ABM que aloca água e possui uma estratégia de comportamento de adaptabilidade dos agentes capazes de captar água mesmo sabendo que o direito foi negado. Para exemplificar o uso da metodologia, comparamos cenários de suscetibilidade de captar água mesmo quando a outorga for negada no Canal do Sertão Alagoano, nordeste do Brasil considerando o canal em sua disponibilidade hídrica total e com capacidade reduzida. Usando o modelo aplicado, encontramos os benefícios de usar um ABM para avaliar não apenas variáveis ambientais, mas também socioeconômicas. No cenário de capacidade hídrica reduzida, agentes com outorga nas últimas seções do canal não conseguiram captar água devido a agentes que captaram ilegalmente. O nível de susceptibilidade de captar água com a outorga negada se mostrou sensível para a manutenção da sustentabilidade do sistema, enaltecendo a atenção e investimentos no setor de fiscalização. Além do caso estudado, o modelo construído pode ser aplicado para avaliar e comparar vantagens e impactos nos níveis de água para diferentes políticas de água como efeitos de subsídios e créditos financeiros, ou diferentes estratégias de priorização na alocação de outorgas.

Palavras-chave: sócio-hidrologia, modelagem baseada em agentes, modelagem de escolha

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, to decide the best allocation strategy is not a straightforward task, as 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 body, this study explores an approach that water users are modelled individually to optimize water allocation and guarantee water availability to multiple uses. Initially, due to this complex system, we propose the development of an Agent-based model that has a water allocation module that accounts for farmers' decision individual behaviour based on choice modelling in a water canal. As a technical feasibility display, we built a functional ABM that allocates water and has an agents' adaptability behaviour strategy of overriding the manager's decision when water rights are denied. We performed a double scenario comparison of override susceptibility from farmers on the Canal do Sertão in the state of Alagoas, northeastern Brazil. Using the applied model, we find the benefits of using an ABM to assess not only environmental variables, but socioeconomic ones. 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 level of susceptibility of capturing water with the grant denied proved to be sensitive to maintaining the sustainability of the system, praising the attention and investments in the oversight sector. Besides the studied effect, the built model can be applied to assess and compare advantages and impacts on the water levels for different water policies such as financial subsidies and credits, or different water allocation strategies.

Keywords: sociohydrology, agent-based model, choice model.

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1 INTRODUCTION

1.1 Rationale

The increasing competition for water to meet the 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 federal and state agencies (BRAZIL, 1997). These agencies' main role in water allocation is to guarantee sustainable use of water for multiple uses. However, in complex systems which depend on a collection of individual decisions by people, to guarantee such sustainable use of water is not a straightforward task.

Interactions and feedback between individuals must be considered as equally important as environment variables when the human-water interaction is strongly related to understanding their respective impacts (SIVAPALAN, SAVENIJE & BLÖSCHL, 2012). For instance, in the irrigation context, besides environmental conditions such as soil, climate and irrigation technology, farmers may be interconnected through social relationships with management authorities and their neighbors. These interactions are the result of conflict resolutions due to negotiation, coordination, cooperation, or competition. This adds a new layer of modelling complexity in human-water systems.

The unpredictability of the impacts increases difficulty for the manager to propose water public politics to ensure effective access to water rights. Policymakers and stakeholders need to evaluate tradeoffs between socioeconomic benefits to decide who prioritize when allocating the often limited water resources available. 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 requires validation data not easily available (CROOKS, CASTLE & BATTY, 2008) and a pan-disciplinary approach (BLAIR & BUYTAERT, 2016), adding even more challenges to efficient water allocation.

Conflicts for water are aggravated in semi-arid regions due to the below-average rainfall and severe droughts. To promote economic development in agro-industrial sector and urbanization, transboundary water canals play essential role and in many places is the main water source in the area, such as in the Canal do

Sertão, a water canal that withdraws water from the São Francisco River in northeastern Brazil. Farmers and other water users in the region have the Canal do Sertão as their main water supply source .

In every water body, including Canal do Sertão, water users will have conflicts in water scarcity scenarios. It is the water agency role to manage those conflicts by proposing water policies. However, as farmers may behave in their own interest, the outcome of those policies may be not easy to predict, not only in water quantity, but in economic and social conditions. In fact, farmers can be considered as adaptive agents, who have autonomy, intelligence, and relative knowledge about their environment. Therefore, what would happen to the future of water canals if farmers, who are individuals who have critical thinking, and may behave in their own interest, are not yet explicitly modelled and taken in consideration? How to define the best water allocation policy towards canal sustainability?

1.2 Objectives

General objective:

Optimize water allocation strategies in canal systems considering coupled human-water interactions

Specific objectives:

- To understand the decision-making behaviour of irrigators in the Canal do Sertão
- To analyze interactions between humans and water availability in a water canal

1.3 Hypothesis

Understanding farmers' decision-making process improves water allocation policies impacts.

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2 HYDRO-COMPLEXITY

Complex systems are structures whose behaviour are difficult to model due to dependencies, competitions, relationships, or other types of interactions between individuals and the environment. In fact, environmental systems are a classic example of multiple interacting individuals (*e.g.*, animals, vegetation, microorganisms, and people) that are influenced by environment variables (e.g., water availability, temperature).

Given the combined effects of population growth and expanding cities, demand for water will continue to grow, while in many regions water availability is becoming more uncertain. Anthropogenic activities are bringing changes in natural systems (MILLY, et al., 2008). Therefore, increasing attention is being given to the impact of human influences on the environment and how these environmental interferences affect back humankind themselves. People were included in modelling for many years only as an input to know quantitatively how much water is needed as a resource or as justification to avoid natural catastrophes such as floods and droughts. Only recently the inclusion of people has been considered as equally important as other environmental variables as may be seen in references throughout this section. Naturally, when studying this complex topic that requires a transdisciplinary approach, authors may give more attention to their particular area of expertise as the integration of human impacts and environment also evolved.

The Integrated Water Resources Management (IWRM; GWP, 2009) approach involved the integration across the whole hydrological cycle by including different water users and established a "…step by step process of managing water resources in a harmonious and environmentally sustainable way by gradually uniting stakeholders and involving them in planning…" (UNESCO, 2009). Environmental flows (POFF & MATTHEWS, 2013) aim to manage water that weighs the benefits of environmental services, especially to less assisted communities, focusing the analysis on the ecological impacts of management actions. The ecohydrology (FALKENMARK, 2004) approach integrates aquatic and terrestrial ecosystems (including human effects) and tries to understand their relationships to improve water security, enhance biodiversity and aim towards sustainable development. This approach, however, focuses on relationships between hydrological and biological processes giving a new perspective to human-water systems by biologists. Sociohydrology (SIVAPALAN *et al.*, 2012) addresses the human-water investigation by analyzing the hydrological and sociological processes involved. Similarly, the Water-Energy-Food Nexus (SMAJGL *et al.*, 2016) proposes a balanced attention to these three sectors and their connections.

In fact, all these different field names correspond to different perspectives of the same problem as a facet of a prism (PARKES et al., 2010). They represent paired interdisciplinary approaches that must be taken more holistically by considering the entire scope of human activities and their respective impacts. To this end, the term *Hydrocomplexity* (KUMAR, 2015) better recognizes complex systems as interconnected processes that may have emergent behaviour. Therefore, Hydrocomplexity is the umbrella of all sorts of expertise fields by researchers towards an integrated watershed governance that considers complex systems.

People's decisions and actions result even in water conflicts due to its temporary unavailability. Therefore, policies to prevent water scarcity need to understand and target factors that influence how people make decisions and their respective effects. The interplay between the society and water is often complex and present some additional challenges:

- Frequently, stakeholders' perception is not taken into consideration when making water management policies (WALTNER-TOEWS *et al.*, 2003). In fact, people's heterogeneity makes modeling human decisions and reaching agreement difficult because of conflict of interests (AN, 2012).
- People are complicated. To understand which influencing factors are the most important when making decisions is not an easy task. As people's decisions directly impact the environment, we need to incorporate human behaviour into water management modelling. This integration has been a major challenge in literature (PANDE & SIVAPALAN, 2017).
- Non-linear interactions and the emergent behaviour often presented in coupled human and natural systems makes it hard to predict future patterns (DI BALDASSARRE *et al.*, 2019). Unintended consequences may arise as consequences of water management policies.

Considering the above statements and questions, the theoretical development we follow is a collection of different fields of research to investigate complex systems related to water resources in a water allocation context. First, in section 2.1, we review the emergence of addressing complex ecological issues by incorporating human behaviour into hydrological modelling and how studies have been incorporating stakeholders' knowledge using some participatory modelling. In section 2.2, we introduce ways to model the decision-making behaviour. Finally, in section 2.3, we present considerations about the Agent-Based Model approach, which is a tool to model complex systems.

2.1 Participatory modelling

TheIntegrated Water Resources Management (IWRM) paved the way bringing guidelines for multi-disciplinary and bottom-up approaches such as the incorporation of stakeholder participation into water management. Since then, much research has been done to increase stakeholders' participation in water management. Integration with stakeholders may vary from updating community of model outputs to the inclusion of stakeholders in all modelling steps (PRETTY, 1995). However, the quality of decisions resulting from stakeholder participation strongly depends on the orchestration process being conducted in a transparent and unbiased manner. The process needs to have clear objectives and should not overlook the need for highly skilled facilitation (REED, 2008). A participatory process can point input datasets and indicators overlooked or considered irrelevant by policy-makers; give the opportunity to overview spatial and time scales, as ecological processes have not the same boundaries as political divisions and indicate areas that are connected in ways not immediately apparent; and, of course, empower and engage communities by providing the opportunity to participate in decisions that will affect them in ways traditional approaches fail to provide (FRASER *et al.*, 2006).

Public participation includes five levels of engagement designed to inform, consult, involve, collaborate, and empower the public (CREIGHTON, 2005). At each level, stakeholder engagement increases leading to a greater impact. However, policy makers need to be transparent with stakeholders regarding legislative mandates, key assumptions, uncertainty and how their feedback will be used in the decision-making process (CLIFFORD *et al.*, 2022).

The success of water policies is completely dependent on the acceptance and implementation in the micro-level scale, *i.e.*, by farmers (JORGENSEN *et al.*, 2009), especially when policies rely on voluntary acceptance by the end users, for instance, prioritize/ban the cultivation of a particular water demanding crop (BOAZAR *et al.*, 2019). In fact, water-saving behaviours strongly rely on increasing users' awareness and motivating individuals to voluntarily make choices that positively impact sustainable water use. Once these choices happen voluntarily, they become more likely to be embedded in social norms (AYER, 1997). Farmers' active participation in water conservation issues are influenced at different levels, which range from individual beliefs and values to community and societal norms (MILLS *et al.*, 2017). By engaging stakeholders into policy making and being transparent on how their knowledge and preferences will be considered could help stakeholders understand why certain decisions were made (CLIFFORD *et al.*, 2022).

While research has been oriented towards engaging and understanding stakeholders' decisions, much less scientific research has been undertaken for exploring the combined use of computational-based models within these participatory planning and decision-making processes.

In the 1970s, it was recognized that farmers do not always make decisions based on solely considering economic aspects, but weights with intrinsic goals (GASSON, 1973). To properly capture the relevant drivers of decision-making in these complex environments, a combination of qualitative and quantitative methods in a single study is highly encouraged (MEEMPATTA et al., 2019; DI BALDASSARRE et al., 2021). While this type of study is extremely challenging, there are approaches for integrating farmers' decisions into hydrological modelling (KELLY *et al.*, 2013).

A distinction is made between participatory modelling and collaborative modelling based on the degrees of participation by stakeholders and types of cooperation. While collaborative modelling stakeholders jointly design and/or take decisions with modelers and decision-makers (there is, in fact, joint action), participatory modelling covers wider levels of participation (no joint action needed). A combination of strategies are recommended for key to other interested stakeholders (BASCO-CARRERA et al., 2017).

Stakeholders participation may be involved in any/some of the seven modelling steps: i) select modelling scope; ii) build conceptual model and discuss system; iii) choose modelling tools; iv) collect and process data; v) apply model to decision-making; iv) evaluate model outputs and discuss results; vii) present results to other stakeholders. For studies which address participatory modelling in these modelling steps, please see Voinov et al. (2016) and references therein. Even though it is evident that stakeholder participation has benefits in modelling, there is still a big gap between model development and the actual use of models to support collaborative decision making. The majority of literature that studies socio-environmental systems is based on single case study applications (ELSAWAH et al., 2020).

Learning which driving factors and goals affect farmers' decision-making process might shift behaviour from an uncooperative equilibrium to a cooperative outcome (HONE et al., 2020). Therefore, it is critical to align water governance policies closely to farmers preferences to willingness barriers to adopt them (BURTON et al., 2020).

So far, we reviewed the importance of including stakeholders into modelling when making water policies. In the next section, we shed light on aspects about decision-making behaviour and the implications of bringing this kind of knowledge into water modelling.

2.2 Decision-making behaviour

Economic theory suggests that people make decisions based on their “well-being”. This well-being is related to the total degree of satisfaction that someone gets from using a product or service (MCFADDEN, 1986). The technical term for well-being in the economy is utility. Utility is related to concepts of happiness, satisfaction, and welfare which are difficult to measure. While these concepts are difficult to measure, economists use the utility to get an idea of these non-quantifiable concepts. As utility is a powerful concept, it permits to quantitatively model behaviour in a conceptual way.

It is generally assumed that individuals attempt to maximize their utility level. In other words, they compare alternatives on a subjective metric and choose the one that provides the most value. Therefore, getting information about those alternatives plays an essential role in defining preferences. At the same time, consumers (in our case, farmers) may sometimes pick bundles that do not necessarily maximize their utility. Personal biases, intuition (NUTHALL & OLD, 2018), and the fact that they hardly ever may have all the possible information to make a decision (EDWARDS-JONES, 2007), might interfere with individuals' preferences.

Economists assume money as a measure of utility. This reasoning leads to the assumption that all farmers try to maximize their profit. While this assumption seems reasonable, it has been used broadly in literature to model farmers decision-making behaviour (ACHEAMPONG et al., 2018; BURTON et al., 2020; MWOLOLO et al., 2019; THOMPSON et al., 2019).

While people try to fulfill their needs at any cost, they try to adapt themselves to the deteriorative environment they live in. To build efficient and sustainable water management policies, we need to understand the psychological factors behind this social paradox. In other words, why people still do whatever it takes to get what they need, even if it means adjusting to a situation that is getting worse or more difficult to live in. In this scenario, behavioural theories capture the main drivers of human behaviour (SAHU et al., 2020), such as the theory of reasoned action (TRA; FISHBEIN & AJZEN, 1975) and the theory of planned behaviour (TPB; AJZEN, 1991). TPB was elaborated for the purpose of improving the predictive power of TRA (AJZEN, 2020) and is based on three core components: personal attitude (PA), subjective norms (SN), and perception of control (PoC). The behavioural intention (BI) is a linear function of the three basic antecedents:

Equation 1: Behavioural Intention formula

$$BI \cong w_1(PA) + w_2(SN) + w_3(PoC)$$

PA is related to individual's preferences to perform (or not) a certain action, which is a result of behavioural beliefs (likelihood a behaviour will produce some effect) and expected outcomes (desirability of a particular outcome). SN is the decision maker's beliefs about people's approval of a certain behaviour. It is a result of the individual normative beliefs' strength (whether most important people will approve such behaviour) and the motivation to comply with those norms. Finally, PoC is the individual's confidence that they are capable of performing such behaviour. w_n are empirically derived weights.

TPB offers a framework for questionnaire design (ANDREWS et al., 2011) and it has been broadly used in studies related to complex water resources systems (KOUTIVA & MAKROPOULOS, 2016; POULADI et al., 2019).

To understand the main drivers that individuals consider when making decisions, the discrete choice experiment (DCE) is an approach to be used. DCE is based on participants assessing a set of options considering a bundle of attributes at different levels. The DCE is based on the random utility theory (McFadden, 1986) which relies on the hypothesis that every individual is a rational decision-maker and chooses the option that yields the highest utility. In other words, the probability of selecting a given alternative is higher if the utility of this alternative is higher among the different options to choose. Mathematically speaking, the utility function for individual i choose the alternative j is given by:

Equation 2: Utility function

$$U_{ij} = \beta_i^{'} x_{ij} + \varepsilon_{ij}$$

where x_{ij} is a vector of attributes, β_i is a vector of parameters that represent the marginal utilities for the attributes and ε_{ij} is a random term which captures the unobserved effect. The assumption for the ε_{ij} element is that it is independent and identically distributed (iid) across individuals and alternative choices. It takes the Gumbel extreme distribution. Gumbel is a skewed distribution with two parameters (a particular case for the Generalized Extreme Value distribution when the shape parameter equals zero). Under the assumption that $\varepsilon_{i1}, \varepsilon_{i2}, \dots \varepsilon_{iJ}$ are iid distributed, the expression for the probability of observing alternative p over all other alternatives in the choice set and conditional upon the observed levels of the attribute vector for all alternatives is:

Equation 3: Probability of choosing alternative *p* over all alternatives

$$P\left(\beta_i^{'}\right) = \frac{exp\left[\beta_i^{'} x_{ip}\right]}{\sum_{j=1} exp\left[\beta_i^{'} x_{ij}\right]}$$

which is the conditional logit model and can be estimated using maximum likelihood estimators.

In this section, we briefly introduced one sociological theory, the Theory of Planned Behaviour, and the basic principles of an economic model, the discrete choice experiment. Together, they could be powerful tools to incorporate human behaviour into water management modelling. In the next section, we review how to finally assess the respective impacts of people’s decisions in the environment.

2.3 Agent-based model

Water modelling generally involves developing mathematical and logic-based representations of real-world relationships between different variables (*e.g.*, meteorology, stream hydrology, water quality). Models are facilitators of real-world problems by mathematically simplifying complex systems into a few equations and relationships that should most represent the overall system. There are two most common ways: either to build up the system from observed patterns or to break it into parts. When starting to build a model, we can divide a complex problem or algorithm into multiple smaller parts (or modules). This concept of breaking down until reaching the most fundamental parts is known as top-down modelling. On the other hand, we may design a model in the opposite manner by designing the most fundamental parts which are then combined to make the higher level module,this is called bottom-up modelling. A disadvantage of the top-down approach is that it can miss some underlying processes, producing a result that may be too simple for certain applications. On the other hand, bottom-up approaches are much more focused on the underlying linkages of the sub-systems and individuals. In complex systems, the bottom-up approach could deliver more accurate results, especially in coupled human-water systems (KELLY *et al.*, 2013; LU *et al.*, 2018)

An ABM is a class of computational models for simulating the actions and interactions of autonomous interacting entities (hereinafter called agents) capable of making decisions based on a set of rules. Agents adapt and co-evolve based on the information received from the environment and each other. Each agent can be both individual or collective entities, such as organizations or groups. This bottom-up approach focuses on attributes of individuals and conclusions about the system characteristics, which need to be drawn from the effect of interaction between the agents. In order to fully represent water use via ABMs, it is necessary to directly include human behaviour (SQUAZZONI, JAGER, EDMONDS, 2013). This important step increases model realism and real-world relevance (O'KEEFFE et al., 2018).

In a socio-hydrological ABM, agents may represent individual stakeholders or a group of individuals interacting with groundwater and surface water resources as their environment. Rules that govern agents' interactions may be due to socioeconomic conditions or to the variation of environmental conditions and information passed by other agents. The definition of rules is based on rationality, heuristics, and learning (Van Oel & Van Der Veen, 2011) and can represent how entities can learn and adapt in response to changes (Wens et al., 2019). The combination of the interactions with each other and the environment can produce macroscale (unexpected) behaviour known in the study of complex systems as *emergence* (EPSTEIN & AXTELL, 1996).

When talking about emergent patterns, they are not reducible to characteristics at the individual level. Such patterns are derived from micro level interactions and behaviours. In those cases, we cannot analytically derive the emergent behaviour from the component's parts. In a bottom-up management regime individual farmers themselves determine their strategies of water extraction aimed at increasing their local agricultural production. When they act at their own interest, an unequal water distribution may emerge (SCHLÜTER & PAHL-WOSTL, 2007), closer to the reality where individuals manage the water resources according to their own rules and not the manager authorities.

Once the set of interacting rules are set, ABM is mostly used to explore policy alternatives. In water resources management, ABMs show usage because of their substantial capacity to design robust policies and incentives to help for water allocation (KHAN et al., 2017; O'KEEFFE et al., 2018), potable water supply (KANTA & ZECHMAN, 2014), ensure the sustainability of aquifers (AL-AMIN et al., 2015; AL-AMIN et al., 2018). Also, coupling an ABM with distributed process-based hydrologic models (KHAN et al., 2017) can give much more accurate results on the impact of those policies on the environment.

2.4 Summary

In this theoretical development section, we addressed the importance of participatory modelling in complex systems, to get system understanding with stakeholders and to gather input data on relevant attributes that people take into consideration when they make decisions. Finally, we reviewed how to put all these things together into a computational model to assess impacts in complex systems regarding environment and socioeconomic aspects.

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3 METHODOLOGY

The methodology is divided in three main sections: the behavioural modelling, the agent-based modelling and the application of both through a study case (Figure 1).

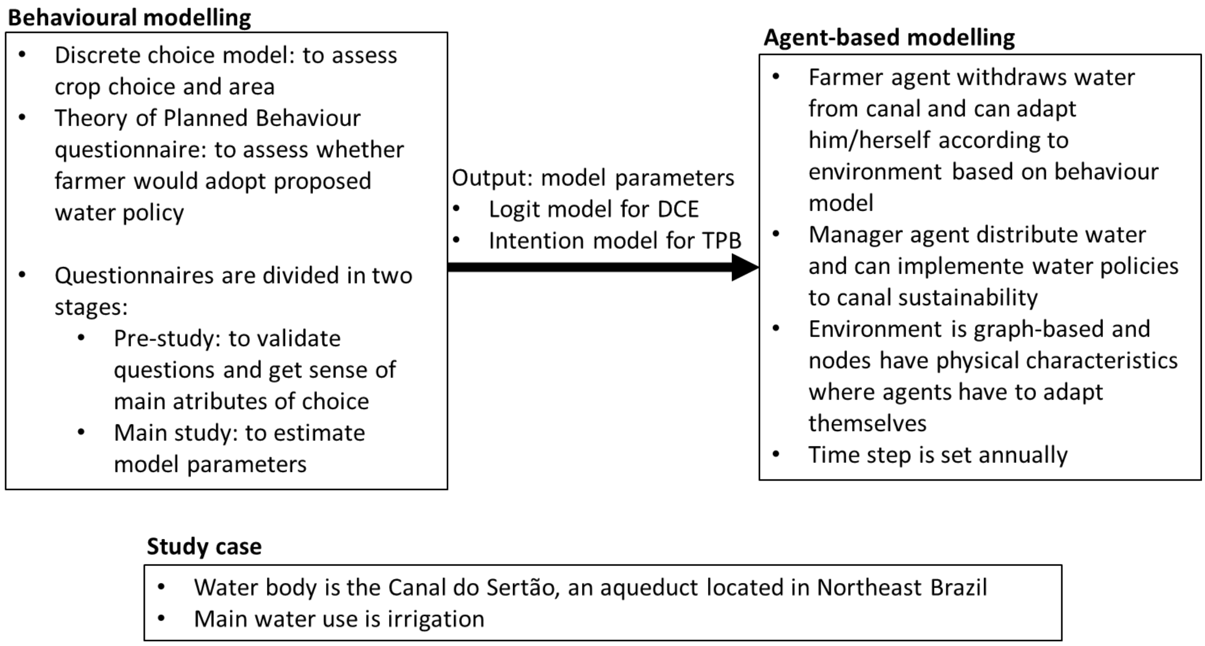

Figure 1: Methodology workflow

Two main methodologies are used in the behavioural model step: discrete choice models and the theory of planned behaviour. They assess behaviour in two separated decision-making steps: i) to choose the crop and respective harvest area within the year; ii) to determine whether farmers will adopt or not proposed water policy. To get main attributes and estimate behavioural model parameters, questionnaires will be used in two stages: the pre-study and the main study.

In the agent-based modelling, two main agents are created: farmer and manager. Farmers are mainly self interested, while the manager tries to guarantee sustainable use of the water resource. We use behavioural models outputs to determine water withdrawal volume (based on crop type and harvest area) and the adaptability behaviour farmers will use based on received water right by the manager.

Finally, the study case will be the Canal do Sertão, an aqueduct located in Northeast Brazil in the semi-arid region. It is a transboundary canal and may be the only source of water for many water users in the region. Main use for the canal is irrigation, the reason why we implement only Farmer Agent in the ABM. The following sections describe each of these model steps in detail.

3.1 Behavioural modelling

For the behavioural modelling input data we will conduct in person surveys. This will help interviewees to deal with abstract attributes and levels that can be problematic for individuals with limited literacy when the interviewer is not presented in person. Also, we believe that face to face interviews will: i) increase farmers' engagement and achieve the largest number of responders; ii) help pay attention to socio-cultural contexts during the research process; iii) help identify innovative partners and means of communication from research findings (SHANTLEY & LÓPEZ, 2009).

In order to understand the behavioural process two surveys will be conducted, each survey has a two-step questionnaire format to: (i) elicit the selection process to choose a crop type to farm and (ii) form a structural behavioural equation about the act of water conservation. In this way, we assume that both processes are independently evaluated by farmers. Two surveys will be conducted, the pre-study and the main study. They are summarized as follows and detailed in the next sections:

- Pre-study: Farmers point main prior attributes and elicit the selection process to choose a crop type to farm (e.g., same as neighbors, family tradition, or profit maximization research). This will be the core of the Discrete Choice Experiment (DCE) in the main study. Then, farmers also respond to a questionnaire based on TPB (Attitude, subjective norms, perceived behavioural control). A reliability coefficient will be calculated to assess the consistency of the TPB-based survey. Questions on the main study may be changed depending on the reliability coefficient.
- Main study: The DCE experiment will be conducted to weight attributes influence on crop type choice. The TPB-based survey will be once again conducted based on the pre-study's reliability coefficient.

3.1.1 The pre-study

Farmers make decisions based on external stimuli and on their own goals (see Meempatta *et al.*, 2019). The influencing factors that impact farmers decisions can be either by extrinsic factors, which correspond to external factors that are out of the farmers control (*e.g.* commodities prices, social, political and economic conditions), and intrinsic factors, which are intrinsic to the farmer (*e.g.* risk appetite, past experience, personal beliefs and/or perceptions).

A preliminary survey with few local water users will be conducted to identify the attributes related to the crop choice. This preliminary survey consists of the identification of the main drivers that farmers consider for crop choice. Farmers may have political mistrust issues (BURTON et al., 2020). Therefore, we avoided including questions that identify the farmer to get more reliable answers.

The data collection form will consist of basic information: age, educational level, farmland area, farmers involvement in farming. Then, it will consist of primarily open-ended questions. This will enable respondents to report their perceptions and experiences with no bias from the prior attributes chosen by experts. Questions were phrased to describe farmers' experience with regards to three aspects: (a) relevant attributes on crop selection, (b) crop selection process, and (c) conditioning factors that guided crop choice. We found crop type and irrigation method not systematically registered in the study case database (study case presented in Section 4. Therefore, question number 1 fulfills this import gap for later modelling, as both information have great impact on water withdrawal volume. We also designed a question (number 5) to assess farmer’s view on possible water policy strategies the managers could take. That shall guide policy scenarios modelling in the final version of this thesis.

1. Which crop are you currently planting in your farm? Which irrigation method do you use?
2. How do you decide which crop to plant each year?
3. How do you decide how much area to harvest each year?
4. Do you see any potential negative consequences to yourself involved in your crop choice strategy? What are they?
5. Can you see which actions the water agency and the canal committee could sanction to better balance local development and water conservation?

Following Yazdanpanah et al. (2014) and Pouladi et al. (2019), the structural behaviour for water conservation will be calculated through the TPB-based questionnaire. Respondents will score each affirmation (Table 1) on a six-point scale (not at all; very low; low; moderate; high; very high) whether they agree or not with each statement. Specifically, we used a six-point scale to reduce the statistical problem of extreme skewness, a statistical problem when assessing results. Highly skewed variable distributions may lead to downward biases in correlation analysis, low reliability and sometimes be misleading (FORNELL, 1992). A six-point scale allows respondents to make finer discrimination regarding each TPB questions. High skewed distributions for some statements can affect the performance of the Cronbach's alpha.

Table 1: Theory of Planned Behaviour questionnaire (adapted from Yazdanpanah et al., 2014)

Attitude
1. Farmers should aim for maximizing the production efficiency, not the conservation of water resources 2. Crop production is more important than water conservation 3. Only during drought, farmers should concern about water conservation 4. In my opinion, at this time it is not necessary to protect water 5. I believe engaging in water conservation measures is beneficial 6. I believe farmers should engage in water conservation measures
Subjective norm
1 Most of the people who are important to me encourage me to engage in water conservation activities 2 People, who are important to me, would agree with me if I want to engage in water conservation activities 3 Most people who are important to me think that I should not engage in water conservation activities
Perceived behavioural control
1. Based on my judgment, it is not possible to conserve water on my farm 2. The apparatus needed for water conservation activities are too expensive for me 3. I do not have the skills and time needed for water conservation activities 4. Engaging in water conservation activities are arduous for me 5. When I feel ready, engagement in water conservation activities is possible for me 6. For me, engagement in water conservation activities is easy

Behavioural intention
1. I intend to engage in water conservation activities
2. I will participate in water conservation in the future
3. I will not engage in water conservation activities

The Cronbach's alpha will be used as the reliability coefficient. Alpha is calculated given a matrix *X* of size (*n* x *k*), where n is the number of respondents (rows) and k the number of questions (columns). Cronbach's alpha coefficient is given by:

Equation 4: Cronbach's alpha coefficient

$$\alpha = \frac{k}{k-1}\left(\frac{\sigma_t^2 - \sum_{i=1}^{k}\sigma_i^2}{\sigma_t^2}\right)$$

where σ_t^2 is the variance of the sum of each row of the matrix X and σ_i^2 is the variance of each column of the matrix X.

Two assumptions are made when using Cronbach's alpha:

1. The questionnaire must be divided and grouped into dimensions. These dimensions should group questions that deal with the same aspect.
2. The questionnaire must be applied to a large and heterogeneous sample of the population.

The suggested minimum of Cronbach's alpha is around 0.6 (POULADI *et al.*, 2019; YAZDANPANAH *et al.*, 2014). However, a high coefficient (close to 1) is also not desirable, which could mean that multiple items are measuring the exact same element of a construct (STREINER, 2003).

A low number of alpha could be addressed to the low number of questions that evaluate a construct (in our case: attitude, subjective norms, perceived behavioural control, behavioural intentions) or poor inter-relatedness between items. Items with poor correlation should be discarded (TAVAKOL & DENNICK, 2011). We will compute the correlation of each test item with the total score test. Low correlations (approaching zero) are deleted. We also will assess correlations between paired items, a too high correlation (approaching one) means that questions are redundant. The current questionnaire is adapted from literature. However, as alpha is a score from a specific sample it must be calculated at every test and reliability coefficient must be calculated for our sample. Values of similar questionnaires in literature can not be relied on a different sample (STREINER, 2003).

3.1.2 The main study

In the main study, respondents will be asked to choose their preferred alternative from a choice set. From the most relevant attributes identified in the pre-study, a combination of attribute levels will be presented in choice cards as exemplified in Figure 1. In the example, farmers choose between three crop types considering aspects of: water use, profitability and resistance to pests and diseases. Respondents are asked to choose one alternative from the choice set.

Crop n. 1	**Crop n. 2**	**None**
Water use: High	Water use: Low	-
Profitability: R$ 10,000 per ha	Profitability: R$ 7,000 per ha	-
Resistance to pests and diseases: Low	Resistance to pests and diseases: Low	-

Figure 1: example of a choice set in the DCE

Multiple choice sets will be displayed for farmers' choice. Each choice set will contain two crop options and an "opt-out" alternative. The "none" option was included so farmers do not have to be forced to choose an alternative they would not in practice in face of the other two unappealing alternatives. It also indicates the proportion of farmers that would not be willing to plant both other crops. When a respondent chooses an option over the others, they indicate which attributes mostly influence their choices and their willingness to trade-off between attributes.

To build the combination of attributes each choice set an orthogonal design was applied. Orthogonal experimental design is usually applied when it is not possible to do exhaustive testing (*i.e.*, try every single combination of crops choice sets). An orthogonal design in discrete choice experiments ensures that each option is varied independently of the others, allowing us to measure the effect of each option separately and draw more reliable conclusions about people's preferences. This approach helps to ensure that the results of a DCE are accurate and meaningful.

In orthogonality, each attribute level appears an equal number of times in combination with all other attribute levels, which balances the experimental design and delivers good test coverage. The orthogonal design underlying the DCE will be generated using the Python Package OApackage (EENDEBAK & VAZQUEZ, 2019). OApackage is originally designed to generate and analyze orthogonal arrays, however with some adaptation it can be applicable to design our experiment.

Statistical analysis will be carried out using the random utility theory. We will use a logit model estimated in willingness to pay (WTP). If a monetary attribute such as profitability is included, WTP for changes in the non-monetary attributes can be estimated.

Finally, the TPB questionnaire will be applied once again with some or no modifications in wording or questions based on correlations, Cronbach’s alpha coefficients, and informal feedback from respondents from the pre-study.

3.2 Agent-based model (ABM)

The agent-based-model (ABM) will be designed to explicitly represent the water withdrawal process in the canal. 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 from the manager. The amount of water to ask for permission to use is based on farm characteristics, such as irrigation area and crop type. The manager decides to conceive the water right based on the water use policy at play and water availability in the canal. By default, farmers withdraw water from the canal based on the requested water volume. However, may withdraw less or more (in the last case, illegally) based on their own sense of adaptability behaviour.

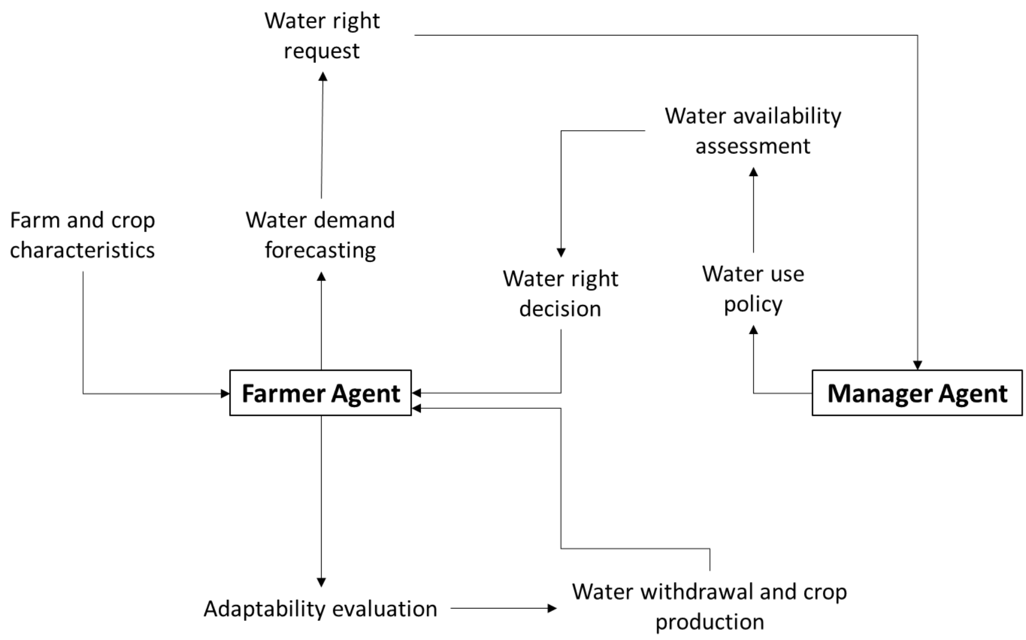

Figure 2: ABM diagram of interactions

The behavioural modelling process impacts ABM in two ways: i) main attributes identified by farmers when deciding crop type for the year will be explicitly modelled in the "farm and crop characteristics" step. They will decide which crop type and farm area they will produce based on the economic scenario (Equation 3); ii) Based on Behavioural Intention (Equation 1) each farmer is susceptible or not to accept water use policy at the moment. A farmer may ignore the water policy at play and continue to withdraw water at own will in the Adaptability evaluation step, or follow the rules of the water policy based on farmers characteristics.

The following section implements an ABM based on the presented diagram interactions considering only a simplified version of the agents' behavioural modelling.

3.3 Study case

The Canal do Sertão is an aqueduct which aims to promote socio economic development in the semi-arid region of Alagoas State, northeastern, Brazil (Figure 3). The water pumping system is located on the shore of Lake Apolônio Sales and the canal was designed to conduct water by gravity throughout the 250 km of length. 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 full capacity, the canal would have 32 m³/s using 12 water pumps (ALAGOAS, 2003). Currently, this amount of water flow is not demanded and only 1 water pump is installed and being used. Besides irrigation, the canal was projected to supply cities, industry usages, livestock feed, among others.

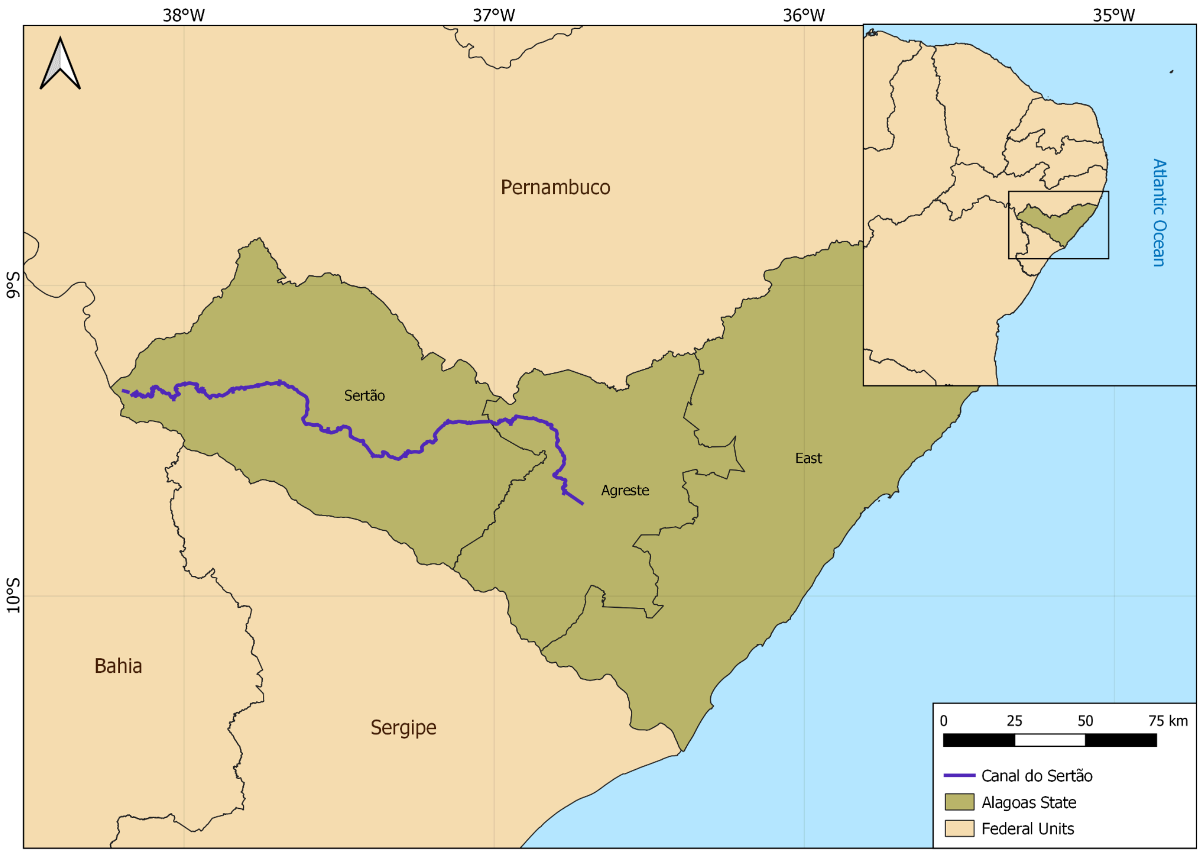

Figure 3: Study site location map

The water canal is divided by 15 sections. Some sections have their own manual water gate to divide itself from the upstream section. The planned water available for each section (Table 2) considers section length and the maximum evaporation (m³/day). Considering the pumping time per day managed by SEMARH/AL, water is allocated to the several users throughout the canal. The available water to allocate is calculated by the water balance considering the pumped water to the canal and the water users are for management purposes and hereafter called virtual water.

Table 2: 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	1447.9
CP01-CP02	8585	757.8	1530.4
CP02-CP03	7993	705.6	1424.9
CP03-CP04	8765	773.7	1562.5
CP04-CP05	8331	735.4	1485.2
CP05-CP06	7858	693.6	1287.9
CP06-CP07	7953	702.0	1224.7
CP07-CP08	7316	645.8	1079.3
CP08-CP09	9553	843.3	981.5
CP09-CP10	8034	709.2	825.5
CP10-CP11	6964	614.7	715.5
CP11-CP12	7921	699.2	651.8
CP12-CP13	7645	674.8	503.6
CP13-CP14	7528	664.5	495.9
CP14-CP15	8768	774.0	577.6

In 2022 water rights for irrigation purposes conceived by SEMARH/AL consisted of 97% (in water volume). Due to its extent, the canal suffers from several illegal withdrawals, which could impose a challenge for its sustainable use in the future.

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4 EXPLORING THE EFFECT OF WATER MANAGEMENT OVERSIGHT FOR WATER ALLOCATION IRRIGATION SYSTEMS

In this chapter we present the preliminary version of the proposed model in section 3.2. The main purpose of the preliminary model is to show an initial assessment of a water allocation strategy and to demonstrate the model's technical feasibility for the thesis completion. The final ABM proposed in this thesis will use the physical aspects implemented herein so far. We simplified farmer decision-making behaviour regarding crop choice/area of irrigation and water policy compliance. The simplifications are explained throughout the next sections. Motives of such simplifications are the lack of observed data to properly implement the proposed behavioural model in the previous section.

4.1 Short overview and objective

Combined with the effects of population growth and expanding cities, demand for water will continue to grow, while in many regions water availability is becoming more uncertain. Particularly in semi-arid regions, where water conflicts are aggravated, transboundary canals may be the main/only water source available for farming.

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

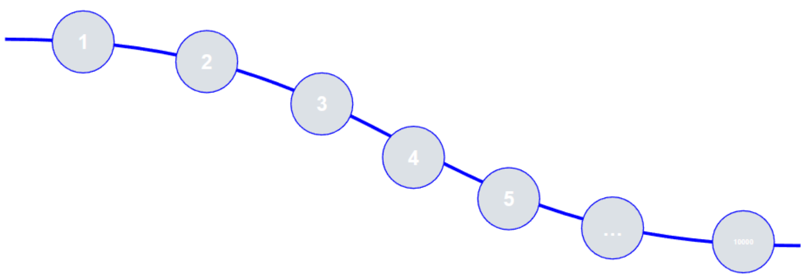
In this scenario, this study aims to assess the joint impacts of oversight of water allocation in an irrigation context. We address the impacts to water users and the canal itself. We develop an ABM that incorporates: 1) a water allocation module for modelling water rights among farmers; 2) an adaptability behaviour called "override", which consists in farmers withdrawing water from the canal even when his/her request is denied by the manager. We apply the model to the Canal do Sertão.

4.2 Model description

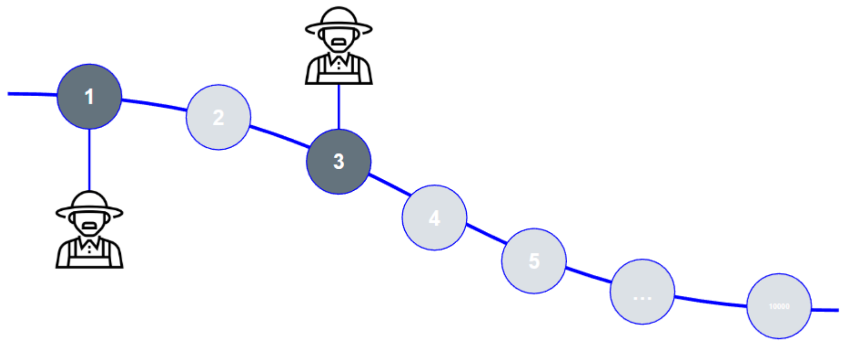
4.2.1 The environment

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

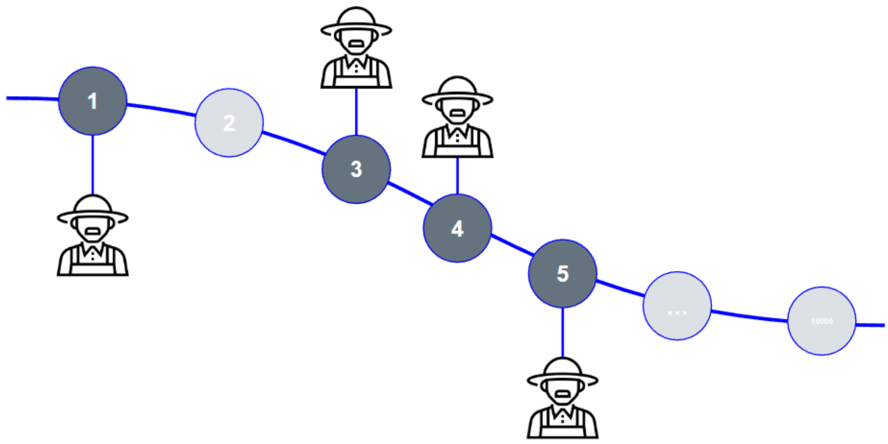
We considered 1 year as the computational time step. This allowed us to assess a multi-annual evolution of the system and simplified the water balance model. Currently at the canal, the water pump works 12 hours/day. Therefore, simple units' transformation was used to calculate water volume in m^3/year. To represent the Canal do Sertão, the spatial world in the model is based on a Line Graph. This enabled 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) that correspond to the segments the Canal do Sertão is divided. Segments are numbered 1 to 15 upstream to downstream. At initialization, 10,000 graph nodes were created (Figure 4a). Each node is a possible position a Farmer Agent can allocate itself. The segment attribute is equally ascribed to all nodes. This means we have approximately 667 nodes for each Canal segment, as there are 15 segments in total. Later we discuss how water balance is calculated for each segment to conceive water rights. See 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 cause water conflicts.



(a) Step 0



(b) Step 1



(c) Step 2

Figure 4: Exemplification how the model starts and modify at each iteration.

Each iteration begins the creation of new farmer agents (Figures 4b and 4c). Each farmer agent has his/her unique (random) characteristics regarding farm area and probability to override . Randomness rules from farm areas are detailed in section 4.2.3.2 from probability to override in section 4.2.5). At each step the farmer updates the crop of choice to harvest in that year.

To decide how many farmers agents to create at every step we looked into the conceived water rights time series (Figure 5). The great amount of water rights conceived in 2019 is justified by a campaign promoted by the manager to register water users with no costs.

Besides the great amount of water rights conceived in 2019 justified by a campaign to register water users, there is no reason 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).

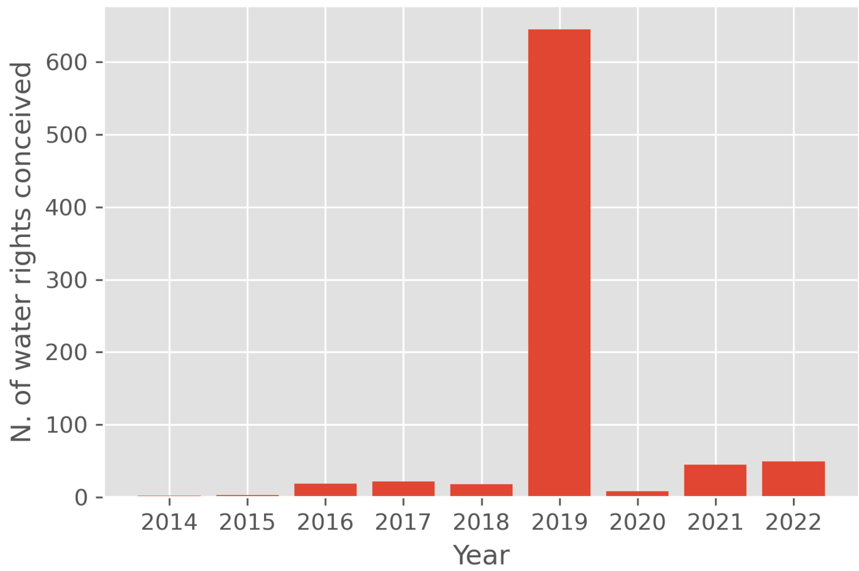


Figure 5: Conceived water rights time series in the Canal do Sertão (data source: SEMARH/AL water rights database until 01-31-2022)

4.2.2 Farmer Agent

We considered the farmer's main objective to maximize the amount of income. In the preliminary model, each farmer is represented by single agents, and not clustered. Clustered farmers, with the same homogeneous properties, although would decrease computational time, and it should be taken carefully, as the loss of micro-scale features that influences the macro-scale system behaviour could be lost in the process. The data collected in the main survey shall address this issue in the main (and final) model.

4.2.3 Water demand forecasting, farm and crop characteristics and water right request

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

4.2.3.1 Crop type

Farmers can decide among a subset of crop types. Considering empirical knowledge of SEMARH/AL officers of 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 3). Crop yield, revenue and production cost was calculated based on the Brazilian Institute of Geography and Statistics (IBGE) data on temporary (IBGE, 2019a) and permanent (IBGE, 2019b) 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 on the Revenue and Cost variables we randomly drew a new value from a normal distribution centered in the values from 2018 data and a standard deviation coefficient of 5% of the 2018 data. In other words, for the step t in the ABM, $Yield_t \sim Normal(Yield_{2018}, 0.05 * Yield_{2018})$ and $Cost_t \sim Normal(Cost_{2018}, 0.05 * Cost_{2018})$.

Table 3: Model parameters on 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

As previously stated, farmers act for their own interest. To choose crop type to plant in each year, farmers take into consideration the profit expected for planting each crop in that year. In the model, farmers 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.

4.2.3.2 Farm area

To calculate farm area, we considered a directly proportional relationship between farm area and water irrigation amount. Another simplification is that the water irrigation amount is equal to the amount conceived in the water right (all water requested is used for irrigation). In the final model of this thesis, this simplification shall be reconsidered depending on the questionnaire's responses.

We used actual water rights data from the Canal do Sertão conceived by SEMARH/AL (Figure 6) to fit a distribution that randomly selected the water demand forecast. We filtered only water rights for irrigation purposes from the dataset and calculated water withdrawal in $m^3/month$.

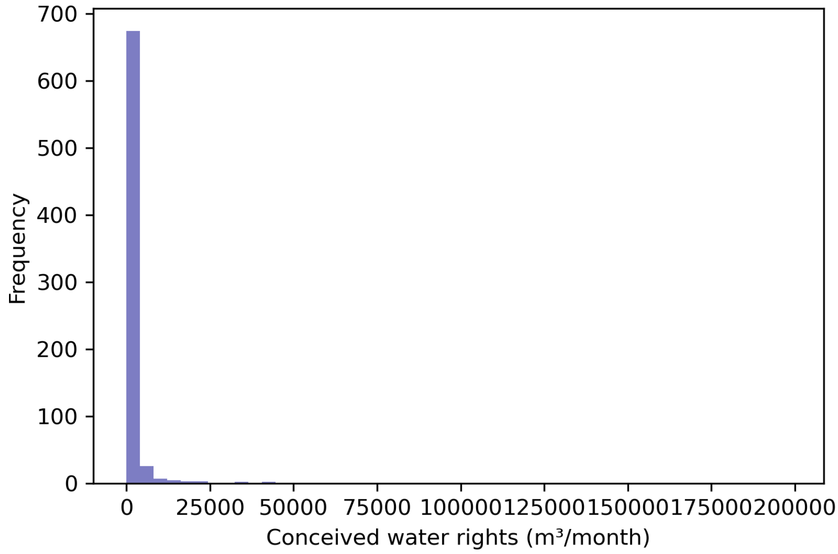


Figure 6: water grants histogram

To convert water rights data into irrigation areas we divided the amount conceived in water rights values by 40 $m^3/h/ha$, which approximates general crop water needs in the region. This value of water is taken empirically from an ad hoc consultation to SEMARH/AL officers[1] and represents the maximum irrigation coefficient which is considered when conceiving water rights. Values above this threshold are usually denied in water right analysis.

To fit data into the distribution, we considered that the amount of 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 has been used as the distribution model to the farm areas dataset. To fit the data, Maximum Likelihood Estimator (MLE) was chosen due to its ease of application and large data series length (Wang & Gui, 2020).

It is important to note that the volume guaranteed in the water right is the main simplification applied in this Preliminary Model. All economic and social factors that influence this specific farmer decision is unknown and shall be identified in the final version of this study.

[1] Augusto H. F. da Cunha, personal communication at SEMARH/AL on January 31st, 2022

Once the farmer agent calculates the predicted water demand for the year, he/she sends a signal to the manager to request the water right if the agent is created (i.e., decided to build a farm) in the current step t. In this preliminary model there is no water rights revision every four years, as it is usual in many water rights policies in Brazil. If the farmer agent already has a 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.

4.2.4 Manager Agent, water use policy, water availability assessment and water right decision

The objective of the manager is to assure the water 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 right to the farmer agent 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.

4.2.5 Adaptability evaluation, water withdrawal and crop production

Once the water right is conceived, farmer agents interact with the environment each year by withdrawing water from the canal. If there is water available, the model calculates the water balance from upstream to downstream, based on the water requested by the farmer to the manager.

In cases where the water right is denied to the farmer, there is a chance that the farmer withdraws water overruling the manager's decision. In the model we call this chance as probability to override P_{over}. To define P_{over}, a random value is taken from a uniform distribution $Uniform \sim (0, 1)$ at agent creation in the model (this is a property inherent to farmer agents and does not change over time). A threshold value is set when starting the model. When water right is denied, if agent P_{over} fall in the threshold oversight value, the farmer agent withdraws water. We explain the chosen threshold value at section 4.3.

In all cases in which farmers withdraw water, they use the requested water amount in its full capacity for production purposes.

4.3 Scenario simulation

Once agents start to override, it will cause conflicts because some other downstream farmer agents will not withdraw water from the canal as expected. The override threshold is a combined effect of farmer personal beliefs, economic aspects and the manager's capacity to oversee whether the water rights conditions have been respected.

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} of 0.3, and scenario B an $T_{over} = 0.1$.

Water shortage in scenario 2 could be a result of long water shortages or issues on the main water pump (currently, the Canal do Sertão only has 1 main water pump that fills the entire canal). Scenario B could be a farmers response to a more stringent oversight due to possible investments in this management sector. Alternate scenarios A and 1 represent the default scenario for comparison. We chose to compose all the scenarios according to Table 4.

Table 4: 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: $WA = 0.6 ; T_{over} = 0.1$

To assess the model results, we ran the model with a time horizon of 20 years. There were two reasons to choose this period: i) watershed 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 horizons.

4.4 Development Framework

In this study, we explore the potential use of ABM under the agricultural scenario using the Project 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. Code and datasets are available at https://github.com/machadoyang/irrigation_abm.

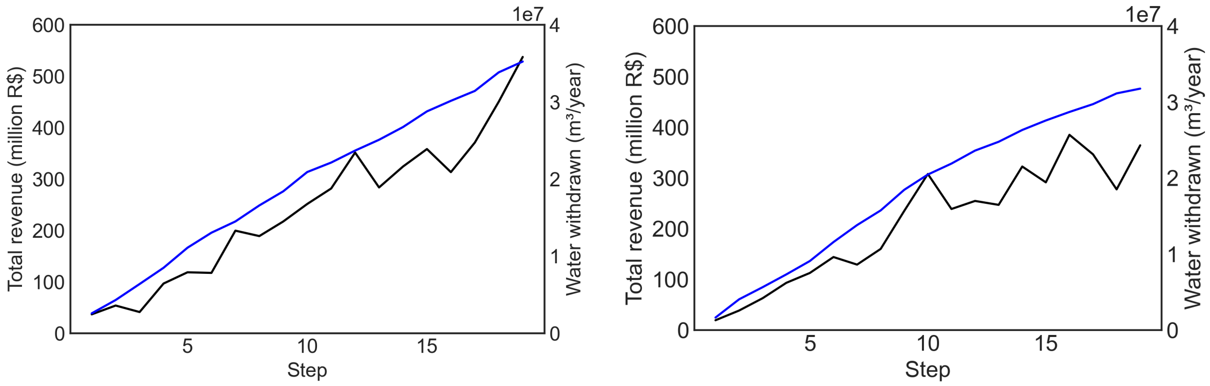
4.5 Results

At the model testing phase, we performed multiple model runs and assessed agents' histograms, water balance, and checked agents at random to evaluate whether their behaviour is according to what is expected in programming. After exhaustive testing, we found no bugs or issues.

4.5.1 Effects from investing in water management oversight (Scenarios 1A and 1B)

For the 1A-scenario, which consists of setting the override threshold at 0.3 and no water shortage ($WA = 1$) total farmers revenue consisted of 537.2 million Brazilian Reais (R$) at the end of the 20 steps (Figure 7a). Compared to the 1B-scenario (Figure 7b), the total revenue ended at 364.3 million R$. Mean revenue for each 1m³/year was R$ 15.25 for 1A-scenario compared to R$ 11.48 for B-scenario. Difference in revenue per unit of water volume is caused by the combination of agents crop choices in both scenarios at this particular step. Monetary predictions do not consider inflation and are based on the Brazilian Real currency from the year 2018.

The total revenue calculated considers only the direct economic impact of the water canal. This would only include effects the farm has on the region due to its operations. The computation of secondary effects, based on the input-output theory (LEONTIEF, 1986), include the impact of local industries buying goods and services from other local industries as a result of withdrawing (and therefore, farming) from the canal. To know the total economic impact from the Canal do Sertão would require the calculation of a regional input-output matrix and its respective economic multipliers, which is out of our scope of this work, and to consider the involved costs to deliver water to users.



(a) (b)

Figure 7: Total farmers revenue over the model steps at (a) A-scenario and (b) B-scenario. Blue line corresponds to water level, and black line to total revenue.

There is a high correlation between total revenue and total water withdrawn. This is an expected result because of the model conceptualization. Farmer area has a direct relationship with the distribution of water requested (i.e., there is a simplification that all crops use the same amount of water). Therefore, the only factor causing the total revenue oscillation throughout the years is a combined effect of crop choice by all farmers. In our model, farmers prioritize crops that are more profitable for the particular year but can also choose a non-optimal profitable crop due to unknown effects.

Considering the 1A-scenario, we performed other model runs until we favored canal drought to evaluate individual farmers (Figure 8). In this particular run, due to stochastic model effects, the canal dried out in this agent canal segment in step 18. Yearly revenue change based on crop choice. In our model, maize is the crop with lowest revenue, followed by cassava and passion fruit (slight variation due to model annual market variability). The combined results of Figure 7 and Figure 8 highlight the importance of elucidating the crop choice step in this thesis final model. Currently agents do not have any memory of previous years and consider only current crops market values to make their decision. This severely impacts the total revenue in the canal.

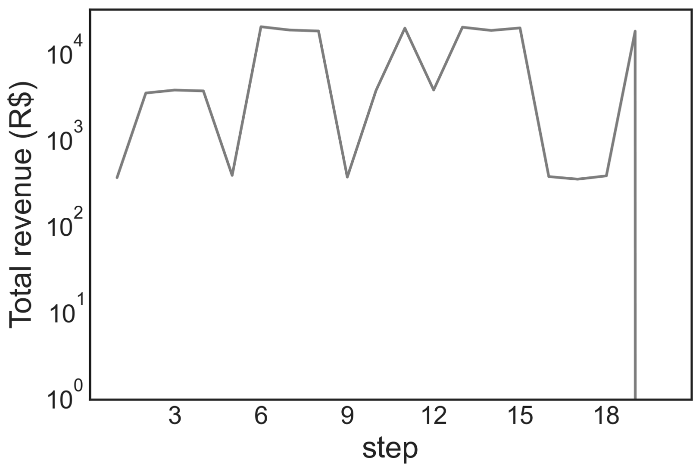
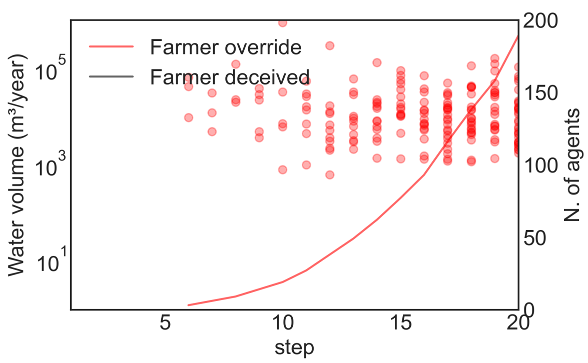
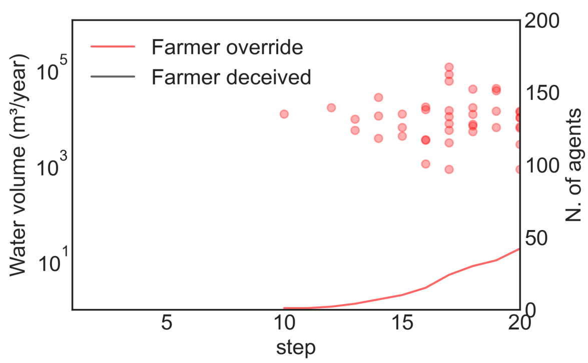


Figure 8: A random farmer revenue over the model steps (1A-scenario).

In the 1A-scenario, farmers started to override at step 6 (Figure 9a) as in segment 14, virtual water reached the zero value at step 5 (Figure 10). When the virtual water ends in any section, following water rights are denied to users. This means that they will accept the denial (and not withdraw at all) or start to override. At step 20, 189 agents were overridden. As the number of steps increase, more agents perform override creating an exponential trend of n. of agents who overrode. This is explained by the increase in the number of segments with no virtual water available. Even with this number of farmers who overrode, by the end of 20 steps, no agent had a water right and could not withdraw water because someone upstream had already withdrawn (no deceived agents). An agent will be deceived only if the real water ends (there is no water to withdraw). In this model run, the canal did not dry out (Figure 10).



(a)



(b)

Figure 9: Override and deceived agents over the model steps. Scatter plot shows only the first-time agents overrode or was deceived. Secondary axis shows cumulative n. of agents over the time steps at (a) 1A-scenario and (b) 1B-scenario.

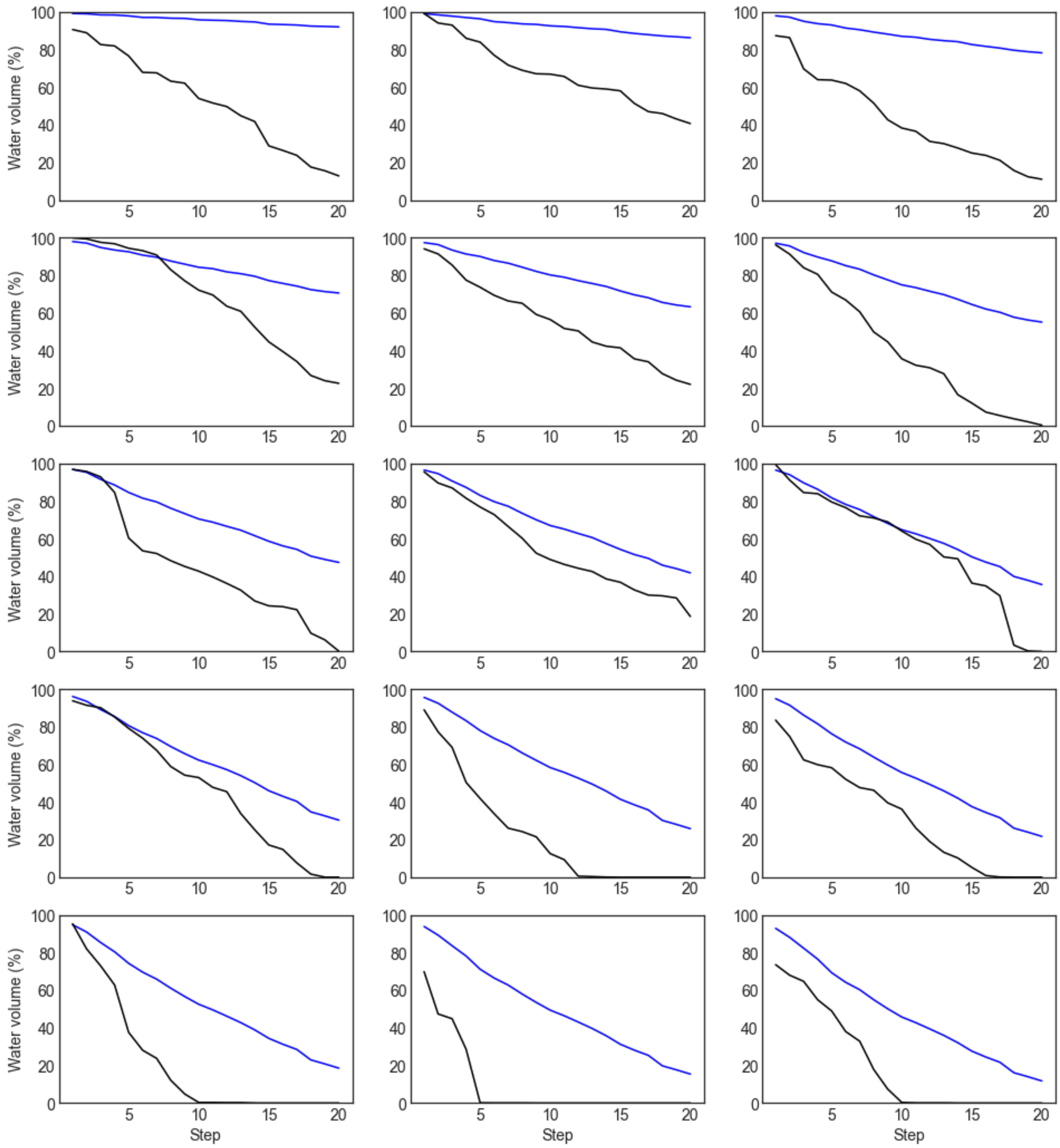


Figure 10: Virtual water volume at each segment. Plots correspond to segments numbers 1 to 15 -in from top to bottom, then left to right at each line (1A-scenario).

Virtual water for segments 13 to 15 ended sooner than other segments, as less water was allocated to these particular segments and agents were randomly allocated in any segment. Interestingly, in this presented model run, segment 14 had no water to allocate at step 5, while segments 13 and 15 only reached this state at step 10. By chance, a great number of agents combined with agents with higher farmer size allocated themselves in segment 14, this can be seen in the attenuated downward slope in the canal water volume in segment 14 at step 5. This elucidates that, in the final version of the model, we need to account for model uncertainty and present results as confidence intervals. This also imposes the challenge of computational burden, which is a disadvantage of ABMs. The personal computer (i7 2.6GHz, 16GB RAM) used to run the presented model took approximately 15 minutes to perform all 20 steps. Naturally, with the increased complexity in calculations of this final model version, this number would be higher. Therefore, we need to review the presented model to decrease the number of loops, processing steps and, wherever applicable, the algorithm complexity.

As expected, less agents overridden in the 1B-scenario (Figure 9b). Also, agents were better distributed in this run (virtual water ended at step 8 at segment 13, Figure 11), as agents only override unless there is no virtual water to conceive. However, even with the difference of over 100 agents overriding when comparing 1A to the 1B-scenario, the difference in water volume between both scenarios was close, remaining 11.72% of water volume in the canal in the 1A-scenario (Figure 10), compared to 11.85% for the 1B-scenario (Figure 11). This, of course, is explained by the combined effect of crop choices and farmland areas of production, as the number of agents in both scenarios are constant. This compensated the inactive agents that did not withdraw in the B-scenario because of the lower override threshold. As in both 1A and 1B-scenarios the canal did not dry out, 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 as long as it is needed to avoid conflicts.

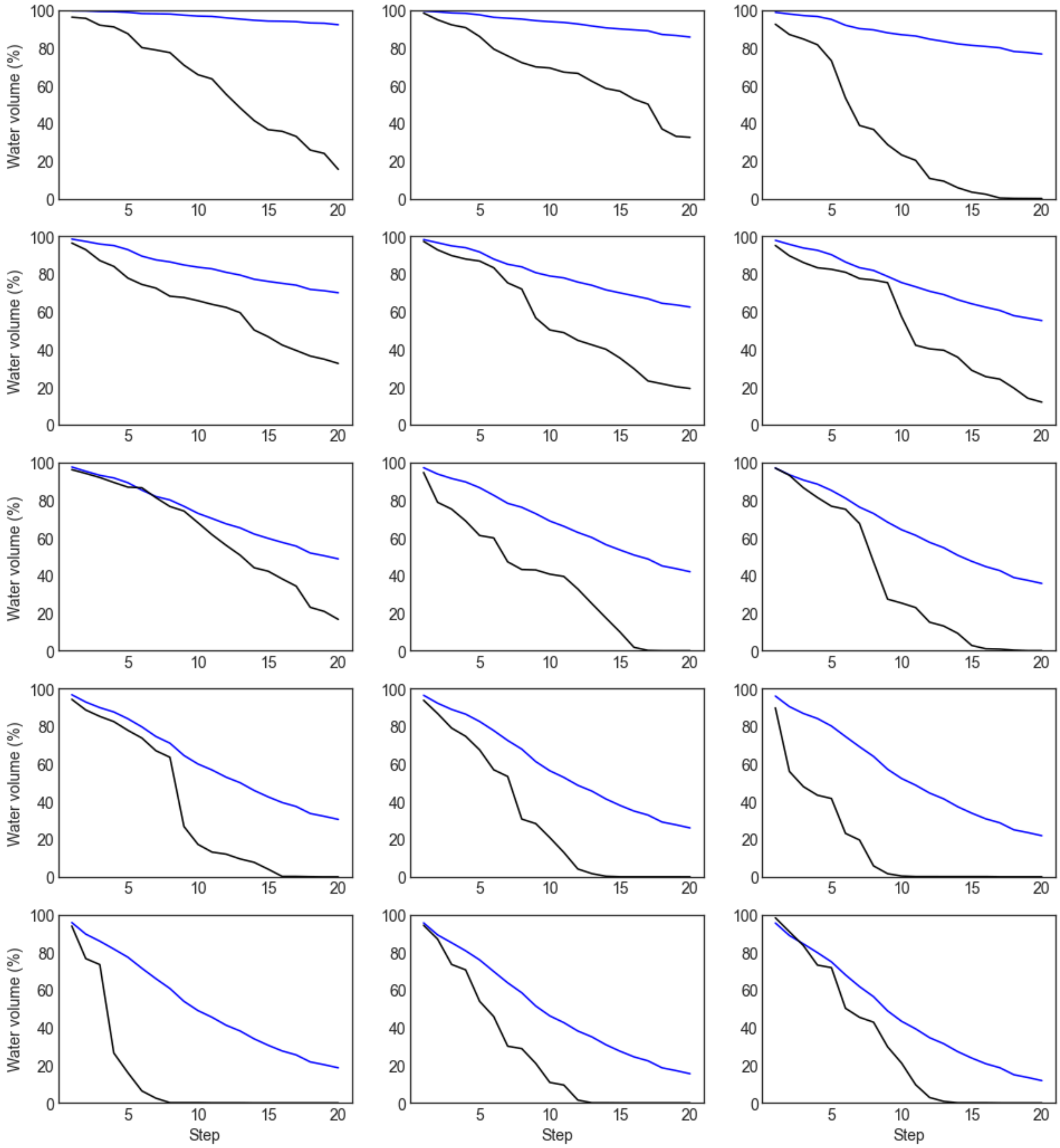


Figure 11: Virtual water volume at each segment. Plots correspond to segments numbers 1 to 15 - from top to bottom, then left to right at each line (1B-scenario).

4.5.2. Effects from water shortage and investing in water management oversight (Scenarios 2A and 2B)

Figure 12 shows the number of agents that overrode and that were deceived at each step for the 2A and 2B-scenarios. As both scenarios consider water shortage conditions, the canal dried out (Figures 13 and 14) and deceived agents started to appear in the latest segments. In the 2A-scenario at the 20th step, 197 have overridden, while 248 were deceived. In the 2B-scenario, where agents had lower probability to override, 67 have overridden and 110 deceived. Comparing both scenarios, in these particular model runs, there was a difference of 130 farmers that had their water right guaranteed.

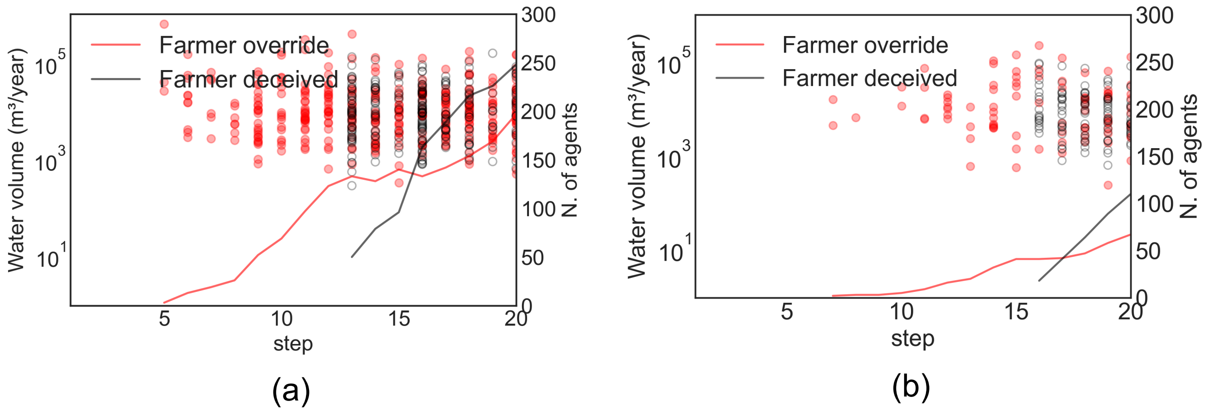


Figure 12: Override and deceived agents over the model steps. Scatter plot shows only the first-time agent overrode or was deceived. Secondary axis shows cumulative n. of agents over the time steps at (a) 2A-scenario and (b) 2B-scenario.

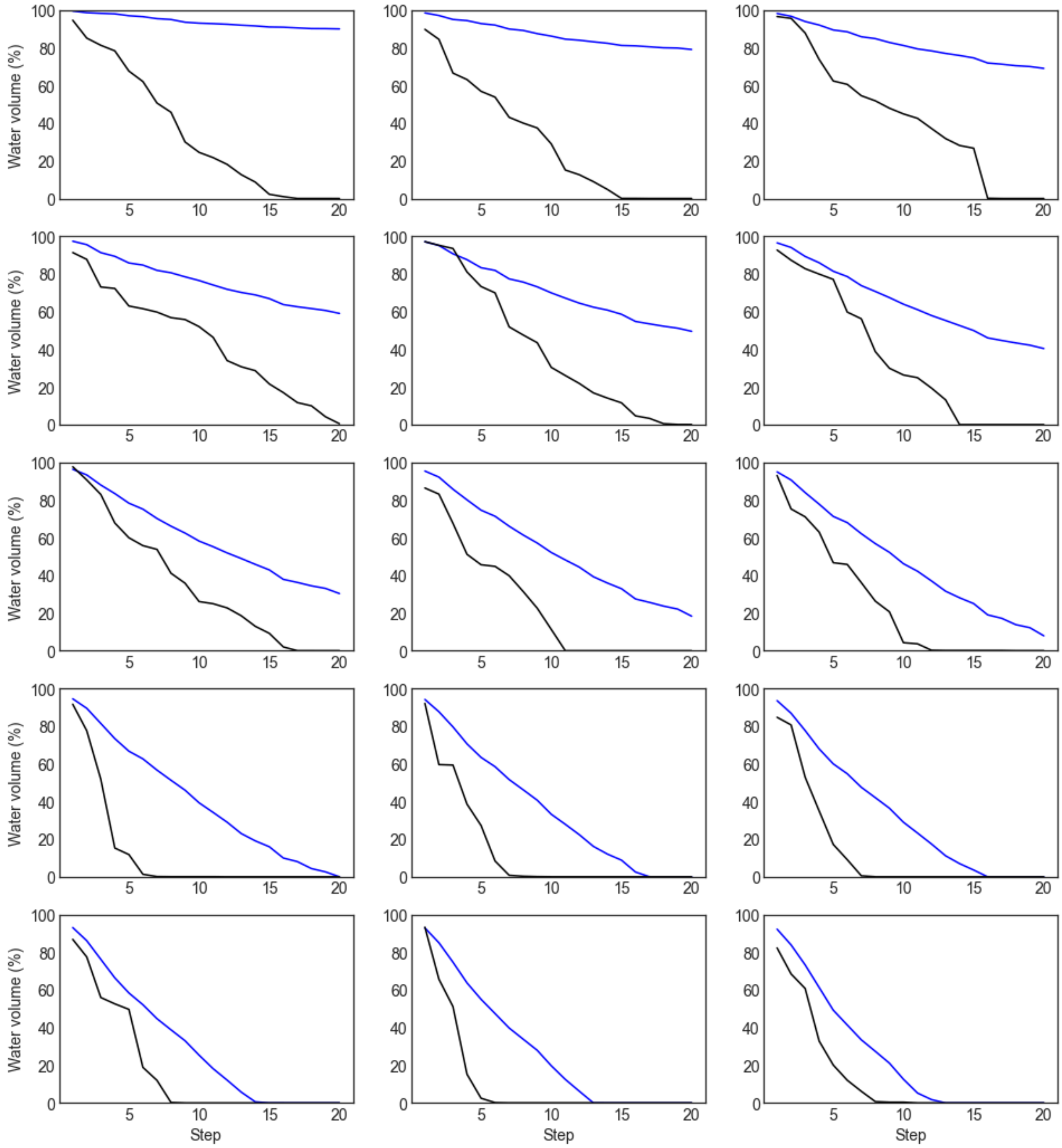


Figure 13: Virtual (black) and real (blue) water volume available to withdraw at each segment. Plots correspond to segments numbers 1 to 15 - in order left to right and top to bottom (2A-scenario)

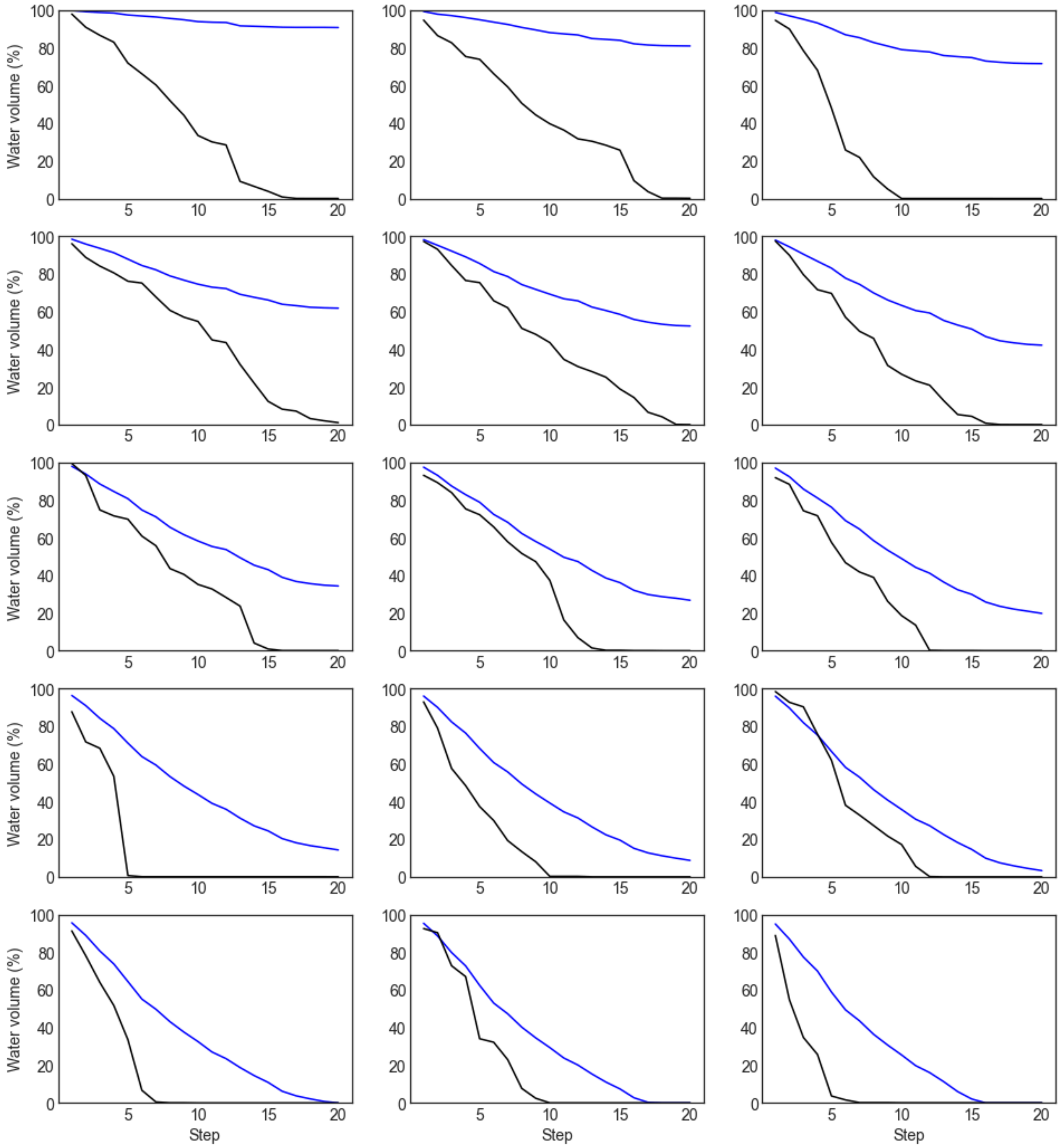


Figure 14: Virtual (black) and real (blue) water volume available to withdraw at each segment. Plots correspond to segments numbers 1 to 15 - in order left to right and top to bottom (2B-scenario)

In both scenarios, there was a lower number of agents to override compared to agents deceived. As the manager denies water considering virtual water by segment, overrides started to be performed well in advance of the apparition of deceived farmers.

Even though all agents are drawn by the same distribution, deceived agents ascend at a much more rapid rate than overridden agents. This behaviour may be explained by the cumulative previous effect of overrides when there was no virtual water, but there was available water volume in the canal. When agents actually stopped withdrawing water due to water unavailability, there were a considerable amount of overrides leading to this effect.

It is expected that when performing more steps in the model, the number of new overrides per step will be similar to deceived when both curves meet. This would be a result of the stationarity structure of the water volume drawing distribution and a result of the maintenance (no destruction) of agents in the model (agents do not move their farmers to other canals or watersheds). The no destruction of agents also implies that deceived farmers continue to fail to withdraw water indefinitely (overrode agents are not “caught” in our model and will also continue to override indefinitely).

4.6 Discussion

The modelling results in this study show the impact that the oversight investment and long water droughts have on both water quantity, and in the local economy to farmers. The resulting impacts can vary considerably depending on the water policy adopted. In our case, we chose to decrease the farmers willingness to override due to a more robust oversight task force. Due to the nonlinear interactions, using an ABM, rather than a traditional top-down model, helped to capture the impacts of individual farmers' decisions in other farmers and in the system. Therefore, policy makers may design more effective water policies and test their expected efficacy by performing scenario-based analyzes. The presented model framework could be used to test implication of different water policies with some adaptation, such as: incentives to a particular crop such as subsidies and credit sources (BYRLEY et al., 2018), or different water rights criteria in face of water scarcity (YANG et al., 2020), the impact of agricultural education programs (EANES et al., 2019), or implementation of pricing charges over water withdrawal (DONO et al., 2010).

This study addresses an agent adaptation measure called override. While we performed a sensitivity analysis (thresholds 0.3 and 0.1) on this parameter, it is paradoxical to get an empirical value for it. Even when performing direct interviews, farmers would not disclose whether they would override if they had a water right denied. On the contrary, they would have no concerns disclosing they would not. Farmers may be self-interested, and it is reasonable to think the dominant strategy would be to override rather than thinking altruistically. The case they would not override shall either be: i) in response to concerns of being fined or suffer legal sanctions; ii) or due to intrinsic characteristics such as environmental preservation, sense of community, faith belief, or normative beliefs (whether most important people to the farmer would approve such behaviour). The latter is not considered in the model so far but could be addressed under the Theory of Planned Behaviour assumption (AJZEN, 1991).

While it is important to study the effects of oversight on water withdrawal, it is equally important to recognize that the need for such analysis suggests that the system is not working as intended. Thus, the focus should be on identifying ways to improve the system and promote sustainable use, represented by the threshold levels. Rather than simply finding ways to enforce compliance, a collaborative approach that involves all stakeholders in the decision-making process may be the most effective way to achieve this goal.

In the study case, when we forced water conflict by restricting the total water available (scenarios 2A and 2B), more farmers were deceived compared to farmers that overrode. In those cases, the manager failed to guarantee water availability to users that had their water right conceived. An incentive in the oversight sector decreased the total amount of deceived water users. Also, the rapid increase in deceived agents compared to overridden agents reiterates that the overridden agents issue could get out of control in just a few years if neglected due to previous effect when no conflict was presented, but overrides were still being made.

One modelling assumption made so far is that farmers' spatial allocation is random. This may not reflect reality, as goods and productive lands (better soil or easier access to water such as by gravity) are not equal, this is in some way mapped by the provided dataset, as later canal segments have less allocated water by default. While the canal division by segments is the first step to account for a more robust model spatiality feature, it is not straightforward. Modelling such non-random behaviour would involve the use of microeconomic datasets (*e.g.*, labor, and cost constraints), and satellite images for land-use mapping. Also, the allocation of farmers already in previous sections are naturally related to construction time from the water canal. Later sections are relatively new.

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 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. The use of empirical data to model farmers' behaviour prejudices model validity, a common challenge in ABMs applications (BLAIR & BUYTAERT, 2016).

As our results showed, crop choice severely impacts the total revenue of the canal. Due to lack of available data on crop types at the Canal do Sertão, secondary data of similar regions were used to address the cost of crop production. Moreover, ad hoc decision was made to choose the main crops planted in the area. We also assumed that decision behaviour among all farmers is homogeneous, which may not be the case for a real-world scenario (SANGA et al., 2021). Conducting interviews to perform behavioural modelling such as discrete choice experiments (see BURTON et al., 2020) and to get descriptive information on crop choice and farming area could be useful for future adaptations. It is also worth considering that when performing such interviews, we get a "picture of the moment". Therefore, we may have to rely on the hypothesis that future farmers will behave in the same way they are now.

To our economy analysis we considered an extrapolation of crop cost, revenue and harvest efficiency. Crop revenue and harvest efficiency were extrapolated from total production of Alagoas State, which may not represent the Agreste production, as this region has a singular climate and soil compared to the rest of the state. Additionally, crop cost information was gathered considering familiar harvesting and similar climate regions. While our model shows beneficial impacts to farmers regarding economic development, we may have to put into perspective what are the costs for water pump and canal maintenance to deliver this water. This of course raises attention for water charge methods. The best method for water charge such as per water volume, per irrigated area or even that considers farmers individual characteristics are all explorable topics in our designed model. For instance, to assess whether a method favors or not the equal distribution of water as a resource using Gini Coefficient (CORREA-PARRA et al., 2020).

The scope of this study was limited to only one type of agent farmer, for the sake of parsimony. However, even though irrigation is the main use, there are a few main players that need to be considered such as withdrawals for human supply for entire cities. Future research could include multiple agent types (AL-AMIN et al., 2018), agents to communicate with each other or to keep memory of previous years when making new decisions. Such modifications would increase model complexity. The impact of climate variability may be explored to evaluate associated impacts in long term planning.

4.7 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 adopts a power law to distribute water rights; ii) an adaptability behaviour strategy of overriding the manager decision. We performed a double scenario comparison of the override susceptibility from farmers. We apply the model to the Canal do Sertão, a transboundary water canal in the Brazilian Northeast semi-arid region.

We found some benefits of using an ABM to assess the impacts in water systems. For the studied case, in 1A and 1B-scenarios, the canal did not dry out for the current water pumping schedule. In 2A and 2B-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 to 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' behaviours would provide more useful modelling results to shape policies towards better water allocation strategies.

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4.9 References

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5 THESIS PAPER PLAN

Paper #	Preliminary title	Expected Results
1	Exploring the effect of oversight for water allocation irrigation systems	Oversight sensitivity analysis in a functional ABM

Paper #	Preliminary title	Expected Results
		(section 4 of this pre-thesis)
2	Understanding the decision-making behaviour of farmers in a transboundary canal in Brazil	Understand how farmers decide through choice experiment
3	Integrating farmers' behaviour and agent-based models for sustainable water management	Address main impacts and identify emergent behaviours