**ODD Protocol**

1. **Overview**
   1. **Purpose**

The present agent-based model (ABM) has the purpose of investigating the effect of collective decision-making strategies during the dry season through different water availability scenarios on the patterns of the consumed water volume for irrigation in agents that respond heterogeneously to the regulatory instruments implemented in the basin.

Additionally, the proposed ABM is part of a frameworkbased on a socio-hydrological approach in which the results generated from the ABM are integrated into a hydrological model to assess the effect of different scenarios evaluated on water availability. The ABM is adapted for one-way and two-way integration methods, and both are presented in this protocol.

This model was motivated by the application of a methodology for managing conflicts over water use in the Formoso river basin (FRB), located in the state of Tocantins, northern Brazil. Thus, the representation of the farmer agents’ reasoning illustrated in this model focuses on behavioral modeling. A study case is applied on the Urubu river sub basin.

The patterns used to evaluate the purpose of the model were defined as the variability observed in the total withdrawal volume values according to the different implemented scenarios.

* 1. **Entities, state variables, and scales**

Two groups of scenarios were executed, namely, reflexive agents and BDI agents, with a different model file being created for each group. The BDI agents model file was derived from the first one, with some additions and alterations that will be better explained throughout the present document.

The model was developed considering four agents: Global, Pump, Farmer and Regulator. Details of each agent type are presented below.

Global Agent

It corresponds to the modeled environment, including georeferenced data (features of rivers, pumps, irrigation areas, irrigation canal system), agent identification tables, scenarios definition, and general functions to the model in a global scope.

Some dynamic variables intrinsic to the simulation were defined:

* Simulation cycle (*cycle*): integer type dynamic variable. Represents the simulation cycle counter.
* Simulation number (*n\_sim*): integer type dynamic variable. Represents the total simulation counter, with all cycles.
* Current date (*current\_date*): date type dynamic variable. Represents the current date.

Two Boolean-type dynamic variables corresponding to the date criteria for the water usage rule were defined:

* Date Criterion 1 (*aux\_date\_07*): Checks if *current\_date* is equal to or greater than the attention/yellow rule date (*attention\_date*). If so, the variable is true; otherwise, it is false.
* Date Criterion 2 (*aux\_date\_08*): Checks if the current date (*current\_date*) is equal to or greater than the restriction/red rule date (*restriction\_date*). If so, the variable is true; otherwise, it is false.

The variables *attention\_date* and *restriction\_date* are date-type static variables. For this application, they correspond to July 1st and August 1st, respectively.

Similarly, a float-type dynamic variable corresponding to the current water level (*current\_level)* is defined. This variable may be determined in two different ways:

* For the one-way integration of the ABM and the hydrological model, *current\_level* is defined using a three-column matrix (*level\_series)*. This matrix is comprised of float-type static elements, each column corresponding to a water availability condition (dry, average, and wet), and each line represents a time step of the model. Thus, the water availability scenario varies according to the selected column (*col\_level)*, which is an integer-type static variable.
* For the proposed two-way integratation between the ABM and a Hydrological Model, there is also a *level\_series* matrix. However, in case there are ‘n’ replications of simulated flow results (as a result of ‘n’ replications of the ABM execution). Accordingly, a matrix of ‘n’ columns and no. of rows corresponding to the period of each ABM execution (e.g., one dry season, one year, one month, etc) may be used. In that case, *col\_level* would be selected as one random integer among the ‘n’ columns of the matrix for each replication of the ABM, such that the set of potential series of levelsis static during each ABM replication within itself. The *current\_level* for each day corresponds to each row of the resulting *level\_series* [column = *col\_level*] array, after the *col\_level* variable is randomly chosen. Such series is derived from the simulated flow results of the prior hydrological model execution, which are, in turn, generated by the daily withdrawal results from the execution of the previous run of the ABM. Thus, such *level\_series* matrix is dynamic throughout each execution cycle of the coupled ABM + hydrological model.

The variable *current\_level* is used to evaluate two Boolean-type dynamic variables corresponding to the level criteria for the water usage rule:

* Level 1 Criterion (*aux\_level\_yellow)*: Checks if the current level (*current\_level)* is equal to or greater than the attention/yellow rule level (*yellow\_level)*. If so, the variable is true; otherwise, it is false.
* Level 2 Criterion (*aux\_level\_red)*: Checks if the current level (*current\_level)* is equal to or greater than the restriction/red rule level (*red\_level)*. If so, the variable is true; otherwise, it is false.

The *yellow\_level* and *red\_level* variablesare float-type static variables.

All variables related to usage rules were based on guidelines defined by the 2018-2019 Biennium Plan (IAC, 2018).

Some static global variables are defined for the calculation of the water withdrawal (to be performed by the Pump agents):

* *limits\_withdrawal*: array type variable containing integer type elements. Columns 1 and 2 of the matrix contain an integer number for each row, in ascending order.

Some variables are defined with the purpose of characterizing the model in a temporal way:

* *twoweeks\_count*: integer-type dynamic variable, representing groups of 15 days each.
* *nb\_days*: integer static variable, corresponds to the number of days in the dry season.
* *starting\_date*: date-type static variable, corresponding to the first day of the dry season.

In BDI scenarios with neighborhood effect, in the Global agent a list of Farmer agents is defined for each demand group (defined as *demand\_g,* an attribute of Pump and Farmer agents*)*:

* *mygroup1*: list-type static variable of Farmer-type agents whose *demand\_g* attributeis equal to D1.
* *mygroup2*: list-type static variable of agents of Farmer-type agents whose *demand\_g* attributeis equal to D2.
* *mygroup3*: list-type static variable list of agents of Farmer-type agents whose *demand\_g* attributeis equal to D3.

Finally, a list-type dynamic variable with float-type elements is defined, which collects the water withdrawal value at each time step for each agent of type Pump (*all\_pumps\_daily\_withdrawal)*.

For the proposed two-way integratation between the ABM and a Hydrological Model, one additional boolean-type dynamic variable is considered in the ABM:

* *aux\_level\_zero*: checks if the current level is equal to zero. This condition is evaluated to avoid the generation of daily withdrawal results by farmer agents when there is no available water in the environment. (see assign beliefs submodel, p. 10).

Pump

Pump-type agents correspond to irrigation pumps in the modeled environment. Each pump is operated and owned by a Farmer agent, who can in turn operate and own one or more Pump agents.

Pump agents have the following attributes:

* *p\_id*: Integer-type static variable that identifies the pump.
* *f\_id*: integer static variable to identify the owner of the pump.
* *demand\_g*: static variable of type string that represents the demand group to which the pump belongs (D1, D2, or D3). Defined based on Volken *et al.* (2022).
* *f\_profile*: string-type static variable that represents the behavioral profile of the Farmer agent who owns the pump. It can assume the following values: NC (Non-Cooperative), CP (Cooperative), or CI (Indeterminate).
* *prob\_matrix*: matrix-type dimensionless static variable with float variables that varies according to the agent's profile. Each index in the matrix represents a probability that the agent's daily withdrawal assumes a value within a certain range.
* *p\_list:* Probability list extracted from the probability matrix corresponding to the current *twoweeks\_count*.
* *interval\_index*: integer type dynamic variable in which the *limits\_withdrawal* indexis randomly chosenaccording to the weights in *p\_list*.
* Lower and upper bounds of the selected range (*a* and *b)*: integer type dynamic variable corresponding to the value of the first and second column of the global variable of *limits\_withdrawal* in the corresponding *interval\_index* line.
* *daily\_withdrawal:* float type dynamic variable (m3). Defined according to the agent’s profile and their corresponding probability matrix.

Farmer

Farmers represent human agents that use water to irrigate their crops. Different types of Farmer agents are defined in the model, represented by three cooperative profiles (CP, NC, CI).

A Farmer agent has the following attributes:

* *f\_id*: integer static variable that identifies the farmer.
* *demand\_group*: static variable of type string that represents the demand group to which the irrigator belongs (D1, D2 or D3).
* *owned\_pumps*: list-type static variable with Pump-type elements.
* *nb\_pumps*: Integer type static variable. Represents the total number of pumps the Farmer agent owns.
* *profile*: static variable of type string, as in Pump agent’s *f\_profile*.
* *f\_daily\_withdrawal:* float type dynamic variable (m3). Defined as the sum of the daily withdrawal of all pumps owned by the Farmer agent.

In the case of Farmer agents with BDI reasoning, sets of beliefs, desires, and intentions are also introduced, which are defined by predicate-type dynamic variables:

* *trigger\_attention\_rule*: Indicates that the attention rule must be obeyed ("*Attention rule must be obeyed* ").
* *trigger\_restriction\_rule*: Indicates that the restriction rule must be obeyed ("*Restriction rule must be obeyed* ").
* *obey\_restriction\_rule*: Indicates that the agent is obeying the restriction rule ("*I am obeying the restriction rule* ").

For neighborhood effect scenarios, a list of Farmer agents corresponding to the demand group (*my\_group)* is included, from which a float-type static variable is calculated, defined as the proportion of agents with NC and CP profile (*n\_NC* and *n\_CP*, respectively) across their corresponding *demand\_g*. Such variables can activate the predicates defined in the BDI architecture regarding the predominance of a certain profile within their neighborhood:

* *most\_NC*: Indicates there is a majority of agents of type NC in their demand group (predicate: *'Most are NC in my group ')*;
* *most\_CP*: Indicates there is a majority of agents of type CP in their demand group (predicate: *'Most are CP in my group ')*;

Regulator

Represents the water regulatory authority in the model.

For BDI scenarios, it has two inspection dates as date-type static variables, corresponding to the attention and restriction rule dates.

The sets of beliefs, desires, and intentions are:

* Attention rule activation belief (*attention\_rule)*: Indicates that the attention rule must be obeyed (" *Attention rule must be obeyed* ").
* Restriction rule activation belief (*restriction\_rule)*: Indicates that the restriction rule must be obeyed (" *Restriction rule must be obeyed* ").

In addition to the 4 agents detailed above, some auxiliary agents were defined for the representation of the graphical interface: Hidro, Land, and Channel, representing the georeferenced features of rivers, irrigation areas, and irrigation canals, respectively.

The scales used in the model were defined as:

* Temporal: A time step represents one day. A simulation corresponds to a dry season (123 days). Each execution was performed with 1000 repetitions.
* Spatial: two-dimensional, on a watershed scale, represented by the case study river basin (Urubu river basin).
  1. **Process overview and scheduling**

For the reflexive agent scenarios, the processes are executed in the following order:

1. The experiment of batch-type simulations is executed.
2. In the Global agent, the initial state of the simulation is defined:
   1. Pump, Farmer, and Regulator agents are created:
   2. The simulation scenario is defined.
   3. *n\_CP* and *n\_NC* variables are calculated.
   4. The submodels that update the following state variables are executed: *current\_date*, *twoweeks\_count*, *aux\_date\_07*, and *aux\_date\_08*.
3. The dynamic state variables of the other agents are updated:
   1. Pump agents update their *p\_list*, *interval\_index*, *a, b*, and *daily\_withdrawal* variable*s* through a submodel (*update\_withdrawal)*.
   2. Farmer agents update their *f\_daily\_withdrawal* state variable.
4. The global variables *cycle*, *n\_sim*, *current\_date,* and *all\_pumps\_daily\_withdrawal* are savedas output data in a CSV file, in a results folder.

For BDI agents’ scenarios, the Pump, Farmer, and Regulator agents’ reasoning control parameter is added. In addition, some actions are added:

* In 1., the column of the water level input file (*col\_level)*, is defined according to the simulation scenario.
* In 2., the variable *current\_level* , *aux\_level\_yellow* , and *aux\_level\_red* are also updated*.*
* The Regulator agent updates its belief state variables (*attention\_rule* and *restriction\_rule)*
* In 3., the agent variables are updated:
  + Farmer: *trigger\_attention\_rule , trigger\_restriction\_rule , obey\_restriction\_rule.*
  + Pump: The *update\_withdrawal submodel* of the agent is changed by checking the existence of the *trigger\_attention\_rule* or *trigger\_restriction\_rule* beliefto execute the rules of decreasing or interrupting withdrawal, according to the profile.
  + Regulator: *restriction\_rule , attention\_rule* .

For the scenarios of BDI agents with neighborhood effect, a function is added that verifies the existence of the predominance belief of CP (*most\_CP)* or NC (*most\_NC)*, which in turn updates the profile of CI agents and CI pumps.

1. **Design Concepts**
   1. **Basic principles**

Farmers’ cooperative profiles (NC, CP, and CI) were identified based on analysis of the frequency of transmission of withdrawal data obtained from the GAN system (GAN, 2022) which were confronted with a classification derived from an interview with specialists who maintain contact with farmers in the study basin (FRB).

The withdrawal patterns of each of the three profiles were generated from statistical modeling of the withdrawal data contained in the GAN system.

The scenarios with reflexive reasoning agents were implemented following the patterns of withdrawal from one of the three profiles, without introducing rules for water use, and based only on the repetition of the emerging pattern from the observed data.

For the scenarios with BDI reasoning agents, the CP agents were defined as being fully compliant with water usage rules. NC (non-cooperative) agents were identified as being completely non-compliant with regulations. CI agents were assumed to be a compromise between the two extreme behaviors (CP and NC).

Thus, for the scenarios of BDI agents with neighborhood effect, it is considered that only CI profile agents could be inclined to change their profile. Consequently, the CI agents have their profile and the corresponding probability matrix altered, so that they start to assume the predominant profile identified (NC or CP) in their demand group.

The restriction usage rule (*restriction\_rule)* is defined as the complete cease of water withdrawal. The attention usage rule (*attention\_rule)* is defined as a 50% reduction of the agent withdrawal pattern.

* 1. **Emergency**

The daily withdrawal results are elements that emerge from the behavior of the Farmer agent, which in turn is influenced by its profile and the state of the environment.

* 1. **Adaptation**

The adaptive behavior of Farmer agents is evident in the BDI and neighborhood scenarios, in which the agent's belief base is influenced by the state of the environment (water level), the profile, and the predominant profile in its demand group. In this sense, the CP and NC agents are, respectively, completely cooperative and non-cooperative with the rules of use, while the CI agents need that all the activation criteria of the rules are true in order to fulfill them.

This influence takes place in the Pump agent *update\_withdrawal (2)* submodel by the existence or not of the *trigger\_restriction\_rule* and *trigger\_attention\_rule* variables. The Farmer agent, on the other hand, influences the *reflex\_neigh* submodel, in which the existence of the belief *most\_CP* or *most\_NC* is verified.

* 1. **Sensing**

The following variables of the Farmer species are assumed to be perfectly detectable by the Pump species corresponding to the pump owner (*pump\_owner)*: *profile*, and the BDI knowledge base (*trigger\_attention\_rule, trigger\_restriction\_rule*, *obey\_restriction\_rule)*.

As for the Farmer agent, the variable *daily\_withdrawal* is perfectly detected for its owned pumps (*owned\_pumps)*.

* 1. **Interaction**

For the neighborhood effect scenarios, an indirect interaction is implemented, mediated by an existing submodel in the species Global.

* 1. **Stochasticity**

In order to demonstrate the intrinsic stochasticity of the behavior of the Farmer agents, a function is used to define the variable *interval\_index* (Pump type) that randomly chooses the index of the element whose probability weight corresponds to the value of the same index in *p\_list*.

Thus, 1000 repetitions were performed for each of the simulation scenarios, aiming to illustrate the variability of possibilities represented by the probability matrix.

* 1. **Observation**

The model's output data is analyzed according to the global variable *all\_pumps\_daily\_withdrawal*, generating a CSV for each scenario run. Thus, each file has *nb\_days* \* *n\_sim* rows, and the number of columns corresponds to the number of Pump type agents.

From this file, the data is treated in an external software to generate boxplot-type graphs. The data resulting from step 4 of the Process Overview section are sorted according to each simulation (1 to 1000) and each cycle (1 to 123), thus having 1000 repetitions of a simulation of 123 cycles. For each simulation cycle (1 day), the daily results of the total number of pumps are added together.

For the reflexive scenarios, boxplots of the daily sum of withdrawals of all pumps for each 15-day group are plotted. As for the BDI scenarios results, daily boxplots can also be plotted, depending on the variability of behavior.

The concepts of objective, learning, and prediction were not introduced in this model.

1. **Details**
   1. **Initialization**

The initialization of agents and initial values of variables is performed in the Global agent.

Pump-type agents are defined from a shapefile-type file of the pumps that exist in the study basin. This same shapefile has an attribute table with the identification of the farmer that owns the pump (*f\_id)*, their demand group (*demand\_g),* and their cooperative profile (*profile)*. The present model creates 37 Pump agents.

The Farmer species is created from the non-repeating listing of the elements of *f\_id*. This model creates 24 Farmer agents.

From a matrix introduced as input data, each pump (*p\_id)* is related to a Farmer agent (*f\_id)*, where the profiles, demand groups, and irrigation area of the Farmer agents are defined. The variable *owned\_pumps* for the Farmer species, and the variable pump\_owner for the Pump agents are also defined.

From the profile of each Pump agent (*profile)*, its corresponding probability matrix (*prob\_matrix)* is defined.

Regulator species are created without predefined input data.

As an initial state for variables of the Global agent, these are defined based on the 2018-2019 Biennium Plan (IAC, 2018):

* *starting\_date*: 01st May 2020, corresponding to the first day of the dry season.
* *current\_date* : *starting\_date*
* *current\_level*: 500 (in cm)
* *nb\_days*: 123 (in days)
* *yellow\_level*: 398 (in cm)
* *red\_level*: 220 (in cm)

For the execution of experiments in batch, the following parameters are used:

* Number of repetitions: 1000.
* Stopping criterion: when the simulation cycle reaches *nb\_days* + 1.
* The random number generator’s seed is kept.

In general, three groups of scenarios were studied: agents with reflexive reasoning, agents with BDI reasoning, and agents with BDI reasoning with neighborhood effect. It was considered that the introduction of regulatory measures may influence water users’ behavior and, consequently, modify the distribution of profiles observed in the study basin (Akhbari and Grigg, 2013).

According to each scenario, individual and collective allocation configurations were tested, the latter being considered from the total adherence of Farmer agents to a common profile (100% CP, CI, or NC).

In addition, variables related to water availability were introduced in the BDI scenarios, varying the column (*col\_level)* of the water levels file according to the availability scenario.

* 1. **Input Data**

The variables used as input data, as well as the source and unit, are presented in Table 1.

Table 1 – Input data: variables, units and sources.

|  |  |  |
| --- | --- | --- |
| Variables | Units | Sources |
| *shapefile\_pumps* | - | GAN (2022) and paper’s methodology |
| *farmers\_data* | - | GAN (2022) and paper’s methodology |
| *limits\_withdrawal* | m 3 | Paper’s methodology |
| *prob\_CI* | dimensionless | Paper’s methodology |
| *prob\_NC* | dimensionless | Paper’s methodology |
| *prob\_CP* | dimensionless | Paper’s methodology |
| *level\_series* | cm | One-way integration: Station 26798500, GAN (2022)  Two-way integration: previous execution of the hydrological model |

**Submodels**

The submodels used in the Global agent relate to the updating of some variables every cycle (1 day):

* *current\_date*: adds a day.
* *current\_level*: loops through a row of the *level\_series* input arrayevery cycle.
* *aux\_date\_07* and *aux\_date\_08*: updated according to the update of *current\_date*.
* *aux\_level\_yellow* and *aux\_level\_red*: updated depending on the update of *current\_level*.
* *twoweeks\_count*: updated every 15 cycles, adding a unit.

In the Global agent, an assignment submodel is also implemented which defines the group of Farmer agents (*my\_group)* and the *n\_CP* and *n\_NC* variables. The ' ASK’ facet means that the current agent (Global) is accessing an attribute of another agent type (in this case, all agents of type Farmer).

Neighborhood assignment submodel

ASK FARMER:

IF *demand\_g* = D1, THEN:

*my\_group* = *mygroup1*

, IF *demand\_g* = D2, THEN:

*my\_group* = *mygroup2*

, IF *demand\_g* = D3, THEN:

*my\_group* = *mygroup3*

n\_CP = LENGTH (*my\_group* WHERE *profile* OF EACH LIST ELEMENT = CP) / LENGTH (*my\_group)*

n\_nc = LENGTH (*my\_group* WHERE *profile* OF EACH LIST ELEMENT = NC) / LENGTH (*my\_group)*

Farmer agents have submodels for assigning beliefs (*assign\_beliefs)*. The *assign\_beliefs submodel* is implemented as follows:

*assign\_beliefs* submodel

IF *profile* = CP, THEN:

IF *aux\_date\_08* OR *aux\_level\_red* , THEN :

ADD BELIEF trigger\_restriction\_rule

IF *aux\_date\_07* OR *aux\_level\_yellow* , THEN :

ADD BELIEF trigger\_attention\_rule

ELSE, IF profile = CI, THEN:

IF *aux\_date\_08* AND *aux\_level\_red* , THEN :

ADD BELIEF trigger\_restriction\_rule

IF *aux\_date\_07* AND *aux\_level\_yellow* , THEN:

ADD BELIEF trigger\_attention\_rule

In the case of BDI scenarios and two-way integration of ABM and hydrological model, the restriction rule may be triggered by the absence of water as a global variable (*aux\_level\_zero*), forcing the agent, regardless of profile type, to not withdrawal water, as follows:

IF *aux\_level\_zero*, THEN :

ADD BELIEF trigger\_restriction\_rule

Also in Farmer agents, two submodels are used to implement the neighborhood effect (*my\_neighbours* and *neighbor\_effect)*.

*my\_neighbours* submodel

IF *n\_NC* > *n\_CP* , THEN:

ADD BELIEF *most\_NC*

IF *n\_CP* > *n\_NC* , THEN:

ADD BELIEF *most\_CP*

*neigh\_effect* submodel

IF *profile* = CI, THEN:

IF THERE IS BELIEF *most\_NC* , THEN:

*profile* = NC

ASK *owned\_pumps* :

*prob\_matrix* = prob\_NC

*f\_profile* = NC

OTHERWISE, IF THERE IS BELIEF *most\_CP* , THEN:

*profile* = CP

ASK *owned\_pumps* :

*prob\_matrix* = prob\_CP

*f\_profile* = CP

Pump agents have a submodel for updating the daily water withdrawal variable (*update\_withdrawal)*:

*update\_withdrawal (1)* submodel

*p\_list* = COLUMN IN *prob\_matrix* CORRESPONDING TO *twoweeks\_count*

*interval\_index* = RANDOM CHOICE IN *p\_list*

a = ELEMENT IN LINE *interval\_index* COLUMN 1 OF *limits\_withdrawal*

b = ELEMENT IN LINE *interval\_index* COLUMN 2 OF *limits\_withdrawal*

RETURN RANDOM NUMBER IN INTERVAL (a,b)

In the case of BDI scenarios, the *update\_withdrawal* submodelis modified to:

*update\_withdrawal (2)* submodel

*p\_list* = COLUMN IN *prob\_matrix* CORRESPONDING TO *twoweeks\_count*

*interval\_index* = RANDOM CHOICE IN *p\_list*

*a* = ELEMENT IN LINE *interval\_index* COLUMN 1 OF *limits\_withdrawal*

*b* = ELEMENT IN LINE *interval\_index* COLUMN 2 OF *limits\_withdrawal*

*daily\_withdrawal* = RANDOM NUMBER IN INTERVAL (*a,b*)

ASK *pump\_owner* :

IF THERE IS BELIEF *trigger\_restriction\_rule*, THEN:

RETURN 0.0

OTHERWISE, IF THERE IS BELIEF *trigger\_attention\_rule*, THEN:

RETURN 0.5 \* *daily\_withdrawal*

ELSE,

RETURN *daily\_withdrawal*

**References**

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