UNIVERSIDADE FEDERAL DE PERNAMBUCO
CENTRO DE TECNOLOGIA E GEOCIÊNCIAS
DEPARTMENTO DE ENGENHARIA CIVIL
PÓS-GRADUAÇÃO EM ENGENHARIA CIVIL

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MODELLING HYDROCOMPLEX PROCESSES FOR WATER ALLOCATION MANAGEMENT

Recife
2025

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Tese apresentada ao Programa de Pós-Graduação em Engenharia Civil da Universidade Federal de Pernambuco como requisito para obtenção do título de Doutor em Engenharia Civil.

Área de concentração: Recursos Hídricos.

Orientadora: Prof. Suzana Maria Gico Lima Montenegro

Orientadora externa: Prof. Mette Termansen

Co-orientador: Prof. Christopher Freire Souza

Recife

2025

.Catalogação de Publicação na Fonte. UFPE - Biblioteca Central

Gomes, Yan Ranny Machado.
Modelling hydrocomplex processes for water allocation management / Yan Ranny Machado Gomes. - Recife, 2025.
101f.: il.

Tese (Doutorado)- Universidade Federal de Pernambuco, Centro de Tecnologia e Geociências, Pós-graduação em Engenharia Civil, 2025.
Orientação: Suzana Maria Gico Lima Montenegro.
Orientação externa: Mette Termansen.
Coorientação: Christopher Freire Souza.

1. Sociohydrology; 2. Agent-based model; 3. Choice model. I. Montenegro, Suzana Maria Gico Lima. II. Termansen, Mette. III. Souza, Christopher Freire. IV. Título.

UFPE-Biblioteca Central

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RESUMO

O acesso à água é um direito de todos, e cabe aos agentes governamentais alocá-la de forma a garantir seu uso sustentável para múltiplos usuários. No entanto, decidir a melhor estratégia de alocação não é uma tarefa simples, especialmente em sistemas complexos que dependem de uma coleção de decisões individuais. Esta tese desenvolveu uma estrutura preditiva integrando modelagem baseada em agentes (ABM) e modelagem de escolha para avaliar os impactos socioeconômicos e ambientais de políticas hídricas considerando as decisões dos agricultores. Utilizando o Canal do Sertão, no nordeste do Brasil, como estudo de caso, a pesquisa ofereceu informações práticas sobre a eficácia de políticas como assistência técnica e tarifação da água. Os resultados revelaram impactos econômicos, incluindo as receitas de agricultores e gestores hídricos, além de avaliar a influência das políticas nas práticas sustentáveis de uso da água. A pesquisa destacou a importância de compreender os fatores socioeconômicos e comportamentais, que melhoraram significativamente a avaliação dos impactos das políticas pelo modelo. O engajamento com stakeholders revelou o desalinhamento de certas políticas testadas e ressaltou a necessidade urgente de políticas de assistência técnica. Ao combinar o envolvimento de stakeholders com modelagem iterativa, esta tese contribui para a elaboração de estratégias mais eficazes de governança hídrica. Aplicações futuras em outros contextos e a integração de mecanismos de aprendizagem adaptativa podem avançar ainda mais as estruturas de gestão sustentável da água.

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. This thesis develops a predictive framework integrating agent-based modeling (ABM) and choice modelling to evaluate the socio-economic and environmental impacts of water policies considering farmers' decision-making. Using the Canal do Sertão in northeastern Brazil as a case study, the research provides actionable insights into the effectiveness of policies such as technical assistance and water pricing. Our findings reveal key economic impacts, including farmer and water manager incomes, and assess the influence of policies on sustainable water practices. Our research highlights the importance of understanding socio-economic and behavioral drivers, which significantly improved the model's policy impact assessment. Stakeholder engagement revealed the misalignment of certain other tested policies while emphasizing the urgent need for technical assistance policies. By combining stakeholder input with iterative modeling, this thesis contributes to designing more effective water governance strategies. Future applications in other contexts and the integration of adaptive learning mechanisms can further advance sustainable water management frameworks.

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

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1 INTRODUCTION

1.1 Rationale

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). Water is a right of all people and, in Brazil, federal and state government agencies manage water withdrawal and use (BRAZIL, 1997). These agencies' main role in water allocation is to guarantee its sustainable use for multiple purposes. However, in complex systems that depend on a collection of individual decisions by people, guaranteeing such sustainable water use is not a straightforward task.

In what we may call "classical hydrology," the focus is primarily on the physical processes of the water cycle, often treating human activities as external factors or boundary conditions. However, this approach falls short in capturing the complex interplay between human actions and water systems, which introduces what is referred to as Hydrocomplexity—an inherent unpredictability in these interactions that challenges effective water policy formulation (SIVAPALAN, SAVENIJE & BLÖSCHL, 2012; KUMAR, 2015). This complexity requires policymakers and stakeholders to carefully evaluate trade-offs, balancing socioeconomic benefits and prioritizing equitable allocation of limited water resources.

In agriculture, farmers often make decisions based on their own interests, weighing various factors such as external conditions (e.g., social, political, and economic contexts) and their previous experiences (MEEMPATTA et al., 2019). Because of this multi-factorial and non-linear behaviour, the outcome of water policies may not be easy to predict. In this scenario, what would happen to the future of water bodies if their users—who are individuals with critical thinking, and may behave in their own interest—are not yet explicitly considered in hydrological models? And how to define the best water allocation policy toward sustainability considering the human-water interface?

In this thesis, we propose a model that integrates social behavior into hydrological modelling, addressing a challenge that remains an ongoing area of research and is recognized as one of the "23 unsolved problems in hydrology" (BLÖSCHL et al., 2019). We demonstrate the application of our model within the context of a water canal primarily used for irrigation, focusing on the Canal do Sertão - a key study case in the semi-arid region of Northeast Brazil.

1.2 Objectives

General objective:

Develop a predictive framework for assessing the impacts of water policies considering the decision-making behaviour of farmers.

Specific objectives:

- Develop a model that captures the intricate interactions and decision-making behaviours of water users.
- Evaluate the trade-offs for policymakers and stakeholders regarding the socio-economic impacts of water-related policies, with a focus on water pricing and incentive policy strategies.
- Predict the socio-economic and water availability impacts of water policies, considering both long-term trends and potential feedback mechanisms.

1.3 Hypothesis

Understanding the socio-economic and behavioral drivers behind farmers' decision-making improves the impact of water policies.

1.4 References

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2 HYDROCOMPLEXITY

This theoretical development is a short collection of different fields of research that investigate modelling of complex systems related to water resources management. We divided the following sections into three main questions: what, why, and how. In "what", we explain in more detail the term Hydrocomplexity and its context. In "why", we explore the complexities of human-water interactions, providing a more comprehensive outlook on the importance of this thesis. Finally, the "how" presents a background on the techniques proposed to solve the water allocation management giving a focus on their application in Brazil.

2.1 What (is Hydro-complexity)?

Complex systems are characterized by behaviors that are difficult to model due to the interdependencies, competition, and various interactions between individuals and their environment (DOWNEY, 2018). Environmental systems provide a classic example of such complexity, where multiple interacting entities, such as animals, vegetation, microorganisms, and humans, are influenced by environmental variables like water availability, land use, land cover, and climate.

Given the combined effects of population growth and expanding cities, water demand 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. In the water management field, people were included in modelling for many years only as 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.

Due to the interdisciplinary nature of hydrocomplex systems, scholars may give more attention to their particular area of expertise leading to a "field bias" in their studies. Some interdisciplinary fields arose in the last few decades in the water sciences. The Integrated Water Resources Management (IWRM; GWP, 2009) approach involved the integration across the whole hydrological cycle by including different water users and establishing 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. Ecohydrology (FALKENMARK, 2004) integrates aquatic and terrestrial ecosystems (including human effects) and tries to understand their relationships to improve water security, enhance biodiversity, and aim toward sustainable development. 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 balanced attention to these three sectors and their connections.

All these different field names correspond to different perspectives of the same problem: how to effectively manage and allocate water resources in a way that balances environmental sustainability, human needs, and socio-economic development? This thesis also tries to answer part of this problem. Each of the interdisciplinary fields takes a perspective as a facet of a prism (PARKES et al., 2010), where each vertex corresponds to a field and because of some limitations (*e.g.* expertise, scope, budget), they only look at a "facet" at a time. Each "facet" represents paired interdisciplinary approaches that must be taken more holistically by considering the entire scope of human activities and their respective impacts.

To this end, we believe the term *Hydrocomplexity* (KUMAR, 2015) better recognizes complex systems as interconnected processes in water resources that may have emergent behaviours. In this sense, we believe Hydrocomplexity as the umbrella term of all sorts of expertise fields by researchers towards an integrated watershed governance that considers complex systems.

2.2 Why (human-water interactions are complex)?

The creation of water problems due to the influence of man's activities has been discussed for long time (FALKENMARK, 1979). However, recently, socio-hydrology called itself a new science for recognizing the dynamics and co-evolution of coupled human-water systems and blaming "traditional hydrology" for ignoring the human factor in water modelling (SIVAPALAN et al., 2012). While this supposedly novel field is being criticized of being a re-worded idea (SIVAKUMAR, 2012), it is undeniable that Hydrology is becoming increasingly interdisciplinary over time and socio-hydrology opened a new space of interest in studying complex human-water systems problems (MADANI & SHAFIEE-JOOD, 2020).

It is not our intention to get in the eye of the storm of the debate whether it is a novel science or not. Even though we acknowledge the overlapping fields of expertise as discussed in section 2.1. We are interested in discussing why human-water systems are complex and why this is a hot topic just recently.

Naturally, our answer relies on an interdisciplinary perspective. The vast majority of socio-hydrology papers are focused on quantitative methods or qualitative methods. However, integrating social sciences and hydrology without oversimplifying one or another is yet a difficult task (MADANI & SHAFIEE-JOOD, 2020).

The conflicts for water not only can involve aspects of hydrology, hydraulic, biology, chemistry, and economy. May need the integration of several public agencies, public and private. May be necessary to accommodate interests of several municipalities, states, and the Union. This number of different sectors and stakeholders makes the relationship between them very complex. In some cases, emergent behaviours may appear.

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.

Some emergent patterns, often counter-intuitive, have been studied in sociohydrology, here we summarize some of them:

- The levee effect: people deal with flooding with a combination of structural (e.g. levees) and non-structural measures (e.g. resettlements). Levees change the frequency and magnitude of floodings protecting areas from such natural disasters. The sense of safety due to the construction of such hydraulic structures increases exposure and vulnerability to rare and catastrophic floods. Because people "forget" how it was when floods occur (known as *flood memory*), the impact of such events is accentuated (COLLENTEUR et al., 2015; HUTTON et al., 2018).

- The reservoir effect: the overreliance on reservoirs increases vulnerability and increases the potential damage caused by droughts. Extended periods of abundant water supply reduce incentives for individuals' preparedness and adaptive actions (DI BALDASSARRE et al., 2018).
- The supply-demand cycle: as the availability of water increases, the consumption tends to increase[1]. In water management, the supply-demand cycle mainly refers to irrigation efficiency. As availability increases, an unsustainable exploitation of water resources and environmental degradation arises (DI BALDASSARRE et al., 2018).

To answer "Why human-water interactions are complex" we narrow down to two answers. The answers derive from partitioning the word "socio-hydrology". First, we start addressing the "hydrology" part.

2.2.1 Because water is a scarce resource

Besides its environmental value, water is seen as a resource by people. The allocation of water involves distributing this scarce resource among various competing users. The water that runs off and is stored in rivers, lakes, reservoirs, and underground aquifers is seen as a public good. These are characterized by their characteristics of non-excludability (hard to limit access) and non-rivalrous consumption (use by one does not deplete for others). Most often, governments play an important role in managing water to guarantee its sustainable use. In this sense, water allocation has its foundation in the property rights theory, providing the legal and institutional framework for governing the access, use, and distribution of water resources among diverse stakeholders (DINAR et al., 1997).

In Brazil, government agencies can grant water rights (BRAZIL, 1997). In case of superficial water bodies, such as rivers and lakes, are within a single state, a state-wide government agency is responsible to give other rights, in case it crosses multiple states, the National Water Agency can grant water rights. A person or entity can request a water right to a water agency. The agency can fully or partially grant the water right or deny the water right respecting prioritized purposes of use, local policies, and water availability.

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[1] This is known in economics as Jevons paradox. It occurs when a technological progress or government policy increases the efficiency which a resource is used, but the lower cost of use induces increasing in demand. This can make efficiency policies counter-productive (ALCOTT, 2005).

According to the Brazilian National's Policy of Water Resources (BRAZIL, 1997), there are six instruments for water management:

1. The water resources plans.
2. The classification of water bodies into categories based on their predominant uses.
3. The right of use of water resources.
4. The charging of water resources.
5. The compensation to municipalities (vetoed).
6. The Water Resources Information System.

As the national water policy recognizes water as a scarce resource, it also sees water as an economic good (ROGERS et al., 2002) and sets water charging as an economic instrument to i) provide users with an indication of its real value; ii) encourage rationalization; and iii) obtain financial resources for water-related programs and interventions.

Manufacturers often see water *cost* and *price* as synonymous: the amount charged to end-users or consumers is equal to the total expenditure incurred in the entire process of providing water services. However, often price does not capture all the cost elements of water use, which should account for economic and social costs related to scarcity and environmental externalities (DAS et al., 2023). The pricing of water should push toward a more holistic approach that quantifies the human welfare benefits and compensates for the loss of services (DAILY & MATSON, 2008).

Some commonly used metrics to quantify the value of water are the shadow price of water, elasticity, and willingness to pay (WTP). The shadow price of water represents the opportunity cost of water. In other words, the value of a good that can be produced by the marginal unit of water used is expressed in terms of R$/m³. By using price elasticity, we analyze the change in water demand concerning change in water price or cost. Finally, the WTP corresponds to the maximum price a consumer will buy one unit of a product (in our case, 1 m³ of water).

There are mainly four water charging methods: volumetric pricing, non-volumetric pricing, quotas, and water market. For irrigation, non-volumetric pricing normally depends on the size of the farm. Due to the costs of implementing a metering system, it applies flat rates per acre and is crop-related. This method is convenient because of its ease of application, especially in places such as the Brazilian semi-arid, where theft of water pumps is a common crime in the region. However, it still cannot guarantee a rational use of water because of lacking water efficiency measures (IMAD et al., 2019). Under the volumetric approach, charges are applied based on the quantity of water consumed. While this can encourage efficient use, as already stated, the high price of implementing metered systems is still a challenge. Water quotas refer to assigned amounts of water for use by a specific entity (*e.g.*, individual, household, agricultural operation). This approach aims to ensure a more equitable distribution of water among various users. Finally, water markets are referred to as a temporary exchange of water-use rights of a given quantity between neighboring users. This sometimes requires government intervention to define the original allocation of water rights, the legal framework that regulates the trading rules, and investing in basic infrastructure to allow water transfers.

As we already know, the use of water involves various stakeholders. When deciding the water price, we must consider the capacity of payment by the various users. The New Legal Framework for Sanitation (BRAZIL, 2020) recognizes the capacity of payment when deciding on charging sanitation services. Subsidies to users who do not have the means to pay may be employed to cover integral costs of services. For instance, the human supply of water has a high capacity for payment because it must attend to basic human needs such as drinking, showering, and cooking. On the other hand, irrigation usually has a lower capacity of payment, as it uses a high amount of water per hectare and does not need to meet high standards regarding water quality (PEDROSA, 2021).

To make this practical, we make the Integration Project of the São Francisco River (PISF) an example. PISF is an artificial water canal that aims to deliver water to 12 million people in four states in Northeast Brazil. Because of the project size and the multistate water supply, finding a consensus on water taxes required effort and political arrangements. First, the project delivers water to four Brazilian states: Pernambuco, Ceará, Paraíba and Rio Grande do Norte. To cover costs in operation and maintenance, a water price is established by the Brazilian Water Agency under the volumetric pricing. This tariff is designated to the state water agencies that are responsible for sharing costs among water users. The water price was divided into two segments: availability and consumption. The availability term accounts for water availability costs such as fixed costs for electricity, operation, and maintenance; while the consumption term accounts for variable costs for electricity and administrative taxes (ANA, 2023).

Price segment	Water price in 2024 (R$/m³)	Water price in 2023 (R$/m³)	Expenses description
Availability	0.322	0.295	Operation and maintenance, environmental costs, asset replacement fund, administrative expenses, water charging, energy (fixed cost), administrative expenses (fixed cost) and depreciation.
Consumption	0.204	0.636	Energy (variable cost) and administrative expenses (variable cost)

Such values are put in perspective regarding the capacity of payment of water users. A comfortable paying price would be based on the capacity of payment and the share of sanitation expenses on total family income. Using Ceará as an example, the comfortable paying price is 1.32 R$/m³. Even though the agro sector shows capacity of payment, the water price would have an impact of 7.2% for properties lower than 10ha, which corresponds to 77% of properties in the state. The industry and human supply sectors could subsidize the agro sector (ANA, 2020). This only highlights, the complexity of establishing prices for multiple purposes.

Even though water legislation has come far in Brazil as we have seen at PISF, water charging policies are still deficient. By 2020 only 6 of 27 states and 6 of 30 federal river basins have implemented charging policies in water bodies. While farming users account for 60% of water abstraction, they represent 1.2% of the total payment collected (BRITO & AZEVEDO, 2020). We agree that to guarantee fair water charging in Brazil, public water prices must be addressed by hydrologists, economists, decision-makers, and other stakeholders such as water users and Hydrographic Basin Committees (BRITO & AZEVEDO, 2022). To do so, increasing stakeholder participation and understanding their interests is key moving towards more sustainable and effective water management. That's why the "socio" part of socio-hydrology cannot be neglected.

2.2.2 Because people are complicated

The Integrated 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 the 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; allow overviewing of spatial and time scales, as ecological processes do not have 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).

Frequently, stakeholders' perceptions are not taken into consideration when making water management policies (WALTNER-TOEWS *et al.*, 2003). Making them part of the process of designing policies could enhance transparency, as this process could help stakeholders understand why certain decisions were made (CLIFFORD *et al.*, 2022).

The success of water policies is completely dependent on the acceptance and implementation on the micro-level scale, *e.g.*, by farmers (JORGENSEN *et al.*, 2009), especially when policies rely on voluntary acceptance by the end users (BOAZAR *et al.*, 2019). 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 is influenced at different levels, which range from individual beliefs and values to community and societal norms (MILLS *et al.*, 2017). It is recognized that farmers do not always make decisions based on solely economic aspects, but weights with intrinsic goals (GASSON, 1973).

While people try to fulfill their needs at any cost, they try to adapt themselves to the deteriorating 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 do 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.

To do this, we need to integrate human behaviour into water management modelling. While this integration has been a major challenge in literature (PANDE &

SIVAPALAN, 2017), a combination of methods is required (KELLY *et al.*, 2013; MEEMPATTA *et al.*, 2019; DI BALDASSARRE *et al.*, 2021). In the following section, we present the background of the techniques used in this thesis.

2.3 How (to address complexity in water management)?

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 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 oppositely design a model 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 an 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. 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).

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 in 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.

In water resources management, ABMs show usage because of their substantial capacity to design robust policies and incentives to help with 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.

Addressing spatiality is often a challenge in socio-hydrological modelling (BLAIR & BUYTAERT, 2016). Khan *et al.* (2017) considered coupling an ABM with a semi-distributed hydrologic model (SWAT) in two transboundary basins, the Mekong River basin in Southeast Asia and the Niger River basin in West Africa. In their model, agents ranked their preferences in order of importance considering hydropower generation, crop production, and ecosystem sustainability. They divided the basins into hydrologically similar sub-catchments and treated each sub-catchment as an agent. Due to system complexity, this is not uncommon in hydrological ABMs. Even though such discretization is necessary to run hydrological models, it is improbable that agents' behaviour is homogeneous exactly following hydrological or political boundaries. Spatiality was also represented using grids (TAMBURINO et al., 2020) and networks (GOMES et al., 2022).

Integrating human behaviour into hydrological ABMs is still deficient in literature and is one of the main challenges of socio-environmental systems modeling (ELSAWAH et al., 2020). Most ABMs lack grounding agents' behavioural rules in existing theories. Most often, agents' actions are based on *ad hoc* decisions that compromise models to represent reality (MAGLIOCCA, 2020). Examples of behavioural theories that can be used are microeconomic theories of rational choice and profit maximization (MCFADDEN, 1986) or sociological theories such as the Theory of Planned Behaviour (TPB; AJZEN, 1991).

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. The technical term for well-being in the economy is utility. Utility is related to concepts of happiness, satisfaction, and welfare. While these concepts are difficult to measure, economists use the utility to get an idea of these non-quantifiable aspects. Utility permits quantitatively modeling behaviour conceptually.

In the utility theory, 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, people (in our case, water users) 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 decide (EDWARDS-JONES, 2007), might interfere with individuals' preferences.

In agriculture systems, economic models such as choice experiments have been greatly used to understand people's priorities to model policies, products, and services. Studies have found that farmers may have economic and non-economic reasons that influence their willingness to participate in farming-related policies. Training (ZHANG et al., 2019), cooperation (PAKMEHR et al., 2020), access to weather forecasts (ALCON et al., 2019), economic incentives (GIANNOCCARO et al., 2022), access to credit (DENKYIRAH et al., 2017), insurance schemes (JØRGENSEN et al., 2020), payment mechanisms (BURTON et al., 2020), and others (MEEMPATTA et al., 2019) have an impact on farmers' adaptation to new water-related policies. Additionally, farmers' characteristics such as gender, educational level, income (KHAN & ZHAO, 2019; MARIE et al., 2020), and their individual values (MOHAMMADINEZHAD & AHMADVAND, 2020) also have an impact on their decisions.

Understanding such reasons that influence farmers' decisions, may help modelling and increase policy acceptance and relevance. However, approaching stakeholders to gather such knowledge is difficult and requires time. Recruiting them

them to help design hydrological models, besides just using experiment data may also improve policy design in order to meet everyone's expectations (HÖHLER et al., 2023). Sometimes, non-governmental stakeholders have mistrust issues with government agencies (BURTON et al., 2020), which can be another barrier to conducting such research. Being transparent regarding research motives and goals, and how their inputs are used in the model is key to building trust.

Conducting field experiments is a difficult task, as farmers' response rates are often low (ROSCH et al., 2021; WEIGEL et al., 2021). Some of them do not have the willingness to spend some minutes answering online surveys (PENNINGS, et al., 2002) or, in our experience, are illiterate and/or technologically unskilled. The alternative is meeting them in person, which increases survey costs and requires local articulation by trusted organizations or people who can facilitate access and communication.

Addressing complexity in water management requires integrating robust modeling approaches that account for human behavior and socioeconomic dynamics. While methods such as ABMs and economic models like choice experiments offer valuable insights, they also highlight the challenges of capturing emergent behaviors and stakeholders' diverse priorities. Building trust with stakeholders, addressing spatial heterogeneity, and incorporating behavioral theories are critical steps to enhance the realism and relevance of these models. Moving forward, the integration of these approaches can provide a more comprehensive understanding of water use dynamics, ultimately supporting the development of policies that are both effective and equitable.

2.4 Summary

The theoretical development presented in this section explored complex systems in water resources management. We defined hydrocompelxity and explained the interdisciplinary connections. It addressed the "what" by defining Hydro-complexity and its interdisciplinary connections. We delved into the complexities of human-water interactions, emphasizing the need for a comprehensive understanding. Finally, we addressed the background of bottom-up models integrating human behavior into them, exemplified through ABM and DCE. In the next section, we show the details of how we can effectively integrate ABM and DCE to pave the way for integrated water governance.

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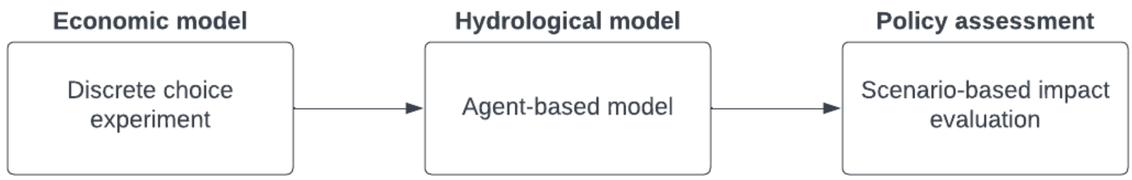
3 METHODOLOGY

The methodology is divided into three main steps (Figure 1). First, the economic model captures farmers' decision-making process. In this step, we a used discrete choice experiment to analyze which farmers' characteristics affect their decision-making and assess their willingness to accept paying for water and willingness to pay for farming-related services. We conducted a survey where farmers responded to hypothetical scenarios regarding farming-related policies. Results from the economic model were used as input for the next step.

Figure 1: Methodology workflow.



Source: The author (2025).

For the hydrological model, we used an agent-based approach due to the complex interactions among water users, the manager, and the water body. As the Canal is mainly used for irrigation purposes, we limited water users to farmers. Their main objective is profit whose decision-making parameters come from the economic model. Then, we created a manager agent that aims to guarantee sustainable water use by controlling the water allocation process and implement policies.

We chose to use Canal do Sertão as a study case. It is a water canal located in Northeast Brazil in the semi-arid region. This canal may be the only source of water for many users in the region. We assess the impact of different policies for Canal do Sertão. We first give context on the studied case, then we detail the methodology steps.

3.1 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 2). 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 water manager, who currently is the Secretary of State for the Environment and Water

Resources of the state of Alagoas (SEMARH/AL). In the writing of this thesis, the management of the canal is being transferred to the Alagoas Sanitation Company (CASAL). The water charging price is going to be defined by a committee including both SEMARH/AL and CASAL, and the Secretaries of State of Infrastructure (SEINFRA) and Agriculture (SEAGRI). For the sake of simplicity, whenever possible, we will refer to them just as “water manager”.

Figure 2: Study location map

Source: The author (2025).

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. The canal was built to mainly supply irrigation purposes. In a smaller water amount, the canal was projected to supply cities, industry usages, and livestock feed, among other purposes.

The Canal its been aim of controversies due to its high investment (over 2.3 billion Brazilian Reais) and low water utilization of 0.9 m³/s (TCU, 2020). Currently, the water manager does not charge for water use in the Canal and the state covers operation and maintenance costs. As the costs are high for the state to keep, a water charging policy was recently proposed in the Canal Management Plan (HIDROBR, 2022). Although discussions on charging are underway and seem imminent, the majority of irrigators in the Canal is composed of small farmers, and charging could highly impact their income, slowing down the local economy by hindering farmers' ability to expand, thereby contradicting the primary objective of the Canal.

The Canal is still under construction and the already section in operation is divided in 15 segments that subdivide the canal for management purposes. Segments have watergates to divide them from the upstream segment. In practice, each segment acts as a reservoir and the water balance is a system of cascade reservoirs. The planned water available for each segment (Table 2) considers segment length and the maximum evaporation (m^3/day). The available water is calculated by a water balance that considers the pumped water to the canal, evaporation losses, and eventual water withdrawals by water users.

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

Source: The author (2025).

3.2 Discrete choice experiment

To understand farmers' decision-making, we used a three-step survey based on a discrete choice experiment (DCE). All three steps, named pre-study, pilot study, and main study, are summarized as follows and detailed in the next sections:

- Pre-study: Farmers were surveyed using open-ended questions to understand which attributes and levels they take into consideration when faced with water policies. In this way, we used their responses to design attributes and levels for the choice experiment.

- Pilot study: We presented hypothetical choice tasks regarding water policies to a smaller number of farmers (~10% of the sample size) to validate the DCE design and to establish informative priors for the main study. We explain later what priors are and their influence on the experiment design.
- Main study: The DCE experiment was conducted once again with updated priors to the whole sample size.

We conducted face-to-face interviews in all three stages of interviews. This allowed us to: i) increase farmers' engagement; ii) help pay attention to socio-cultural contexts during the research process; iii) assess whether the survey communication is effective to respondents. Due to illiteracy issues, we discarded online-based surveys.

3.2.1 Pre-study

Farmers make decisions based on external stimuli and their own goals (MEEMPATTA *et al.*, 2019). The influencing factors that impact farmers' decisions can be either 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 inherent to the farmer (*e.g.* risk appetite, past experience, personal beliefs and/or perceptions).

A preliminary survey with 12 local farmers was conducted to identify the attributes related to water policy adherence and crop choice. This preliminary survey consisted of eight open-ended questions, followed by a socio-demographic questionnaire. Questions were carefully designed to capture farmers’ decision-making regarding crop choice and to explore alternatives for a more profitable production with enhanced water efficiency. Below we see the questions that guided this study phase:

1. Which crop are you currently growing on your farm?
2. Which irrigation method do you use?
3. How do you decide which crop to grow each year?
4. What could the water manager do to help farmers produce more and save more water?
5. How could farmers help water management in the Canal do Sertão?
6. What would make farmers want to participate in decisions about water use from Canal do Sertão?

7. What do you think about having withdrawal information open for water management in the Canal do Sertão?
8. Related to water management, which actions should be taken to reduce economic inequality in the region?

Questions number 1 and 2 revealed preferences for crop production and irrigation technology, as both information are required to estimate water withdrawal volume in the physical model. Question number 3 elicits the relevant attributes of crop selection. Questions 4 to 8 assess farmer's point-of-view on possible water policy strategies and how they can contribute to these policies.

3.2.2 Pilot and main studies

In the pilot study, 10 irrigators from Canal do Sertão were surveyed (~10% of the sample size), and respondents were presented with stated choice tasks. In this stage, we identified possible interpretation issues and checked if trade-offs represent real-life scenarios. Based on the pre-study results, we selected five attributes for hypothetical water-related contracts, they are: crop type binding, minimum irrigation efficiency, technical assistance, production selling secured, and water price (Table 1).

Table 1: Choice model levels and attributes

Attribute	Description	Levels	Expected sign	Type
Crop type binding	When signing a contract, farmer ensure they will plant at least 50% of their farm with this crop type	**Fruits** Vegetables Maize, cassava, beans No binding	+/-	Dummy coded
Minimum Irrigation efficiency	Water efficiency for irrigation technologies	80%, 90%, 95%	-	Continuous
Technical assistance	Technical assistance regarding crop planting and water saving techniques	**No** Yes	+	Dummy coded
% of selling secured	% of crop production bought from local association	0%, 25%, 50%	+	Continuous

Attribute	Description	Levels	Expected sign	Type
Water price	Water charge in Brazilian Reais per cubic meter of water used in irrigation	R$ 0.10/m³, R$ 0.14 /m³, R$ 0.19 /m³, R$ 0.25/m³, R$ 0.32 /m³, R$ 0.40/m³	-	Continuous

Note: The bold levels are used as base levels in the econometric estimation.

Source: The author (2025)

In the pre-study, respondents showed a lack of technical assistance as the main motivation they cannot produce more while being water efficient. They showed risk aversion as the main driver for crop selection, mainly producing crops that they are used to or that neighbors produce. That motivated us to suggest two water policies for economic incentives in the transition to charging water: technical assistance and selling secured. Crop type binding levels correspond to the most planted crops in the area. They were grouped conforming to their production risks and profitability. Fruits are the most profitable but involve more risks in production. Maize, cassava, and beans have lower risks, but lower profits. As vegetables require freshness, they need to be sold quickly. Thus, we put them as middle risk in our assessment. In pre-study, some farmers reported other farmers using inefficient irrigation methods. Therefore, we included minimum irrigation efficiency for water saving strategy. We referred to ANA (2013) for irrigation efficiencies. We chose conventional aspersion (80%), perforated tubes (90%) and dripping (95%) as irrigation technologies. We combined the used techniques by water users considering their efficiency towards saving water. Finally, we chose water charge as the pricing attribute. The utility function was defined as:

$$U(contract_A) = \beta_1 Crop\ binding + \beta_2 Irrigation\ efficiency + \beta_3 Technical\ assistance + \beta_4 Selling\ secured + \beta_5 Water\ price$$

$$U(contract_B) = \beta_1 Crop\ binding + \beta_2 Irrigation\ efficiency + \beta_3 Technical\ assistance + \beta_4 Selling\ secured + \beta_5 Water\ price$$

$$U(contract_C) = \beta_1 Crop\ binding + \beta_2 Irrigation\ efficiency + \beta_3 Technical\ assistance + \beta_4 Selling\ secured + \beta_5 Water\ price$$

$$U(SQ) = \beta_1 Crop\ binding + \beta_2 Irrigation\ efficiency + \beta_3 Technical\ assistance + \beta_4 Selling\ secured + \beta_5 Water\ price$$

The DCE survey consisted of scenario description, stated choice experiment, and follow-up questions. The scenario description set the respondent into the context of the survey, remembering them important concepts, and explaining our assumptions (see appendix A). The stated choice experiment consisted of three unlabeled contracts and a none option (Figure 3). When choosing "none", they would not benefit of any incentive policy or be obliged to offer any countermeasure. However, they would still pay R$ 0.12/m³ of water withdrawn. 12 cents is the price in effect in a different Canal

We chose R$ 0.12/m³ as a "standard price" because this is a value being discussed by stakeholders during the writing of this thesis. This price is in effect in a differen

Figure 3: example of a stated preference choice task in DCE

	Contract 1	**Contract 2**	**Contract 3**	**None**
Crop obligation	 Maize, cassava or beans	 Vegetables	 Fruits	
Minimum irrigation efficiency	 80%	 95%	 90%	
Technical assistance	 Yes	 Yes	 No	
Selling secured	 25%	 0%	 50%	

	Contract 1	Contract 2	Contract 3	None
Water price	 R$ 0.19/m³	 R$ 0.14/m³	 R$ 0.32/m³	 R$ 0.12/m³
Choice:	▢	▢	▢	▢

Source: The author (2025)

To generate the choice tasks, we considered the full factorial design design impractical (i.e., a combination of every attribute and levels), due to the number of existing levels in our design. Alternatively, we chose an efficient design.

More specifically, we used a d-efficient design. D-efficient designs are based on the d-error, which is calculated by taking the determinant of the parameters' variance-covariance matrix. We used Ngene (CHOICEMETRICS, 2021) to find a d-efficient design. The software iteratively calculates the d-error of several possible designs. A d-efficient design corresponds to the design with a low d-error. Finding an efficient design is important because we can get the most information from trade-offs by a single respondent due to the combination of attribute levels.

D-efficient designs require the assumption of parameter priors, which correspond to our initial guesses for the parameters. We decided to use fixed priors based on literature for the pilot study. Then, we used Bayesian priors based on pilot to design the main study. The main study design consisted of 12 choice sets (Appendix B). 12 is a common multiplier for the attribute levels, which enables proper level balance among choice sets. As 12 choice tasks can be burdensome for a single respondent and can prejudice data quality, we decided to divide the choice tasks into two blocks, giving six choice tasks for each respondent.

We carried out analyses considering marginal rates of substitution (MRS), and the willingness to pay (WTP). MRS represents the relative impact on utility of unit changes in two attributes. It is calculated by dividing two parameters. WTP is a particular case of MRS when the denominator is a monetary attribute. For example, if $\beta_{technical\ assistance}/\beta_{water\ price} = -0.05$ it means that the decision-maker is willing to pay 0.05 R$/m³ for technical assistance.

In this study, we used a multinomial logit (MNL) model. In mixed logit models, parameters are estimated as distributions instead of single values. When estimating

RMS in MXL models, we now have a division of two distributions instead of two single values. So, we need to calculate WTP space.

When estimating the WTP, we may define convenient distributions for the coefficients (numerator and denominator), we call this “models in preference space” because it is calculated directly using the preference of both attributes. When we use models in preference space the data fit better, but the calculated WTP has an unreasonably large variance (*e.g.*, when the denominator distribution approaches zero).

To avoid this behaviour, an alternative is to reparametrize the model in terms of WTP, this is called “models in WTP space” (TRAIN & WEEKS, 2005).

3.3 Agent-based model

To represent all the complex interactions between water users and the manager, we chose an agent-based approach to model the Canal physically. In the following sections, we detail what are the agents’ behaviours and how the environment is set. In order to contribute to model reproducibility and replicability we present it in a detailed approach in APPENDIX E using the Overview, Design concepts, and Details (ODD) protocol (GRIMM et al., 2020). In brief, the ODD protocol is a methodology to document agent-based models as fully as possible.

3.3.1 Farmer agents

Farmer agents follow the logit model in their decision-making process. Each agent is then randomly assigned each of the parameters of the economic model based on their respective distributions: $\beta_{crop\ binding}$, $\beta_{irrigation\ efficiency}$, $\beta_{technical\ assistance}$, $\beta_{selling\ secured}$, $\beta_{water\ price}$. For multinomial logit models (MNL), the probability to choose option n under J choice options is:

$$P(choose\ option\ i) = \frac{e^{V_n}}{\sum_{j=1}^{J} e^{V_j}}$$

The probability depend on the J options under consideration at the moment. The number and the content of choice options are dependent of the scenario characteristics. How the scenarios affect the choice options are further discussed in section 3.4.

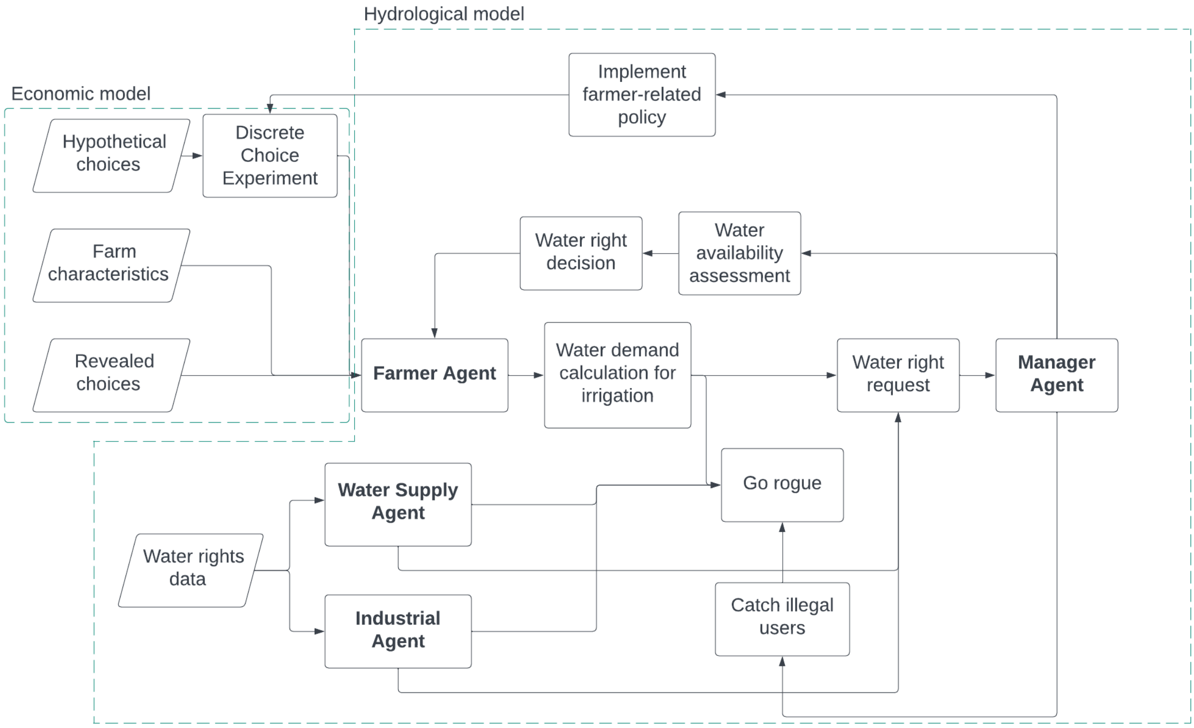
Each farmer has a random coefficient P_{rogue} that varies from 0 to 1 that represents the probability of the agent to “go rogue”. Go rogue is an action in the agent-based model in which an agent withdraws water illegally. When rogue, a farmer does not pay for water and is not accounted for in the water manager's water balance. This can affect downstream users and cause conflicts. If some water users have a water right and cannot withdraw water (because of illegal users), a signal is sent to the water manager informing this.

Farmers go rogue depending on a threshold $T_{oversight}$ that also varies from 0 to 1. $T_{oversight}$ is a global variable that accounts for the oversight power in the canal by the manager. If $P_{rogue} < T_{oversight}$, farmer activates the rogue mode. A farmer can go rogue at two times: if they choose the option of not entering in any incentive program, or if the water right is denied. If they choose not to enter any incentive program (the status quo option), they can go rogue based on their P_{rogue}. If their water right is denied, whichever option they choose, they can also go rogue depending on their P_{rogue}. A similar behaviour of going rogue is presented in the literature (BOUZIOTAS & ERTSEN, 2017). In results section 4.1 we refer to this behaviour as “override”. However, in override, farmers only go rogue if their water right is denied (they override the manager's decision). In section 4.3, we refer to this behaviour again as “go rogue”, when farmers can go rogue in the two abovementioned situations.

To calculate farmers’ revenue, we considered the most planted crops in the area for our sample and considered *ad hoc* information. Using production revenue for the Sertão mesoregion in the state of Alagoas (), we calculated the mean revenue per area (in R$/ha) for each crop type, then multiplied by agent’s farm area to get yearly revenue. Check Appendix C for calculation details.

The agents’ interactions flowchart is summarized in Figure 4. When a farmer agent is created within the model, they ask for a water right based on the farm characteristics (if they go rogue, they skip this behaviour). The amount of water to ask for permission to use is based on farm characteristics, such as irrigation area and crop type. Each crop type requires an amount of water. This calculation of water volume is detailed in Appendix D. The manager decides to conceive the water right based on the water use policy at play and water availability in the canal.

Figure 4: Detailed diagram of interactions.



Source: The author (2025)

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3.3.2 Human supply and industrial agents

Water users for industrial purposes and human supply only withdraw water from the Canal. Industrial users withdraw water based on the fitted probability distribution of current water users in the water manager database. Differently from other water users, the human supply agent type is not created iteratively. In the model, we account for the main human supply services administered by the state sanitation company CASAL. They are all created at simulation start and cannot be removed.

3.3.3 Water manager agent

The manager receives water user agents' water rights requests. Based on the water balance, it conceives or denies water rights. Water rights do not expire, as in the real world in Brazil. However, as renewal acceptance is common in case there are no further water conflicts, we chose to simplify the model in this aspect.

The manager can implement farmer-related policies, such as making technical assistance available or creating a local association that partially buys farmer production. In these cases, the manager will require efficient irrigation technologies and may request water-efficient crops. These variables are affected by the policy scenarios discussed in section 3.4.

The manager is actively looking for illegal users. We already know that $T_{oversight}$ is used for farmer agents decide to go rogue. $T_{oversight}$ also defines how many agents are caught at each year. When an agent is caught, it is removed from the agent-based model. In the real world, this it is more complicated. When someone gets caught, there are legal and financial sanctions. In our model, we chose to simplify this to the extreme case where farmer is forced to withdraw from farming in the area.

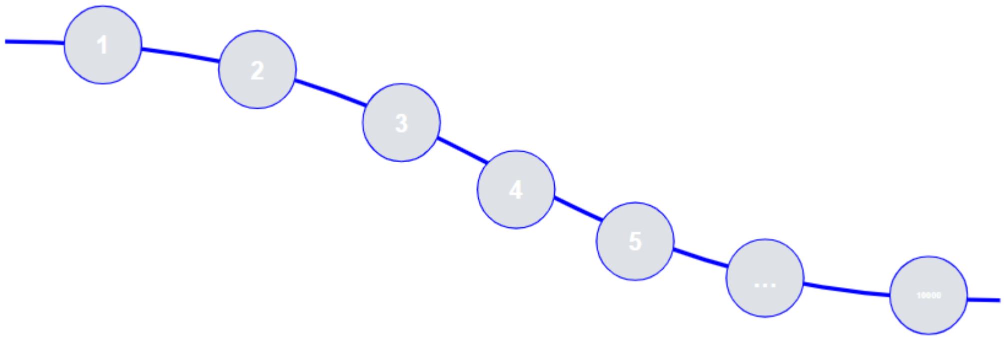
If some agent that has the water right cannot withdraw water because of illegal users, the manager respond in two ways: i) increasing water availability within that year if possible (respecting the boundary conditions of available water pumps and their maximum pumping volume per year); and ii) increase oversight to catch illegal users for the following years.

$T_{oversight}$ is modelled as a Beta distribution. We chose this, because of its boundaries on 0 to 1, and the possibility to asymptotes at the upper boundary when their coefficients are greater than 1 (as in the real world, to catch 100% of the users is hardly possible).

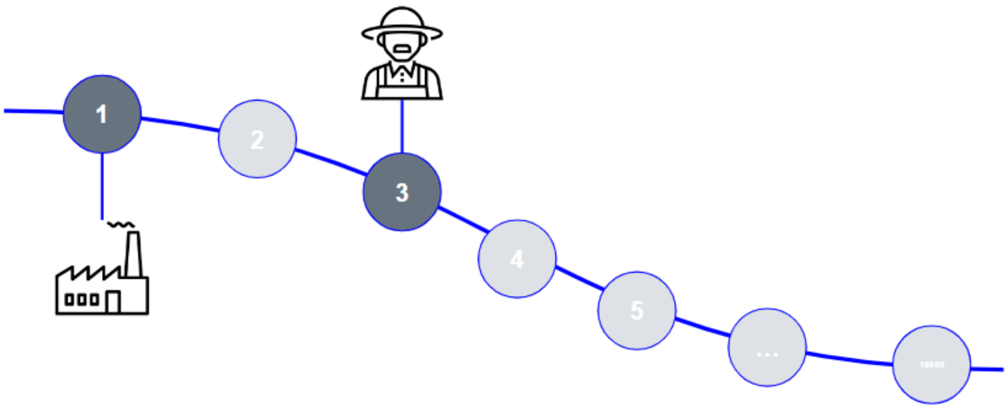
3.3.4 Environment

To account for spatiality, we built a graph-based model. At initialization, 10,000 graph nodes were created. The linear pattern accounts for the upstream-downstream relationship (Figure 5a). Each node is a possible position for water users to allocate themselves. We set the model time step equal to 1 year. This means that all values are averaged over 1 year simplifying the water balance, and the income estimates for some agents. We ran 20 time steps for each scenario, as this is the time frame for watershed planning in Brazil. To account for uncertainty of the stochastic behaviour of the agents, we ran 50 times each scenario. 50 was an arbitrary number that considers the model runtime and the capability to capture uncertainty.

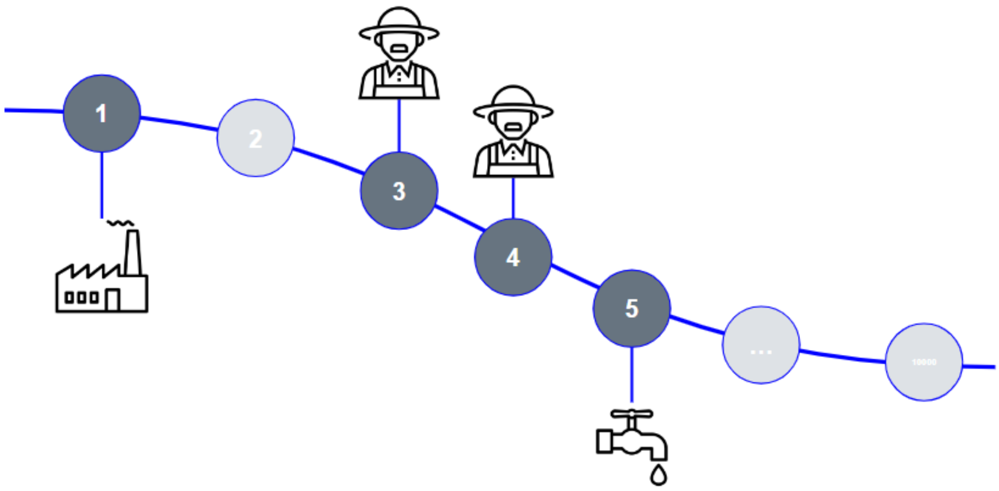
Figure 5: Exemplification of how the model starts and is modified at each iteration



(a) Step 0



(b) Step 1



(c) Step 2

Source: The author (2025).

At each step new agents allocate themselves in a random node (Figure 5b and Figure 5c), then they interact based on the Figure *4* diagram of interactions.

We built the agent-based model using the Mesa Python Package (KAZIL et al., 2020). It is an open-source package for ABM design and simulation. We can inherit functions by using their core features and customizing them for the studied case.

3.4 Policy assessment

We addressed a scenario-based approach to evaluate the impacts of different water management policies. The base scenario assumes farmers are presented only with the status quo option, where water is priced at R$ 0.12/m³, serving as a reference point for comparisons. Scenario 2 introduces technical assistance services, where farmers pay a premium for this support. The policy's effect is assessed by varying service prices to farmers' estimated willingness to pay (R$ 0.08/m³, R$ 0.16/m³, R$ 0.24/m³, and R$ 0.32/m³). The premium is charged based on the volume of water withdrawn, enabling insights into its affordability and effectiveness in improving farming practices. Farmers that comply with using efficient irrigation method (i.e., drip irrigation) and produce specified crop pay half the price for technical assistance.

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4 RESULTS

In this chapter, we present the results of the proposed methodology in this work. Results are divided into three papers as follows:

1. The first paper aims to test whether the proposed ABM can well capture the interactions of the hydrological model and whether it is properly programmed in Python. For this preliminary model, we simplified the farmer's decision-making behaviour by not including the choice analysis using DCE. To effectively test the model, we analyze the impact of oversight as a mechanism to prevent illegal water withdrawals.
2. The second paper analyses irrigators' willingness to pay for farming-related policies in the Canal do Sertão and their willingness to adopt a water charging scheme. The proposed policies are designed to stimulate socioeconomic development while encouraging rational and sustainable water usage. As we discussed in the methodology section, the findings of this work are key inputs in the next paper that covers the final version of the proposed model.
3. Finally, the third paper explores the socioeconomic and environmental impacts of implementing some farming incentive policies and the impact on water charging. We also revisited the oversight issue in a more robust hydro-economic model.

4.1 Paper #1: Impact of water allocation oversight in irrigation systems: an agent-based model approach

A modified version of this section was published as: GOMES, Y. R. M.; SOUZA, C. F.; CUNHA, A. H. F.; MONTENEGRO, S. M. G. L. Impact of water allocation oversight in irrigation systems: an agent-based model approach. RBRH, 28, e41, 2023 https://doi.org/10.1590/2318-0331.282320230065

Abstract: As access to water is a right of all people, government agents are responsible for allocating 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.

4.1.1 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.

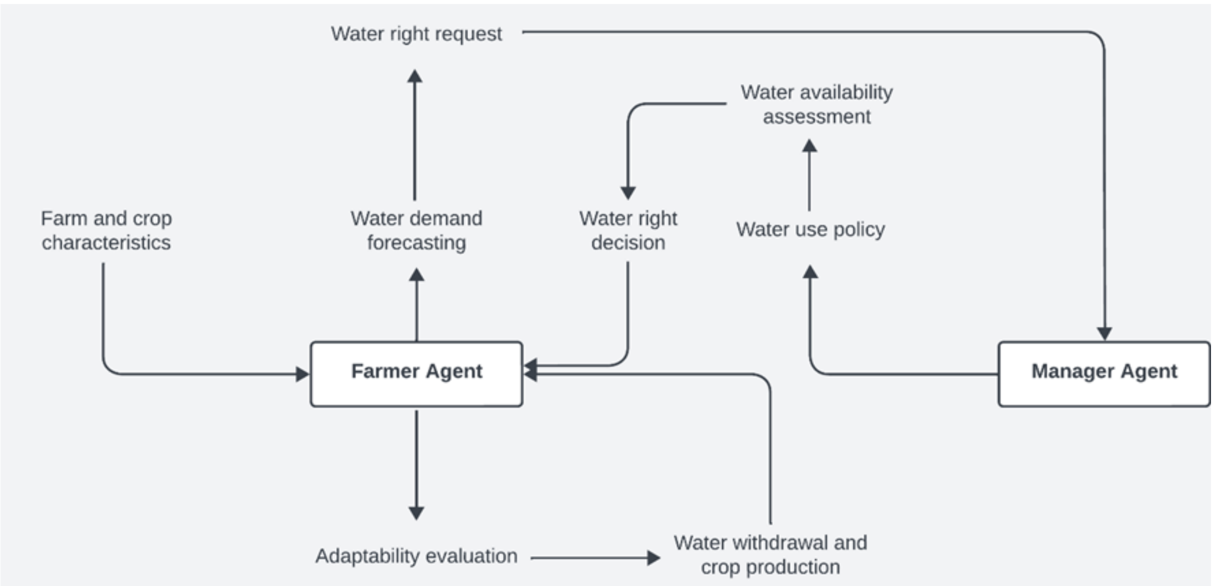
4.1.2 Methods

In the methodology section 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.

4.1.2.1 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 *6*. 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 withdraw more or less than permitted based on their own sense of adaptability behaviour.

Figure 6: ABM diagram of interactions.



Source: The author (2025).

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. 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 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).

4.1.2.2 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.

4.1.2.3 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 (IBGE, 2018a) and permanent (IBGE, 2018b) crop production for the year 2018 in the state of Alagoas. We extrapolated the state average for the Canal do Sertão.

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

Source: The author (2025).

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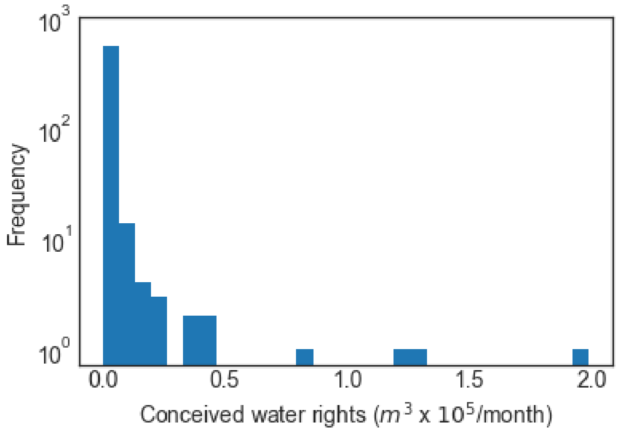
To represent market fluctuations in the revenue and cost variables, we randomly drew a new value from a normal distribution centered on the values from 2018 data and a standard deviation coefficient of 5% of the 2018 data. Mathematically, for the year t in the ABM, $Yield_t \sim Normal(Yield_{2018}, 0.05 \times Yield_{2018})$ and $Cost_t \sim Normal(Cost_{2018}, 0.05 \times Cost_{2018})$.

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 7) 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 $m^3/month$.

Figure 7: Water rights histogram.



Source: The author (2025).

To convert water rights data into irrigation areas, we divided the amount of water in water rights by $40\ m^3/ha$, approximating 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.

4.1.2.4 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.

4.1.2.5 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 P_{over} 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 if a water request is denied. Farmers override if P_{over} falls below T_{over}.

4.1.2.6 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.

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: $WA = 0.6$; $T_{over} = 0.1$.

Source: The author (2025).

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.

4.1.2.7 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.

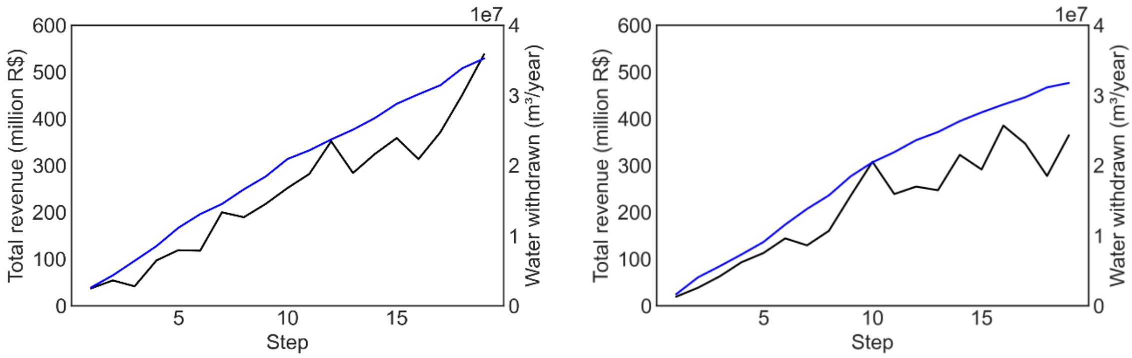
4.1.3 Results

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).

4.1.3.1 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 *8*a) was 47% higher compared to the oversight scenario (Figure *8*b) 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.

Figure 8: Total farmers revenue over the modelling years. The blue line corresponds to the water withdrawal, and the black line to the total revenue.

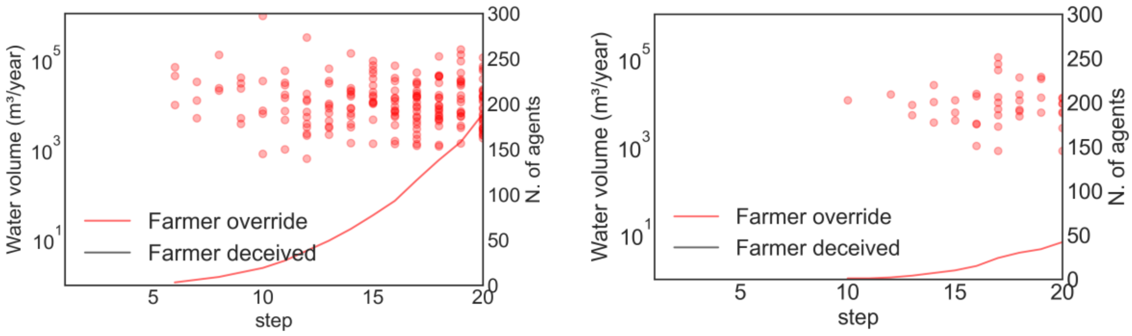


(a) base scenario (b) oversight scenario

Source: The author (2025).

In the base scenario, farmers began to override from year 6 (Figure *9*a) as virtual water reached zero in segment 14 at year 5 (Figure *10*). When virtual water ends in any segment, the following 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}.

Figure 9: 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.

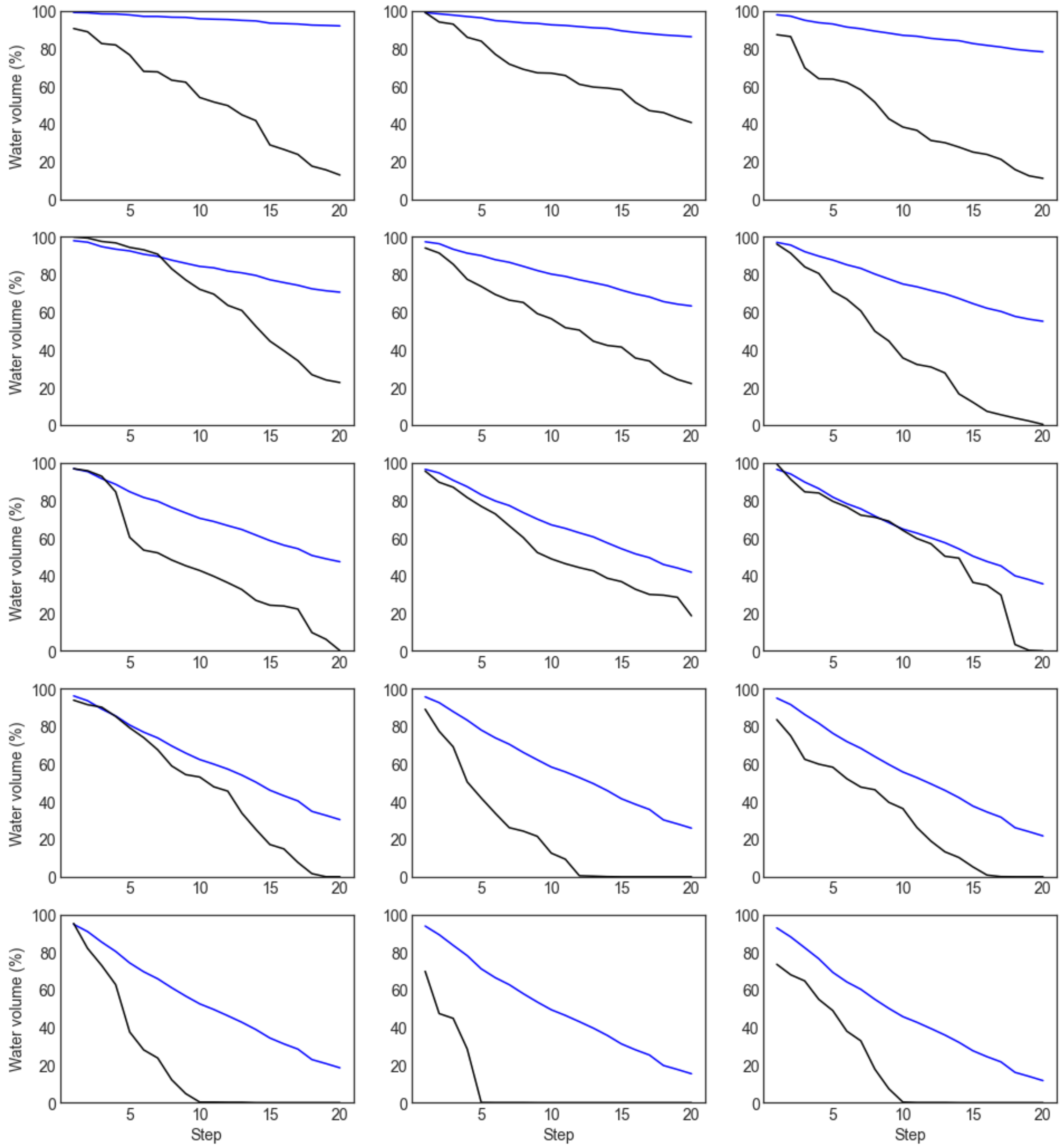


(a) base scenario

(b) oversight scenario

Source: The author (2025).

Figure 10: 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.



Source: The author (2025).

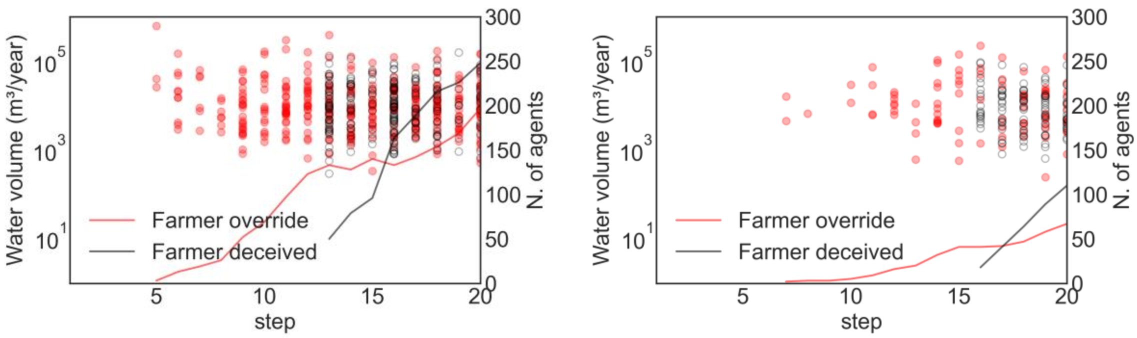
By year 20 in the base scenario, 189 agents had overridden the manager's decisions. Over time, more agents followed suit, creating an exponential trend as the number of segments with no virtual water increased. We called deceived agents, farmers who had their water right, but could not withdraw because 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 *10*). 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 9b). 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.

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

Figure *11* 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.

Figure 11: 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.



(a) water scarcity scenario

(b) water scarcity+oversight scenario

Source: The author (2025).

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.

4.1.4 Discussion

4.1.4.1 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 (ALAGOAS, 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.

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, affecting 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.

4.1.4.2 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 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 similarly.

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 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.

4.1.5 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 distributes 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.

4.1.6 Acknowledgements

We thank the State Department of State of Environment and Water Resources of Alagoas - SEMARH/AL for providing the water rights database and availability for study discussion.

4.1.7 Author contribution

- Yan Ranny Machado Gomes: Conceived the presented idea, built the model and performed computations, analyzed and discussed the results, wrote the manuscript, and wrote the final draft.
- Christopher Freire Souza: Conceived the presented idea, analyzed, and discussed the results, and reviewed the draft.
- Augusto Hugo Farias da Cunha: Analyzed and discussed the results, and reviewed the draft.
- Suzana Maria Gico Lima Montenegro: Analyzed and discussed the results, and reviewed the draft.

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4.2 Paper #2: Exploring farmers' adoption of water charging for sustainable development in the Brazilian semi-arid

A modified version of this section is under journal peer-review with authorship as follows: GOMES, Y. R. M.; ZEMO, K. H.; TERMANSEN, M.; SOUZA, C. F.; MONTENEGRO, S. M. G. L.

Abstract: This study investigates farmers' willingness to adopt a water charging system in the semi-arid region of Alagoas, Brazil, in a water canal, the Canal do Sertão. The study uses a discrete choice experiment to evaluate how farmers respond to proposed water pricing policies and complementary incentives, such as technical assistance and crop obligations. The results reveal a divided response: while some farmers are willing to participate in policies that include technical assistance, many opt for the status quo, largely due to concerns about the financial impact of water charges and past negative experiences with short-term incentive programs. The analysis shows that flexibility in crop selection and the provision of technical assistance are key factors influencing farmer participation. Despite the challenges, introducing water charges is deemed necessary for sustainable water management in the region. However, a gradual implementation, coupled with well-designed incentives and efforts to build trust among farmers, will be critical to the success of these policies. The findings provide important insights for policymakers aiming to promote efficient water use while supporting small-scale farmers' livelihoods.

Keywords: water management, discrete choice experiment, water pricing

4.2.1 Introduction

Population growth is projected to increase food needs and energy demand and decrease water supply in a world where food demand is rapidly growing (FAO, 2011). In 2015, world leaders adopted the Sustainable Development Goals (SDGs) to provide a road map to address challenges regarding poverty, health, inequality, and environmental change (ARORA & MISHRA, 2019). To stimulate economic activities is expected to positively impact economic productivity and to meet basic needs. However, it is essential to acknowledge that such development may come with negative environmental consequences, particularly in terms of increased water demand and potential resource depletion (VAN ZANTEN & VAN TULDER, 2021). Therefore, an interdisciplinary approach, aligning with the spirit of the SDGs, is crucial to address the growing water demand sustainably and ensure that economic progress does not compromise environmental and social goals (YILLIA, 2016).

The Canal do Sertão is a water Canal in the semi-arid region of Brazil in the state of Alagoas. The project aims to increase water supply to 46 municipalities in the most critical regions of Alagoas throughout 250 km of length to human, and animal supply and industries, but mainly for irrigation purposes. Delivering water to such arid regions aims the local socio-economic development. Even though the Canal's estimated use is 32 m^3/s (HYDROS & TECNOSOLO, 2003), it has been an aim of controversies due to the high investments (over 2.3 billion Brazilian Reais) and low water utilization of around (~0.9 m^3/s) compared to the projected supply volume (TCU, 2020).

Currently, the Canal does not charge for water use. The state covers operation and maintenance costs. As the costs are high for the state to keep, water charging was proposed in the Canal Management Plan (HIDROBR, 2022). Although discussions on charging are underway and seem imminent, the majority of irrigators in the Canal are composed of small farmers, and charging could highly impact their income, slowing down the local economy by hindering farmers' ability to expand or relocate, thereby contradicting the primary objective of the Canal. Incentive policies could be employed once water charging is initiated, potentially reducing economic inequality while encouraging water-efficient use.

Previous studies showed that farmers have economic and non-economic reasons that influence their willingness to participate in farming-related policies. Training (ZHANG et al., 2019), cooperation (PAKMEHR et al., 2020), access to weather forecasts (ALCON et al., 2019), economic incentives (GIANNOCCARO et al., 2022), access to credit (DENKYIRAH et al., 2017), insurance schemes (JØRGENSEN et al., 2020), payment mechanisms (BURTON et al., 2020), and others (MEEMPATTA et al., 2019) have an impact on farmers' adaptation to new water-related policies. Additionally, farmers' characteristics such as gender, educational level, income (KHAN & ZHAO, 2019; MARIE et al., 2020), and their individual values

(MOHAMMADINEZHAD & AHMADVAND, 2020) also have an impact on their decisions. Due to the numerous factors that influence farmers' behavior, and their complex interactions, it is challenging to determine the most effective policy, as farmers may not adopt measures incompatible with their objectives and beliefs.

The knowledge of incentive policies could significantly influence policymakers to a smoother transition into a water charging scenario. Hence, this study investigates farmers' adoption of a water charging policy. We assess the influence of two different incentive policies and restrictions on crop type and irrigation technologies towards local economic development while being water efficient. Specifically, this study seeks to investigate: i) understand farmers' willingness to adopt a water charging policy in the context of the Canal do Sertão in Brazil; ii) assess water-efficiency and incentive policies as complementary mechanisms to water charging; iii) assess interaction effects.

4.2.2 Methods

4.2.2.1 Modelling framework

The empirical design of discrete choice experiments is based on the utility concept and the random utility (RU). The RU theory asserts that decisions can be represented as a function of the attributes associated with the available alternatives (MCFADDEN, 1973; TRAIN, 2009). It is assumed that individual i selects alternative j that has the greatest overall utility. The utility U_{ij} can be calculated as:

$$U_{ij} = V_{ij} + \epsilon_{ij}$$

The utility U_{ij} is a variable composed of a deterministic element V_{ij} and a random part ϵ_{ij} which represents the unobserved part of the expected utility. The deterministic term is a function $(V_{ij} = f(\beta_k, x_{ijk}))$, where (X_{ijk}) is a vector including the observable determinants of utility and β_k contains the associated coefficient estimates for the marginal utilities of choice attributes k. To assess trade-offs among different attributes we chose to use a Discrete Choice Experiment (DCE). To analyze the DCE data, a multinomial logit (MNL) model was used.

4.2.2.2 Discrete Choice Experiment

A stated preference method was chosen over revealed preference methods due to the hypothetical nature of the water charging scheme. To identify relevant attributes and levels we consulted experts and conducted a pre-study. The pre-study consisted of 12 face-to-face interviews with farmers who use water from the Canal do Sertão in their farms. The interviews were semi-structured and designed to capture farmers' decision-making processes regarding crop choices and explore alternatives for achieving more profitable production with enhanced water efficiency (see questions in the thesis methodology in section 3.2.1).

Based on specialists' expertise and the pre-study results, we set attributes and levels for the DCE. The list of attributes (refer to Table 1 in the methods section) included two incentive policies: the creation of an association that buys a percentage of the production of local farmers (based on the experts' opinion); and a technical assistance policy (based on farmers' from pre-study), to ensure farmers know how to produce more and save more water. Attributes also included a minimum irrigation efficiency, which is related to the irrigation technology used, and a crop obligation attribute, which ties farmers to produce at least half of their production of specific crops in case they would choose to sign a hypothetical contract. The cost attribute was defined as the price of water per cubic meter.

To cover operation and maintenance costs in the Canal, the recommended base price in the management plan is R$ 0.38/m³ (HIDROBR, 2022). In the pre-study, price levels ranged from R$ 0.23/m³ to R$ 0.48/m³. However, during interviews, farmers claimed that these prices were beyond their capacity to pay, and some indicated they would even cease farming activities if these prices were applied. Consequently, we decided to adjust the price level range. In the main study, they ranged from R$ 0.10/m³ to R$ 0.40/m³ based on current local discussions of potential prices. This adjustment is feasible, as other sectors (e.g., industrial and human supply) have a greater capacity to pay (CERME, 2022) and could subsidize smaller farmers. Price levels remain variable as they may depend on contract options and government subsidies.

As the combination of attributes and levels may be large for a full factorial design, we chose to construct choice sets using a D-efficient fractional factorial. The D-efficient fractional factorial design was optimized using Ngene software (CHOICEMETRICS, 2021). The design for the final survey consisted of 12 choice tasks divided into two blocks using priors from a pilot study. In each choice set, three unlabelled hypothetical water-related contracts were available and the status quo option (Appendix B). In the scenario description (see Appendix A), individuals were informed that even though they do not pay for water at the moment, they will have to pay in the near future. Therefore, the status quo consisted of no incentive policies and countermeasures, and a water price of 0.12 R$/m³, price that has been put under consideration for irrigation purposes. After answering all choice tasks, respondents were requested to provide information about gender, age, farm size, current crops, current irrigation technology, education, income, labor, and their belief that the research will impact water policies in the region. We used Apollo software for model estimation (HESS & PALMA, 2019).

4.2.2.3 Survey administration and sampling

Surveys were conducted from January to June 2024. Meetings with farmers were facilitated through trusted local contacts. As some local farmers have limited literacy (Table *4*: sample characteristics.Table 4), we conducted in-person interviews. In-person interviews also helped farmers acceptance to participate in the survey. Survey campaign routes were planned with local partners to ensure comprehensive coverage of the Canal area. Farmers from four cities (Delmiro Gouveia, Pariconha, Água Branca, and Inhapi) were interviewed to cover most of the cities supplied by the constructed section of the Canal. Besides spatial coverage, sampling criteria were based to cover different farm sizes and crop types. In total, 122 farmers were interviewed: 12 in the pre-study, 10 in the pilot study, and 100 in the main study.

Table 4: sample characteristics.

Descriptor	Stratum	Farmers answers
Gender	Male	78 (70.9%)
	Female	32 (29.1%)
Age (years)	31-39	19 (17.2%)
	40-49	30 (27.3%)
	50-59	30 (27.3%)
	60-78	31 (28.2%)
Crop area (tarefas)	0-2	65 (60.7%)
	2-4	24 (22.4%)
	4-6	12 (11.2%)
	6 or above	6 (5.7%)
Education	Illiterate	6 (7.0%)
	Elementary school 1st (incomplete)	12 (14.0%)
	Elementary school 1st	41 (47.6%)
	Elementary school 2nd	3 (3.5%)
	High school	23 (26.7%)
	Higher education	1 (1.2%)
Income comes from agriculture (%)	0	10 (11.4%)
	1-50	61 (69.3%)
	51-100	17 (19.3%)

"Tarefa" is a local unit of land measurement that corresponds to approximately 3,000 m². In Brazilian education, Elementary school 1st covers 5 grades, followed by Elementary school 2nd which covers 4 grades, and High school that covers 3 grades.

Source: The author (2025)

4.2.3 Results

4.2.3.1 Descriptive results

The results from the choice experiment revealed a divided preference among participants regarding the proposed contracts. On average, participants selected one of the proposed contractual options 44.1\% of the time, demonstrating some interest in the attributes presented, such as crop obligations, technical assistance, and water pricing. However, a significant portion of farmers (54 out of 110) consistently opted for the status quo alternative across all scenarios.

Some of these farmers had prior experience with technical assistance programs funded by municipal or state governments. For those who found such assistance beneficial, it positively influenced their likelihood of choosing a contract. They reported that technical assistance helped improve their crop yields and water use efficiency, making the contractual options more appealing. Conversely, farmers who had negative experiences with these policies, which they found to be temporary or inadequate, were more likely to choose the opt-out option. Furthermore, many farmers plant different crops each year and expressed concerns about the crop obligations in the contracts, which required them to commit to specific crops. This flexibility in crop choice, along with dissatisfaction with past assistance programs, contributed to their preference for the status quo alternative.

Farmers expressed additional concerns that may explain the high opt-out rate. Due to their experiences with short-term incentive policies, many worry that the proposed contracts are merely a pretext to begin charging for water—something they perceive as unfair, given their history of not paying for it. Some farmers also pointed out that certain rural properties exploit canal water under the guise of farming but primarily use it for leisure, raising doubts about the fairness of water charges. These widespread issues contribute to skepticism about whether fair water charging will be enforced in the future.

4.2.3.2 Estimated choice model

The results of the Multinomial Logit (MNL) model provide insights into farmers' preferences and behaviors regarding water use, crop choices, and participation in incentive policies in the Canal do Sertão region. They are presented in Table *5*.

Table 5: MNL estimates.

Variable	Coefficient	Standard Error	T-ratio
β_{fruits}	0.0000	N/A	N/A
$\beta_{vegetables}$	0.0077	0.1936	-0.0399
β_{mcb}	0.3353	0.2208	1.5183
$\beta_{no\ obligation}$	0.4340	0.2174	1.9960*
$\beta_{irr\ eff}$	-0.0015	0.0134	-0.1102
$\beta_{no\ tech\ assist}$	0.0000	N/A	N/A
$\beta_{tech\ assist}$	0.5684	0.1502	3.7849**
$\beta_{sell\ secured}$	0.0035	0.0042	0.8450
β_{price}	-1.7866	0.9207	-1.9404*
ASC	1.2723	0.2889	4.4030**

** Significant at 1%, * Significant at 5%.

Source: The author (2025)

For crop obligation constraints, the model included dummy variables representing different crops: β_{fruits}, $\beta_{vegetables}$, β_{mcb} (maize, cassava, and beans), and $\beta_{no\ obligation}$. Among these, only $\beta_{no\ obligation}$ was significant at the 5% level, indicating that farmers preferred not to plant specific crops. Naturally, farmers may have valued flexibility and autonomy in crop choice, particularly in a semi-arid region where crop sensitivity to climate is a concern. The positive and significant coefficient suggests that farmers may want the freedom to adjust their crop selections based on market conditions and water availability. On the other hand, while the coefficient for β_{mcb} was positive, reflecting a preference for secure crops like maize, cassava, and beans, it missed the significance threshold. $\beta_{vegetables}$ was near zero and was not a major driver of choice behavior compared to fruits. These results may suggest that farmers in the Canal do Sertão prefer to avoid committing to risky crops.

In terms of incentive policies, technical assistance was found to be significant at the 1% level, demonstrating a strong preference among farmers for support mechanisms that offer technical guidance. This highlights the importance of knowledge transfer and assistance in optimizing production processes, particularly in regions with complex water management challenges. On the other hand, the variable related to establishing a purchasing association for farmers was not statistically significant. This suggests that farmers may not be interested in such a policy. Several factors could explain this: some farmers primarily harvest for family consumption or produce in quantities too small to sell. Additionally, past experiences with discontinued policies may have caused mistrust in institutionalized selling mechanisms, contributing to the lack of interest. Further investigation is needed to determine whether these factors fully explain the limited appeal of this policy or if there are other reasons why it is not seen as a viable solution for farmers.

Irrigation Efficiency was negative, though not statistically significant. The negative sign is coherent with the expectation that as irrigation becomes more efficient, farmers may adopt more advanced irrigation methods, which could reduce the need for additional water inputs. However, the lack of significance could be due to several factors. For example, a government campaign distributed efficient irrigation systems (e.g., drip irrigation), which may have reduced variability in irrigation efficiency among farmers. Additionally, some farmers in the region are concerned with soil salinization, a known issue that arises from excessive irrigation, which could further complicate the relationship between irrigation methods and water use.

A significant ASC indicates a strong preference for the opt-out option that goes beyond what is explained by the observed variables in the model. One potential explanation is that farmers may not perceive clear benefits from participating in the water management system, especially since they currently do not pay for water, even though future charges are foreseen. Additionally, unmeasured attitudes and perceptions — such as mistrust in government or fear of upcoming policy changes — could also be influencing the decision to opt-out.

The willingness to pay (WTP) for technical assistance is estimated at 0.3181, indicating that farmers are willing to pay a moderate premium for access to support services aimed at improving their agricultural practices. This reflects the perceived value of technical assistance in enhancing productivity, particularly in a challenging environment like the semiarid region.

4.2.4 Discussion

Introducing water charges for farmers in the Canal do Sertão is likely to face significant challenges, as indicated by the high opt-out rates observed in the study. Many farmers remain skeptical of the fairness and enforcement of such policies, fearing that water charges will disproportionately impact their income and livelihoods. Historically, these farmers have relied on free water, and introducing fees could hinder their ability to maintain or expand their agricultural activities. This resistance suggests that successful implementation of such a charging policy would require careful consideration of incentive mechanisms and gradual phasing of charges to minimize economic radical change.

The study offers valuable insights into farmers' preferences, but there are notable limitations. The choice experiment conducted captures a fraction of the complexity inherent in farmer decision-making processes. One significant concern is hypothetical bias, as participants were required to envision scenarios involving water charging, despite not currently incurring any costs for water usage. Farmers showed interest in technical assistance. However, a high WTP for this service of approximately 0.32 R$/m³ might indicate that farmers have not fully considered the actual costs involved in such pricing structures. This suggests that their responses may reflect an optimistic outlook rather than a realistic assessment of their financial capacity. Additionally, heterogeneity among farmers was not considered in our study, potentially oversimplifying their preferences. Expanding the sample size and incorporating a broader range of behavioral and environmental data could provide a more comprehensive understanding of the challenges associated with implementing such a water charging policy.

Interestingly, the creation of an association that buys farmers' production, which was proposed by the water managers' officials, did not contribute significantly to the utility function. On the other hand, the technical assistance, that was proposed by the farmers themselves, had better acceptance. This only highlights the importance of consulting farmers about future policies, as they may not represent their real-life conditions.

Our study highlights farmers' skepticism regarding new policies, likely due to previous short-lived or inadequately implemented incentive schemes, which have severed confidence in new initiatives. To improve the adoption of future policies, efforts should focus on building long-term trust through transparent communication, ensuring that any policy changes are clearly explained, and demonstrating that these measures aim to promote long-term sustainability.

4.2.5 Conclusions

This study examines farmers' willingness in the semi-arid region of Alagoas, Brazil, to adopt a water pricing system, focusing on complementary incentive policies like technical assistance and crop obligations. While technical assistance was positively received, many farmers remain resistant to water charges, opting out due to financial concerns and distrust of past incentive programs. The findings highlight the need for flexible policies that support farmers without imposing excessive financial burdens. For effective water management, gradual implementation of water charges, combined with trust-building and transparent policies, is essential to ensure sustainable agricultural practices in the region.

4.2.6 Acknowledgements

We acknowledge the contributions of Eraldo Souza (locally known as Lau da Barragem) for his valuable insights into the local context and help with the survey administration.

4.2.7 Ethics approval

The Research Ethics Committee reviewed and approved this Research under project no. CAAE 72647523.3.0000.9430.

4.2.8 Authors contributions

- Yan Ranny Machado Gomes: Designed the experiment, analyzed the results, wrote the paper and wrote the final draft of the paper.
- Mette Termansen: Designed the experiment, discussed results, and reviewed the paper.
- Kahsay Haile Zemo: Designed the experiment and discussed the results.
- Christopher Freire Souza: Discussed the results, and reviewed the paper.
- Suzana Maria Gico Lima Montenegro: Discussed the results, and reviewed the paper.

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4.3 Paper #3: Integrating Socio-Behavioural Dynamics into Water Governance: A Framework for Modelling Policy Impacts on Agricultural Water Use

A modified version of this section will be submitted for journal peer review after the thesis presentation and consideration of suggestions and commentaries by the examining committee.

Abstract: This study examines the economic and policy implications of water allocation strategies in the Canal do Sertão region, focusing on farmers' decision-making under varying water-related policies. A choice model was employed to analyze farmers' preferences, while an agent-based model (ABM) incorporated these findings to evaluate the regional impacts of water pricing policies. Results reveal a state return returns for technical assistance ranging from 0.714 million R$ at 0.08 R$/m³ to 2.548 million R$ at 0.32 R$/m³ giving an insight whether policy is feasible. As expected, higher technical assistance prices led to a decline in contract adoption as farmers increasingly opted for the status quo. While the increased revenue suggests the pricing strategy's potential, the higher costs may disproportionately affect smaller or less-resilient producers, raising concerns about equity and sustainability. The study underscores the need for balanced policies, including potential cross-subsidization from higher-paying sectors, to ensure equitable access and long-term viability of water resource management in the region.

4.3.1 Introduction

Water management is a critical global challenge, as the demand from agricultural, industrial, and domestic sectors continues to rise while freshwater resources remain finite. This challenge, influenced by climate variability, population growth, and socio-economic pressures, highlights the need for policies that ensure equitable access and long-term sustainability. Integrated approaches, which combine ecological, hydrological, and socio-behavioral disciplines, have gained prominence for addressing this complexity (FALKENMARK & ROCKSTRÖM, 2004; KUMAR, 2015; SIVAPALAN et al., 2012). These models provide interdisciplinary insights, enabling policymakers to predict user responses to water policies and evaluate the trade-offs across policy scenarios (ALAM et al., 2022; BLAIR & BUYTAERT, 2016; POULADI et al., 2019; TAMBURINO et al., 2020; WENS et al., 2019).

Traditional hydrological models often emphasize physical processes, while neglecting socio-economic behaviors and preferences that critically shape water use decisions (PANDE & SIVAPALAN, 2017). Integrating hydro-economic approaches offer a more holistic understanding of the interplay between social and environmental factors in water management by incorporating human behaviour. However, accurately capturing the relationship between policy impacts and individual decision-making, particularly at localized scales, remains a significant challenge \citep{bloschl2019}. Insights into these dynamics are crucial for understanding compliance, adaptation, and consequences of policy interventions (AN, 2012; PANDE & SAVENIJE, 2016).

Although advances in hydro-economic models have enhanced our understanding of these systems, gaps remain in accounting for adaptive behaviors and socio-economic factors that shape user choices (ELSAWAH et al., 2020). Addressing this gap, this study develops a framework that integrates hydrological impacts with socio-behavioral dynamics to evaluate water policy effects on agricultural decision-making. Using the Canal do Sertão in northeastern Brazil as a case study, we examine how policy changes influence farmers' choices and explore their consequences. By grounding the analysis in local contexts, this study aims to provide insights for policymakers, supporting the design of water governance strategies that balance socio-economic needs with environmental sustainability.

4.3.2 Methods

We employed an agent-based modeling (ABM) approach to simulate the Canal's dynamics and capture the intricate interactions between water users (farmers) and the canal manager. In the proposed model, farmers make decisions regarding their agricultural activities and policy adoption based on a choice model that reflects their preferences and constraints. This section is structured as follows: first, we describe the model explaining how agents make decisions and interact with the environment. Then, we describe the policy scenarios used to assess the potential impacts of different policy strategies on the overall system.

4.3.2.1 Model development

The proposed model has two main components: economic and hydrologic models. The diagram of interactions is summarized in Figure 6. There are two agent classes: farmers representing the water users and the manager. We decided to leave out users that withdraw water for human supply and industrial uses for two main reasons: i) simply for the principle of parsimony, as farmer behaviour is the main focus of our work; and ii) in the water rights dataset for the studied region, their withdrawal volume is insignificant when comparing to the total farmers' volume withdrawal. We detail each agent type behaviour in the following sections.

4.3.2.1.1 Farmer agent behaviour

We conducted a choice experiment to understand farmers' preferences for agricultural attributes and the trade-offs they consider when making decisions. Farmers were presented with hypothetical scenarios and asked to choose between a set of contract options and the status quo. A summary of the evaluated attributes is provided in Table 6.

Table 6: parameters descriptions and respective MNL estimates.

Variables	Levels	MNL estimated parameters
Crop obligation	**Fruits=0;** Vegetables=1; Maize, cassava and beans=2 No obligation=3	$\beta_{fruits} = 0\ [N/A]$ $\beta_{vegetables} = 0.0077\ [0.1936]$ $\beta_{mcb} = 0.3353\ [0.2208]$ $\beta_{no\ obligation} = 0.4340\ [0.2174]$
Minimum irrigation efficiency	80%; 90%; 95%	$\beta_{irr\ eff} = -0.0015\ [0.0134]$
Technical assistance	**No=0;** Yes=1	$\beta_{no\ tech\ assist} = 0\ [N/A]$ $\beta_{tech\ assist} = 0.5684\ [0.0134]$
Selling secured	0%; 25%; 50%	$\beta_{sell\ secured} = 0.0035\ [0.0042]$
Water price	0.10 R$/m³; 0.14 R$/m³; 0.19 R$/m³; 0.25 R$/m³; 0.32 R$/m³; 0.40 R$/m³	$\beta_{price} = 1.2723\ [0.9207]$
ASC		$ASC = 1.2723\ [0.2889]$

Bold levels are used as a reference in the econometric estimation and, therefore, have MNL parameter fixed at zero and no estimated standard error.

Each year, farmers must decide what to plant from a limited set of alternatives, including contract options offered by the manager and the status quo. In the status quo, farmers do not receive incentive policies and are not required to take countermeasures, but they are still obligated to pay for water. For those choosing the status quo, planting and irrigation decisions are based on market shares, following a revealed preference study.

Attributes are modelled as normal distributions with mean in the estimated parameter and standard deviation was set as the standard error. The probability of selecting a given option depends on its relative utility compared to other alternatives. In multinomial logit (MNL) models, the probability of selecting option i from a set of J alternatives is calculated using the following equation:

$$P(i) = \frac{e^{V_i}}{\sum_{j=1}^{J} e^{V_j}}$$

Here, utility is expressed as a linear function of the estimated model coefficients and the attributes of each alternative. However, we excluded $\beta_{sell\ secured}$ from the contract attributes, as the choice experiment indicated that it may not be a relevant policy.

Illegal withdrawals is a current problem in the Canal do Sertão (GOMES et al., 2023). To capture this behaviour, each farmer has a random coefficient P_{rogue} that varies from 0 to 1 that represents the probability of the agent to "go rogue" and is modelled as a Beta distribution. Go rogue is an action in the agent-based model in which an agent withdraws water illegally. When in rogue mode, a farmer does not pay for water and is not accounted for in the water manager's water balance. This affects downstream users and can cause conflicts. If some water user who have a water right cannot withdraw water (because of illegal users), a signal is sent to the water manager informing this. The Beta distribution's asymptotic behavior near the upper boundary effectively captures the increasing difficulty of monitoring all users as the oversight effort approaches its maximum. This reflects real-world challenges, where achieving complete oversight becomes progressively more difficult as more resources are required.

Farmers go rogue depending on a threshold $T_{oversight}$ that also varies from 0 to 1. $T_{oversight}$ is a global variable that accounts for the oversight power in the canal by the manager. If $P_{rogue} > T_{oversight}$, farmer activates the rogue mode. A farmer can go rogue at two times: if they choose the option of not entering in any incentive program, or if the water right is denied. If they choose not to enter any incentive program (the status quo option), they can go rogue based on their P_{rogue}. If their water right is denied, whichever option they choose, they can also go rogue depending on their P_{rogue}.

4.3.2.1.2 Manager agent behaviour

The manager's main objective is to guarantee water-sustainable use of the Canal. They receive water user agents' requests to use water and, based on the water balance, they conceive or deny water rights. In Brazil, the manager usually conceives water rights for a time span (for example, for four years). When this time ends, the water user can request a renewal and the manager reassess the water rights. As it is common to accept the renewal in case there are no conflicts, we chose to simplify the model, and water user agents' rights do not expire.

The manager is responsible for monitoring and identifying illegal water users, with the variable $T_{oversight}$ representing the level of oversight. When an illegal user is caught, they are required to start paying for water under the status quo and are excluded from participating in any contract options. If water allocation to these users becomes impossible, they are removed from the model altogether. This is a simplified representation of real-world dynamics, where illegal users would typically face fines and sanctions. We chose to set $T_{oversight}$ at 0.3. This value was identified by the authors as a reasonable oversight level This value could vary due to investments in this sector. However, we considered the sensitivity analysis of this parameter out of the scope of our work.

4.3.2.1.3 Environment

To incorporate spatial dynamics, we developed a graph-based agent model. At initialization, 10,000 graph nodes were created to represent potential locations for water users. The graph follows a linear pattern to simulate the upstream-downstream relationship between these nodes. Each node serves as a possible allocation point for agents, representing water users. The model operates on a yearly time step, meaning that water balance and income values are averaged over the course of a year, simplifying some calculations related to agent behavior. The model was run for 20 time steps per scenario, aligning with the typical watershed planning timeframe in Brazil.

To account for the stochastic behavior of agents and capture uncertainty, each scenario was simulated 50 times. This number was chosen arbitrarily, balancing model runtime with the need for robust uncertainty capture.

At each time step, new agents are randomly assigned to available nodes. Agents then interact based on a predefined diagram of interactions. The agent-based model was built using the Mesa Python package (KAZIL, 2020), an open-source toolkit that provides core functions for designing and simulating agent-based models. These functions were customized to suit the specifics of our case study. The model source code is available in the supplementary materials.

4.3.2.1.4 Policy assessment

We addressed a scenario-based approach to evaluate the impacts of different water management policies. The base scenario assumes farmers are presented only with the status quo option, where water is priced at R$ 0.12/m³, serving as a reference point for comparisons. Scenario 2 introduces technical assistance services, where farmers pay a premium for this support. The policy's effect is assessed by varying service prices to farmers' estimated willingness to pay (R$0.08/m³, R$0.16/m³, R$0.24/m³, and R$0.32/m³). The premium is charged based on the volume of water withdrawn, enabling insights into its affordability and effectiveness in improving farming practices. Farmers that comply with using an efficient irrigation method (i.e., drip irrigation) and produce specified crops pay half the price for technical assistance.

4.3.3 Results

Figure 12 illustrates the total revenue generated by farmers in the base scenario over 20 years in the simulation. The model demonstrates the capacity to estimate the progressive increase in farmers' revenue, reflecting realistic growth dynamics under the given policy and market assumptions. The results indicate an expected total revenue of approximately 60 million reais by the end of the 20 years (based on 2023 values). This finding underscores the model's potential to support decision-making in agricultural water policies by providing clear economic projections.

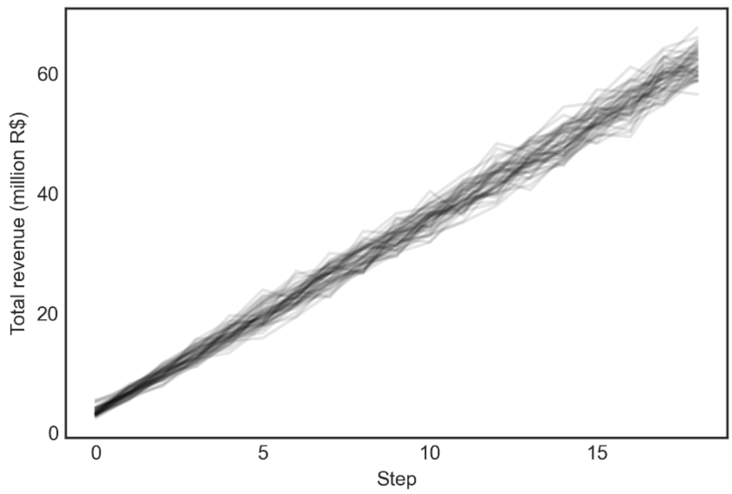

Figure 12: Economic projections for a 20 years time frame.

The model's ability to predict water deficits across canal segments provides actionable data to inform policy interventions. Each subplot in Figure 13 corresponds to a specific canal segment, organized row-wise (e.g., the first row represents segments 1, 2, and 3, while the second represents 4, 5, and 6). The results reveal a steady decline in water availability over time. In the final segment, the mean water volume available at approximately 68% for the last modelelled year. Linear water withdrawal was expected due to the model's parameterization, where a fixed amount of agents are allocated in the Canal throughout the years. Also, the high water availability indicates the need for targeted incentive policies to optimize water use and ensure the hydraulic infrastructure's long-term viability.

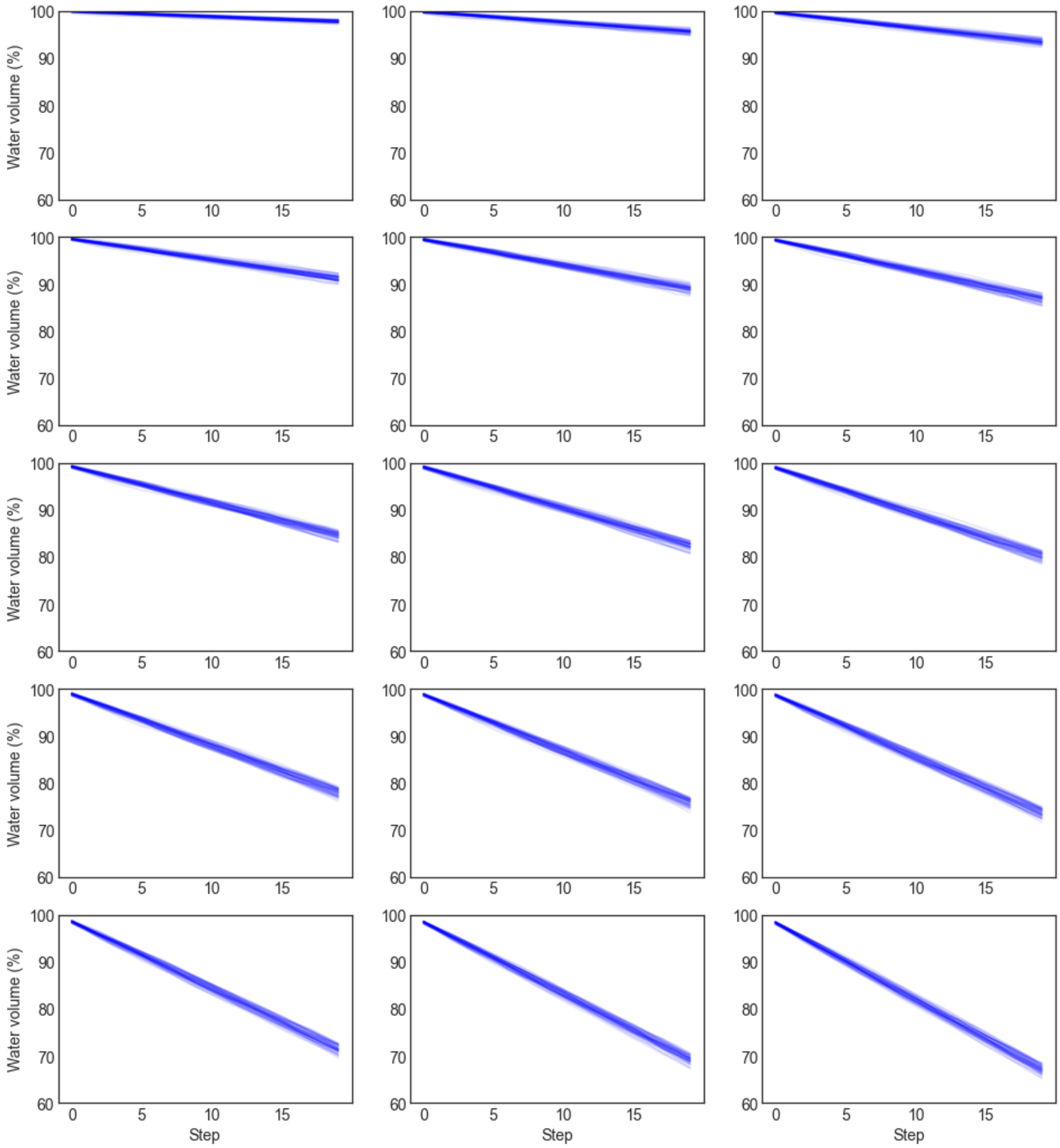

Figure 13: Water availability for Canal’s segments 1 to 15.

When analyzing different pricing scenarios for technical assistance, the number of contracts declined as expected with increasing prices (Figure 14). This suggests that higher prices made contracts less attractive, encouraging more farmers to opt for the status quo. Despite this decline in contracts, state revenue increased significantly with higher prices from 0.714 million reais at 0.08 R$/m³ to 2.548 million reais at 0.32 R$/m³ (Figure 15), indicating that the reduction in contracts was insufficient to offset the higher revenue per unit. Although a price of 0.32 R$/m³ aligns with the reported willingness to pay, caution is warranted due to potential hypothetical bias, as farmers currently do not bear the cost of water. Furthermore, higher prices may disproportionately burden smaller or less-resilient producers, jeopardizing equity and the region's long-term sustainability. To address this, policymakers could consider cross-subsidization strategies, wherein sectors with greater capacity to pay, such as industrial and municipal water users, subsidize agricultural users.

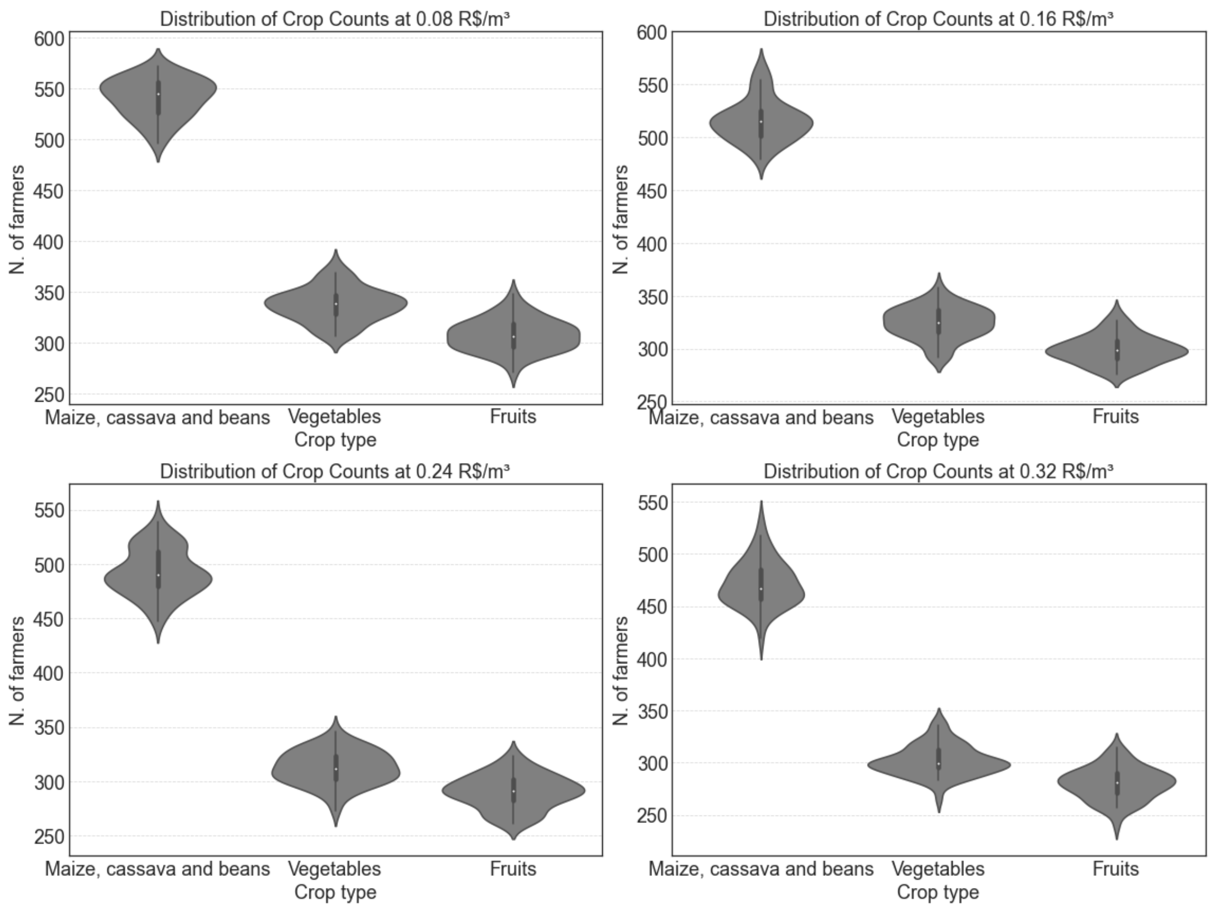

Figure 14: Distribution of selected crops by farmers who chose a contract.

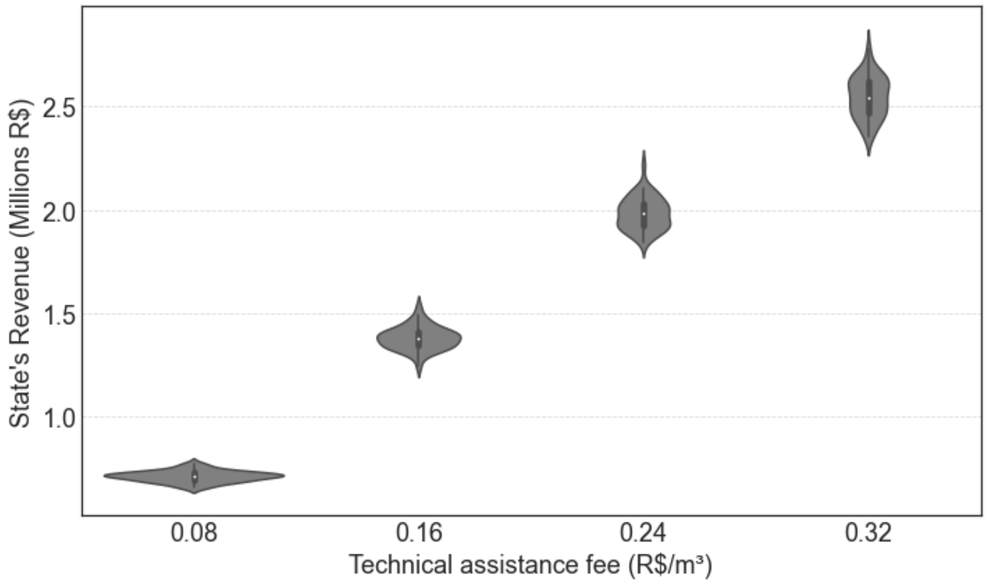

Figure 15: State revenue at year 20.

4.3.4 Discussion

We chose to model farmer's behaviour using a choice model. In this way, our model excels in capturing individual agent preferences and trade-offs. While the data collection through surveys offers model realism, it can be resource-intensive. Also, as it makes sense for farmers to maximize their utility due to profit focus behaviour, choice experiments may not be adequate in places where farmers may make decisions based on emotional or cultural influences. Combining choice models with other approaches could improve agents' decision-making. The Theory of planned behavior (AJZEN, 1991) could capture social normative pressures, and the nature of environmentally friendly choices (POULADI et al., 2019), as those choices often carry a positive normative belief. While game theory could help capture strategic interactions and competition between agents, especially in competing and cooperative scenarios (OKURA et al., 2022), it relies on complete rationality and usually diverges from real-world behaviors. A mix with the trade-off assessment of choice models could mitigate this drawback. Lastly, our model could also benefit from the fuzzy logic due to its ability to capture the self-learning behaviour (NOURI et al., 2019). Even though combining approaches is tempting in a way to capture real-life decision behaviour better, they clearly add model complexity and require even more data and expertise in interdisciplinary fields.

Enhancing the model from a multinomial logit (MNL) framework to a mixed logit (ML) approach would enable the analysis to account for heterogeneity among farmers, capturing variations in preferences and behaviors that the MNL model cannot address.

Additionally, incorporating interaction terms into the utility functions (e.g., farm size, and education) would improve the model’s ability to evaluate how water policies influence economic inequality.

In our study, farmers determine their crop choices for the upcoming year at each time step, but the model could be expanded to account for long-term strategies. Such strategies may incorporate memory effects, where past experiences—positive or negative—influence current decisions, or biases stemming from cultural preferences or market dynamics not captured in our model. In the case of the Canal do Sertão, where farmers endure severe climatic conditions but have access to canal-secured water, sustainable behavior might not always yield immediate benefits (TAMBURINO et al., 2020). This highlights the critical need for government policies to incentivize sustainable practices and preempt water scarcity through proactive measures. Additionally, incorporating adaptive learning mechanisms into the model could better reflect the evolution of farmer behaviors under changing environmental or economic conditions.

The incorporation of features such as system dynamics, feedback mechanisms, heterogeneity, and spatiality significantly enhances the model's ability to estimate the impacts of diverse policies. These elements provide decision-makers with the flexibility to design interventions to specific groups, such as small or large farms, urban regions, or institutional stakeholders. The predictive potential demonstrated in this study highlights the model’s utility in simulating policy outcomes across varied scenarios. While initially designed for a specific water canal, its framework is adaptable to other canals or watersheds, provided spatial structures are addressed using graph-based methodologies. Future developments should integrate the perspectives of water managers and other stakeholders in both modeling decisions and data collection, ensuring the model addresses a broader spectrum of actionable water-related policies effectively.

4.3.5 Conclusion

This paper presents an integrated hydro-economic framework that combines choice modelling with agent-based simulations, offering a novel perspective to evaluate how water policies influence farmers' decisions. By applying our model to the Canal do Sertão in northeastern Brazil, the study highlights the critical interplay between socio-economic behaviors and hydrological systems in shaping policy outcomes.

Expanding such frameworks to other regions can provide valuable guidance in managing water resources under varying climatic and socio-economic pressures. We recommend the model exploration and adaptation to different contexts. Besides novel modelling techniques, a collaborative effort between researchers, water manager and stakeholders is essential to find answers to water users' real needs.

4.3.6 References

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5. FINAL REMARKS AND CONCLUSIONS

This research develops a predictive framework that integrates agent-based modeling (ABM) and choice modeling to assess the impacts of water policies on farmer decision-making. Our model presented the ability to provide actionable insights of different water-related policies regarding economic aspects such as i) farmer income and water manager income, to verify to what degree policies effectively economically develop the region; ii) water repletion, to check whether policies have a positive impact in sustainable practices.

Understanding the socio-economic and behavioral drivers behind farmers' decision-making improved our model and, consequently, the impact of water policies. Our model revealed the misalignment of certain policies, like creating an association that buys farmers' production. On the other hand, we learned that they urge for a technical assistance policy. We learned the willingness to pay for water and technical assistance. And learned the driving factors that influence crop choice. This thesis shows that engaging stakeholders and understanding their actual needs to design efficient policies is critical to uncover contextual nuances and improve modelling and make results actionable.

Equally critical is dialogue with water managers to identify the most pressing challenges and design more actionable policies. We highlight the importance of building a simpler model (the one in paper #1), to increase complexity (the one in paper #3). This approach is of importance for hydrocomplex problems, as we learned throughout the process of model design and talking to farmers. Moving forward, integrating adaptive learning mechanisms and exploring applications in other contexts can enhance the model’s versatility and impact in advancing sustainable water governance.

APPENDIX

Appendix A: Choice experiment scenario description

The Canal do Sertão is an ongoing project to deliver water to the semiarid region of Alagoas. Currently, there are no water charges for water withdrawal. However, to cover expenses, especially due to energy costs from pumping water from the São Francisco River, the Canal do Sertão Management Plan estimates a water tariff of 0.38 R$/m³ (R$ 0.38 for every 1000 L) for withdrawal from the Canal.

The primary objective of the Canal do Sertão is to promote the local social-economic development. For this reason, we are studying the impact of the project on farm production and farmers economic returns. In particular, we are studying farmers' preferences for adoption of different water saving technologies when water charging begins. The first initiative is the creation of a farmer association that buys a share of farmers produce each year and is then responsible for selling it. The other policy initiative is a technical assistance program to help farmers in their farm production. The technical assistance would assist farmers in development of farming practices to avoid the loss of production and information about how to use water saving techniques effectively.

To enter in one or both programs, farmers may be tied in some aspects, for example be required to use efficient irrigation technologies or be tied to specific crop productions. The base water price (0.38 R$/m³) can also vary based on costs for implementing the incentive policies and the support from government.

Now, we will ask you to imagine that you are offered different incentive contracts when the water tariff is implemented. You will be asked to choose between a number of alternative contracts. For all possible contracts you consider the following points:

- Water tariff is a policy that will be implemented in near future.
- Dripping has 95% of water efficiency, followed by perforated tubes (90%) and conventional aspersion (80%). This means that for dripping, 95% of water is used by the plant, the others 5% are lost (for example, by evaporation).
- The irrigation technology you may be tied to the alternatives are represented as water efficiency percentages. For example, if it is required a water efficiency above 90% for a contract, you may install perforated tubes or dripping as irrigation technologies.

- When choosing a contract with a required crop choice you need to plant at least half of your farm area with that specific crop.
- Water charges are paid to the water manager of the Canal and is used to cover expenses of the canal maintenance and incentive policies.

Appendix B: Main study design and follow-up questions

Scenario 1 – block 1

	Contract 1	**Contract 2**	**Contract 3**	**Future status quo**
Crop bindind	Fruits	No binding	Maize, cassava or beans	No binding
Minimum irrigation efficiency	90%	80%	95%	Your irrigation efficiency
Technical assistance	Yes	Yes	No	No
Selling secured	25%	0%	50%	0%
Water price	R$ 0.32/m³	R$ 0.19/m³	R$ 0.19/m³	R$ 0.12/m³

Scenario 2 – block 1

	Contract 1	**Contract 2**	**Contract 3**	**Future status quo**
Crop bindind	Maize, cassava or beans	Vegetables	Fruits	No binding
Minimum irrigation efficiency	80%	95%	90%	Your irrigation efficiency
Technical assistance	Yes	No	No	No
Selling secured	25%	0%	50%	0%
Water price	R$ 0.19/m³	R$ 0.14/m³	R$ 0.32/m³	R$ 0.12/m³

Scenario 3 – block 1

	Contract 1	**Contract 2**	**Contract 3**	**Future status quo**
Crop bindind	Vegetables	Fruits	Maize, cassava or beans	No binding
Minimum irrigation efficiency	95%	80%	90%	Your irrigation efficiency
Technical assistance	No	Yes	Yes	No
Selling secured	50%	0%	25%	0%
Water price	R$ 0.25/m³	R$ 0.10/m³	R$ 0.40/m³	R$ 0.12/m³

Scenario 4 – block 1

	Contract 1	**Contract 2**	**Contract 3**	**Future status quo**
Crop bindind	No binding	Maize, cassava or beans	Vegetables	No binding
Minimum irrigation efficiency	95%	90%	80%	Your irrigation efficiency
Technical assistance	No	No	Yes	No
Selling secured	0%	25%	50%	0%

Water price	R$ 0.10/m³	R$ 0.40/m³	R$ 0.19/m³	R$ 0.12/m³

Scenario 5 – block 1

	Contract 1	Contract 2	Contract 3	Future status quo
Crop bindind	Vegetables	No binding	Fruits	No binding
Minimum irrigation efficiency	80%	90%	95%	Your irrigation efficiency
Technical assistance	Yes	No	No	No
Selling secured	0%	25%	50%	0%
Water price	R$ 0.19/m³	R$ 0.40/m³	R$ 0.14/m³	R$ 0.12/m³

Scenario 6 – block 1

	Contract 1	Contract 2	Contract 3	Future status quo
Crop bindind	No binding	Fruits	Maize, cassava or beans	No binding
Minimum irrigation efficiency	90%	95%	80%	Your irrigation efficiency
Technical assistance	No	Yes	No	No
Selling secured	25%	50%	0%	0%
Water price	R$ 0.40/m³	R$ 0.25/m³	R$ 0.10/m³	R$ 0.12/m³

Scenario 1 – block 2

	Contract 1	Contract 2	Contract 3	Future status quo
Crop bindind	Maize, cassava or beans	Fruits	No binding	No binding
Minimum irrigation efficiency	95%	90%	80%	Your irrigation efficiency
Technical assistance	No	No	Yes	No
Selling secured	50%	25%	0%	0%
Water price	R$ 0.19/m³	R$ 0.32/m³	R$ 0.14/m³	R$ 0.12/m³

Scenario 2 – block 2

	Contract 1	Contract 2	Contract 3	Future status quo
Crop bindind	Vegetables	Maize, cassava or beans	No binding	No binding
Minimum irrigation efficiency	80%	90%	90%	Your irrigation efficiency
Technical assistance	No	Yes	No	No
Selling secured	50%	0%	25%	0%
Water price	R$ 0.25/m³	R$ 0.14/m³	R$ 0.32/m³	R$ 0.12/m³

Scenario 3 – block 2

	Contract 1	Contract 2	Contract 3	Future status quo
Crop bindind	No binding	Vegetables	Fruits	No binding
Minimum irrigation efficiency	95%	95%	80%	Your irrigation efficiency

Technical assistance	Yes	Yes	No	No
Selling secured	0%	25%	50%	0%
Water price	R$ 0.10/m³	R$ 0.32/m³	R$ 0.25/m³	R$ 0.12/m³

Scenario 4 – block 2

	Contract 1	**Contract 2**	**Contract 3**	**Future status quo**
Crop bindind	Fruits	Vegetables	No binding	No binding
Minimum irrigation efficiency	90%	80%	95%	Your irrigation efficiency
Technical assistance	Yes	No	Yes	No
Selling secured	25%	0%	50%	0%
Water price	R$ 0.32/m³	R$ 0.10/m³	R$ 0.25/m³	R$ 0.12/m³

Scenario 5 – block 2

	Contract 1	**Contract 2**	**Contract 3**	**Future status quo**
Crop bindind	Maize, cassava or beans	No binding	Vegetables	No binding
Minimum irrigation efficiency	90%	80%	95%	Your irrigation efficiency
Technical assistance	Yes	No	Yes	No
Selling secured	25%	50%	0%	0%
Water price	R$ 0.40/m³	R$ 0.25/m³	R$ 0.10/m³	R$ 0.12/m³

Scenario 6 – block 2

	Contract 1	**Contract 2**	**Contract 3**	**Future status quo**
Crop bindind	Fruits	Maize, cassava or beans	Vegetables	No binding
Minimum irrigation efficiency	80%	95%	90%	Your irrigation efficiency
Technical assistance	No	Yes	Yes	No
Selling secured	0%	50%	25%	0%
Water price	R$ 0.10/m³	R$ 0.19/m³	R$ 0.40/m³	R$ 0.12/m³

1. What is your gender?
2. What is your age?
3. What is your crop area?
4. Which crops do you plant currently?
5. What is your irrigation method?
6. What is your educational level?
7. How much of your income is from agriculture?
8. Do you hire people to work on the farm? If yes, how many people?
9. From 0 to 10 how much do you think this research will make a difference in water policies in the Canal do Sertão?

Appendix C: Income of crops planted in the Canal do Sertão and surroundings

The farmer's revenue was estimated using regional data from the Brazilian Institute of Geography and Statistics (IBGE). We analyzed data from both temporary and permanent crops for 2022 (IBGE, 2022). The dataset provided the gross revenue of Brazilian producers, categorized by states and their respective mesoregions. From this, we filtered the data for the Sertão region of Alagoas (Table 7), the area impacted by the Canal do Sertão.

Table 7: revenue for agricultural productions in the Sertão mesoregion of Alagoas

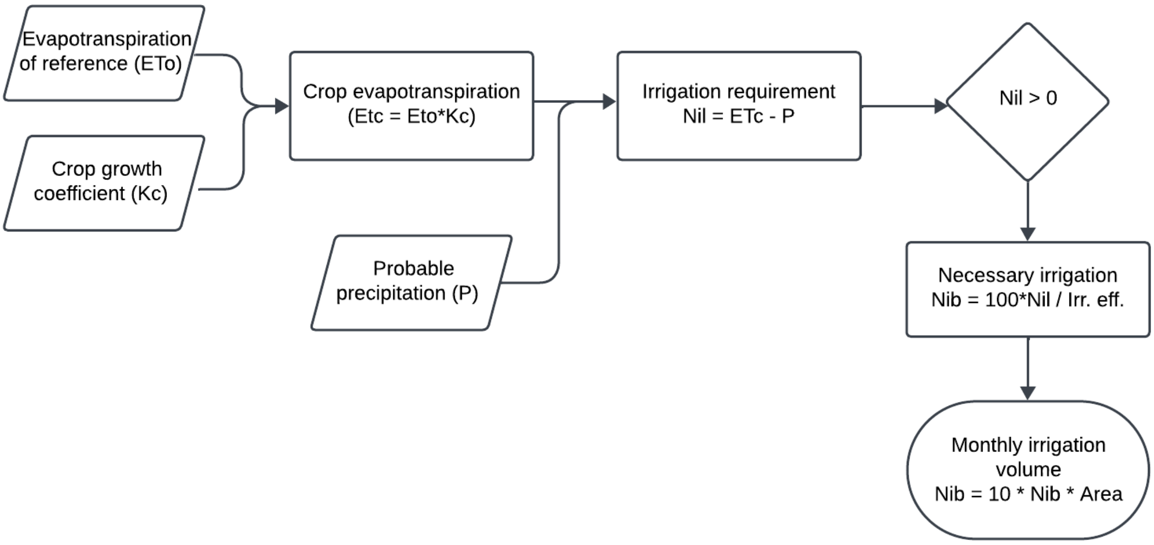
Crop type	Crop	Harvested area (ha)	Production (ton)	Yield (kg/ha)	Production value (thousand R$	Revenue per area (thousand R$/ha)
Fruits	Watermelon	427	8366	19593	10708	25
	Passion Fruit	28	301	10750	1067	38
	Banana	129	1725	13372	3225	25
Vegetables	Tomato	117	4891	41803	12335	105
	Bell Pepper	-	-	-	-	-
	Kale	-	-	-	-	-
	Lettuce	-	-	-	-	-
MCB	Maize	5604	6266	1118	9499	2
	Cassava	995	11675	11734	11680	12
	Beans	4106	2051	500	7466	2

Using the available data, we calculated the revenue per unit area by considering the main crop types identified through field surveys and additional information provided by water management officials. We then calculated the simple mean revenue for each crop type. To determine the revenue for each farmer, we multiplied the revenue per unit area by the total area of their farm.

Appendix D: Calculations of crop water demand in the semiarid of Alagoas

The water requirement depends on crop type, precipitation, and evaporation (Figure 16).

Figure 16: calculations flowchart of required irrigation water volume.



Source: The author (2025).

Three main variables are required to calculate the required irrigation for each crop: the evapotranspiration of reference (ETo), the probable precipitation (P) and the irrigation coefficient (Kc) for the respective crop. We considered main crop types from field surveys and ad hoc information from water manager officials. We grouped each crop type into three categories (Fruits, Vegetables; and maize, cassava, and beans) according to the crop binding levels from the choice experiment (Table 1). The value for Kc considers different crop growth phases, however, we chose to choose mean values for this variable for the sake of parsimony.

Table 8: Irrigation coefficients for considered crops in the Canal do Sertão

Crop group	Crop type	Kc
Fruits	Watermelon	1.0
	Passion Fruit	0.93[a]
	Banana	1.1 (Year 1) 1.2 (Year 2)
Vegetables	Tomato	1.15
	Bell Pepper	1.05
	Kale	1.05
	Lettuce	1.05
Maize, Cassava and Beans	Maize	1.2
	Cassava	0.8 (Year 1) 1.1 (Year 2)
	Black-eyed beans	1.05

Source: ANA 2013 and references therein
[a] Weighted average considering different growth stages from Silva et al. (2006)

Values for precipitation (P) and reference evapotranspiration (ETo) were geospatialized. Xavier et al. (2013) interpolated meteorological variables in Brazil considering the time frame from 1980 and 2015. The 0.25º × 0.25º spatial resolution gridded data was made available in NetCDF by the authors. We interpolated these data using the inverse of the quadratic distance method using QGIS software and Python. Then, we buffered 20km from the constructed section of the Canal do Sertão, considering this as the area of direct influence of the canal. We calculated the mean values for each month (Table 9).

Table 9: Precipitation and reference evapotranspiration for the Canal do Sertão

Month	P	ETo	Month	P	ETo
Jan	42.6	128.0	Jul	83.7	89.2
Feb	47.3	109.3	Aug	45.9	109.9
Mar	71.0	111.1	Sep	45.5	119.2
Abr	59.8	94.5	Oct	16.9	130.6
Mai	68.0	83.6	Nov	17.2	133.4
Jun	78.8	83.7	Dec	31.6	134.7

All values in mm

To exemplify calculations, we consider a hypothetical farmer that plants an area of 2 ha entirely of fruits using dripping irrigation. The total precipitation is 608.3 mm/year, while total reference evapotranspiration is 1757.2 mm/year. Considering the mean value of Kc for the three fruit types:

$$ETc = \frac{(1.0 + 0.93 + 1.15)}{3} \times 1327.2 = 1362.6\ mm/year$$

$$Nil = 1362.6 - 608.3 = 754.3\ mm/year$$

As $Nil > 0$, it is necessary irrigation. As dripping irrigation has 95% efficiency, so:

$$Nib = \frac{100 \times 754.3}{95} = 794.0\ mm/year$$

Finally, considering the area of irrigation, the yearly irrigation volume is:

$$Nib = 10 \times 794.0 \times 2 = 15{,}880.0\ m^3/year$$

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