Integrated Agent-based model and frequency-based risk models to explore Mexico City Socio-Hydrological Vulnerability

ODD Protocol

**Introduction**

This document describes the implementation of an Agent-Based Model and its integration to the biophysical risk models of the MEGADAPT project (Megacity Adaptation to Climate Changes). The full MEGADAPT model simulates the coupling between biophysical processes and the decisions of influential actors associated to the socio-hydrological vulnerability of Mexico City. The goal of the model is to simulate the two way coupling of a complex socio-environmental system. The two way coupling is obtained by simulating two feedback. The feedback between risk, socio-political infrastructure and socio-institutional decisions, and the feedback between agent learning and environmental information (Bojorquez-Tapia et al., *in review*).

The agent-based model simulates the decision-making processes of different socio-institutional and socio-political actors of Mexico City, and their actions and decisions to adapt to hydrological risk and vulnerabilities in the landscape of Mexico City. The model is spatial explicit and dynamic that is, the landscape of Mexico City is represented by spatial units with socio-environmental attributes that change in time due to the decision and actions of the different agents, based on environmental forcing, such as rainfall. The actions of the agents are connected to frequency-based models that simulate the risk of exposure to water-related hazards, associated to water scarcity, flooding and infectious disease diseases burden.

The model is composed of three modules with a set of procedures that together simulate the socio-hydrological vulnerability of Mexico City: The socio-Institutional module, the risk module and the socio-political module. The three modules include agents, objects, and procedures that interact internally and with the other modules. From the simulations vulnerability patterns, thresholds, and trade-offs are generated. Thus, the model can help to explore how the decisions of the different actors influence the vulnerability of the city at multiple spatial and temporal scale.

Within the socio-institutional module, the decisions of socio-institutional agents are simulated. In this module, institutional agents invests in actions to manage infrastructure systems associated to water. Each socio-institutional agent is “built” with a multi-criteria decision analysis (MDCA) model constructed based on the institution’s mental model that was obtained from consultation with the institution represented. The MCDA model contains the actions made by the institution, the criteria considered for each action and the relative value it gives to the criteria. The MCDA model, together with other procedures is used by the agents to allocate resources for investments to improve the condition and the provision of the different infrastructure systems in selected spatial units.

The second module is the risk module, which contain procedures to simulate the risk to and the frequency of water-related hazards. These models simulate the number of events of hazards in the city over time. The frequency of events is represented as an independent variable that is influenced by environmental factors as well as factors associated to infrastructure systems management elicit with consultation with the stakeholders or by data driven relationships.

The outcomes from the risk module influence the subsequent decisions of the socio-institutional and socio-political agents. Which take us to the third and final module, the socio-political. In the socio-political module, the model simulates the actions of others (non-institutional) agents that can influence the decision of socio-institutional agents. Therefore the name socio-political. Because based on how much importance some socio-institutional agent give to socio-political criteria, socio-political actors can influence and “steer” the decisions of the socio-institutional actors. The socio-political agents can also take actions for adaptation that can influence the social or physical attributes of the spatial units. These changes in the attributes in turn can influence the sensitivity of the residents to the exposure to hazards they suffer in their spatial unit. In the current version, the socio-political module simulates the neighborhoods of Mexico City as resident agents. Resident agents suffer the exposure to hydrological hazards of water scarcity, flooding and health and can protest to the authority when their exposure crossed certain threshold of sensitivity. Therefore, the model have the potential to simulate the feedback loop between actors’ decisions, risk, and biophysical changes.

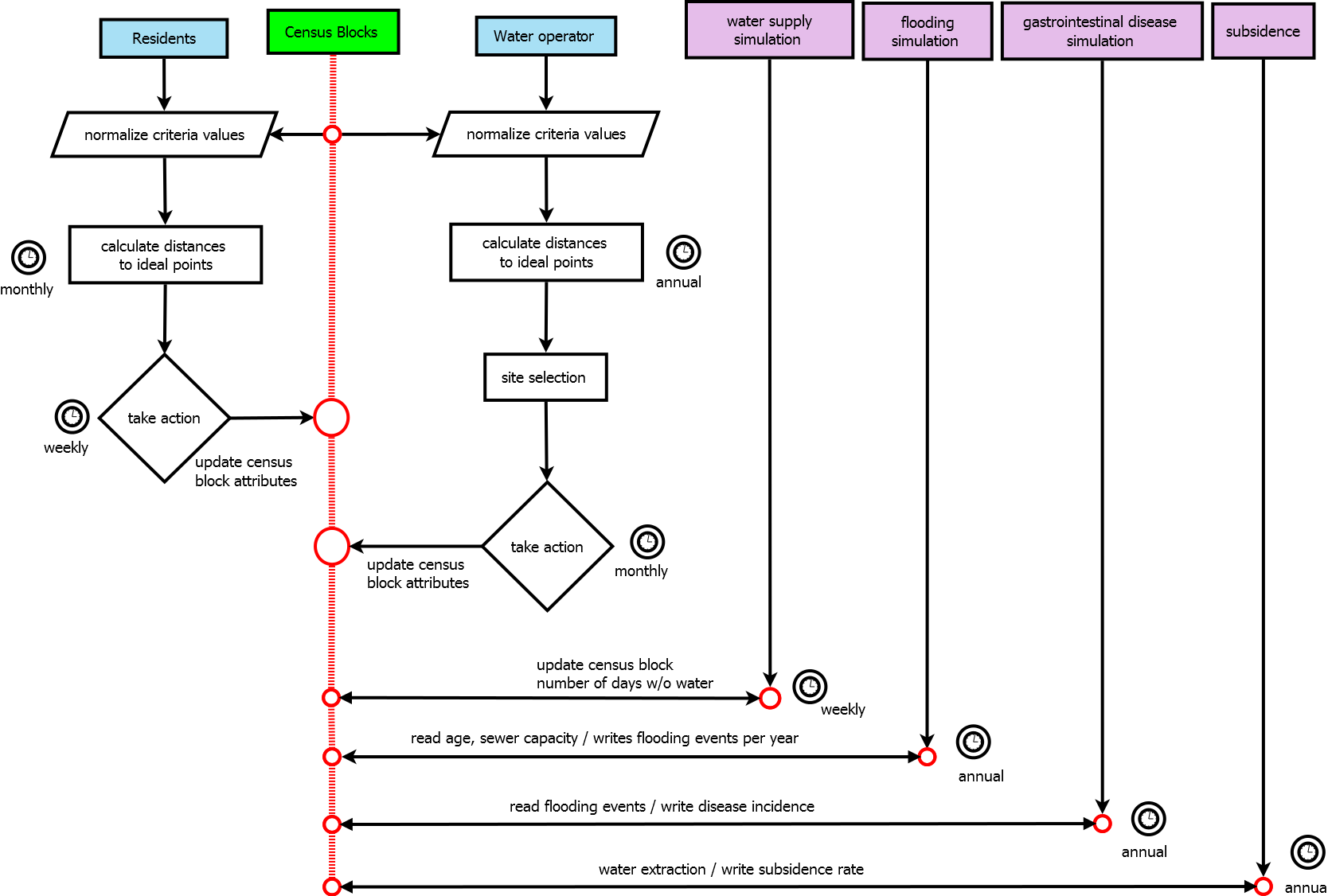


Figure 1:Flow diagram of the processes and sub-models included in the current agent-based model. To the left in purple color are represented the simulated models inside the risk module. Residents and Water operator are simulated in the socio-political and socio-institutional modules. The actions of the agents change the attributes of the census blocks of Mexico City that in turn influence the risk module.

**Definitions and Notation**

**Spatial Units**

Minimal unit in the landscape where the agents make modifications with their actions. Each spatial unit is indexed using the symbol , and the total number by , such that . Each census block contains a set of attributes, .Attributes are social, biophysical, and environmental indicators that differentiate each spatial unit.

**Agents**

Computational objects that make decisions and take actions that modify the attributes of the landscape. The agents make these decisions by evaluating environmental information obtained from the attributes of the landscape.

**Action**

Action is a change in attributes in the landscape or infrastructure systems caused by the agents. Actions are labeled with the symbol .

**Alternatives**

Set of actions available to the agents

**Multi-criteria decision (MCDA) model**

A directed network of interactions between a set of biophysical and social concepts associated to an agent mental model. A MCDA model is composed of criteria, actions and the links between criteria. Each criterion is associated to a particular attribute of the spatial units. The links between criteria represent the relative importance between them. The information inside a MCDA model is used to define a policy scenario for a socio-institutional agent, which define the actions and how they are undertaken.

**Infrastructure Systems**

Infrastructure systems are objects in the landscape that influence risk of water-related hazard and are managed by the socio-institutional agents. These are labeled with the symbol . The condition and capacity of the infrastructure systems are key properties influenced by the socio-institutional agents. Infrastructure systems can also be agents itself when they are defined as objects, with properties and methods similar to those of other agents.

**Frequency-based risk model**

Models that simulate the frequency of hazards events. The models’ outcome is assumed to be influenced by the management of the infrastructure systems, that is, by the actions of the socio-institutional agents, by the biophysical conditions, by time, and by the actions of other agents. These outcomes inform subsequent decisions made by the socio-political and socio-institutional agents.

**Exposure**

Exposure is the outcome of the risk models that is associated to specific agents. Thus, for example, the exposure of water scarcity is the result of the disruption of the service simulated by the water supply model, and it is suffered by resident agents.

**Decision Cycles**

Interval of time in which agents evaluate and take decisions and the attributed are modified. Depending on the module, the type of agent, and the action taken, cycles of decisions are invoke at different temporal scale.

**Standardized value function**

A transformation in scale of a biophysical or social attribute of the landscape to another scale between 0 and 1, to represent the judgment of institutional agents to the criteria.

**Site suitability**

The process by which socio-institutional agents rank spatial units according to their need for investment and based on a multi-criteria metric. Each spatial unit is rand according to the alternatives of actions.

**Site selection**

The selection of spatial units according to an optimization process that find the best strategy of investment according to maximizing the suitability for investment.

**Policy Scenarios**

The set of actions, criteria and criteria weights associated to each actor’s MCDA model. These include the criteria names, the biophysical variables associated with each criterion, the set of criteria weights, the set of alternative weights, and standardized value functional form.

**Overview of the agents and modules implemented in this version**

**Agents and actions**

The socio-institutional module in this version simulate the actions of the two divisions of the water authority of Mexico City (SACMEX for its initials in Spanish). The two divisions represented in the models are sewage management and the potable water management. The water authority agent makes decitions on investments in selected census blocks. These investments are related to the following set of actions: 1) repairs and maintenance,, 2) construction of new infrastructure, , 3) distribution of water, , and 4) extraction of water, .

Socio-Residents can take different actions as well. These actions are: 1) house modification, , 2) collective actions, , and 3) protesting, .

**Infrastructure systems**

The current version of the model includes the following infrastructure systems associated to SACMEX: 1) the water distribution system (pipes and wells for potable water distribution) , and 2) the sewer system, . In the current version, the system of pipes and sewer system are represented in each census block as a set of attributes, such as coverage, average age, condition, and capacity. The system of wells, on the other hand, is represented as a set of agents with particular attributes. The model associates the set of wells with its corresponding census block based on the location of both the wells and the census blocks.

**Spatial Unit and spatial scale.**

The spatial resolution of the model implemented here is the census blocks of Mexico City and the state of Mexico. The spatial scale of the model engulfs all the census blocks in these two states. Each census block is also identified by the municipality to which it belongs.

**Risk models**

The risk module implemented in this version contains procedures for representing the stochastic production of hazard events related to the number of flooding per year, ; number of days with disruptions of water supply per year, ; and number of cases of waterborne disease, . These models are defined based on empirical information about past events in Mexico City.

**Temporal resolution and decision cycle**

The temporal resolution of the model is a week. The decision cycle for the Socio-Institutional agents making decisions about maintenance and new infrastructure actions is a year. Thus once a year, socio-institutional agent SACMEX re-evaluates the census blocks and a new subset of census-blocks are selected each year for investment in maintenance, new infrastructure, and water extraction. For residents, the cycle of decisions is the week for protests, and the month for house modifications.

**Overview of the current version and the files included**

The model is implemented in NetLogo 6.2.1, and is connected to a geospatial platform with a representation of Mexico City landscape. The advantage of NetLogo is its versatility to develop agents as objects, allowing modelers to define multiple actors, their actions, and their interaction with other objects. This provide modularity to integrate multiple agents create realistic scenarios.

The model is currently composed of three files. A setup file (“setup.nls”), a value-function file (“value-functions.nls”), and the code file (“ABM-Empirical-MexicoCity\_6.nlgo”). The setup file defines global variables, the agents and their attributes. It also contain procedures for reading the MCDA model of the agents, namely their actions, the criteria set, criteria weights, and action weights. Finally, in setup, the landscape is configured by loading a set of GIS layers, from which the attributes of the spatial units are defined (Table 1).

Inside the code file, is where the dynamical simulation is implemented, and the different modules are used. In each cycle of the model, which corresponds to a “tick” in Netlogo terminology, the model call the risk module the socio-institutional module and the socio-political module. In the risk module the number of hazard event per spatial unit and unit of time are calculated using biophysical frequency based models. Then, the socio-institutional module simulate the decision of the socio-institutional actors about selecting census blocks for investment. This implies running procedures for site suitability assessment and site selection (see socio-institutional module). Based on the outcome of the socio-institutional simulation and the decisions made by the socio-institutional agents, the attributes of the landscape are updated in the selected spatial units. Finally, the socio-political module simulate the decision of resident agents, which implies deciding between protesting or modifying their houses.

To run a single simulation of the model, the observer needs to invoke the procedure setup by clicking on the bottom with the same name. Once the landscape is populated and the agents are created. The observed can click on the bottom “GO”. Which will trigger the procedures in the code file. Within each decision cycle, the actors will collect new information and will take actions in selected neighborhoods that will modify the attributes of the census block.

**Initialization of the model**

The model is initiated by invoking the procedure “SETUP”, which triggers the procedures inside the setup.nls file. These procedures are: 1) “define-global-variables”, 2) “define-type-of-agents”, 3) “define-agents-attributes”, 4) “load-GIS-data”, 5) “define-census-blocks”, 6) “define-ActionsCriteria”, 7) “define-infrastructure-systems”, 8) read”-statistical-data”, 9) “set-initial-values-globals”, 10) “set\_maximum”, and 11) “set-matrix-contj”. Procedure 1) defines the global variables needed (Table 1). In 2) the model sets the type of agents, or “breeds” in NetLogo terminology, and in 3) their attributes are set. Procedure 4) contains methods for reading layers of geo-spatial information using the GIS-NetLogo extension. In procedure 5) this GIS layers are used to fill up the initial condition of the attributes of the census blocks, including location. Procedure 6) contains methods for reading the data to define the actions and to define the information making up the multi-criteria decision mechanism involved in the actors’ decision-making. In 7) are the algorithms for defining the infrastructure systems, . In 8) are methods for reading data needed to simulate stochastic realizations of flooding and water supply. Procedure 9) defines the initial values for the global variables, and 10) sets the maximum values of the attributes of the census blocks. This is needed to define the range of variability of the attributes, which in turn will inform the computation of the decisions. Finally, procedure 11) defines the census blocks that are associated with each other based on the contiguity matrix. This defines the local network of interaction between census blocks that influence each other, which is needed to simulate the health model.

**Input data and input models**

The setup procedure invokes a procedure that loads layers of geographic information to fill the attributes of each census block that will define the decision-making criteria. Table 1 shows the list of attributes. The model also need to loads files to define the actions, the criteria, criteria weights, and action weights to use the MCDA model. Figure 2 shows an example of the data from a socio-institutional actor. This information is read using .csv files in the “SETUP” procedure using the netlogo csv-extension. The setup-file also contains procedures to manipulate R commands to read and use statistical models developed in R. These models are used in the risk module to simulate the frequency of flooding events, gastrointestinal disease burden, and potable water disruptions.

**Modules and agents implemented**

**Socio institutional Module**

Currently the model simulates the actions of Mexico City water system manager agent SACMEX. The decision module is currently implemented by allocating resources to different actions to a subset of spatial units selected based on the suitability of the site and constraints by resource limitations. The decision to invest in actions and spatial alternatives depend on two procedures. The site suitability and site selection. Here we explain these two procedures and the specific changes that each action of the agent produces on specific attributes of the infrastructure systems.

**Site suitability**

An assessment of the census blocks that are prioritized for investment is obtained through multicriteria evaluation of the distance of each census block from an “ideal point,” or utopian state, defined as a set of decision-making criteria and the relative importance of each criterion for the decision makers (Bojórquez-Tapia *et al* 2011). Formally, we calculate a distance , such that:

(1)

where is the distance to the ideal point of census block with respect to decision and system ; is the criterion weight of criterion related to system , is the alternative weight of action with respect to system (Fig. 2); is the normalized value in a census block of the attribute corresponding to criterion , with respect to infrastructure system and decision ; is the departure of an alternative from the ideal point for a criterion. This variable is the standardized score , which represents a judgment about the importance of an observable stimulus (census block attribute value) in the water authority’s decision; , , , , and are indices for criteria, census blocks, action, time, and infrastructure system, respectively. Finally, In Equation 1 is the compensatory parameter that define the metric to compute the distance. With , the metric is Euclidian.

Given that the variables representing the criteria are continuous and interval- and ratio-scaled, these scores are obtained by means of value functions (Beinat 1997), which transform the natural scale of a criterion to a [0, 1] value scale (1 represents the most undesirable state and 0 the most desirable state).

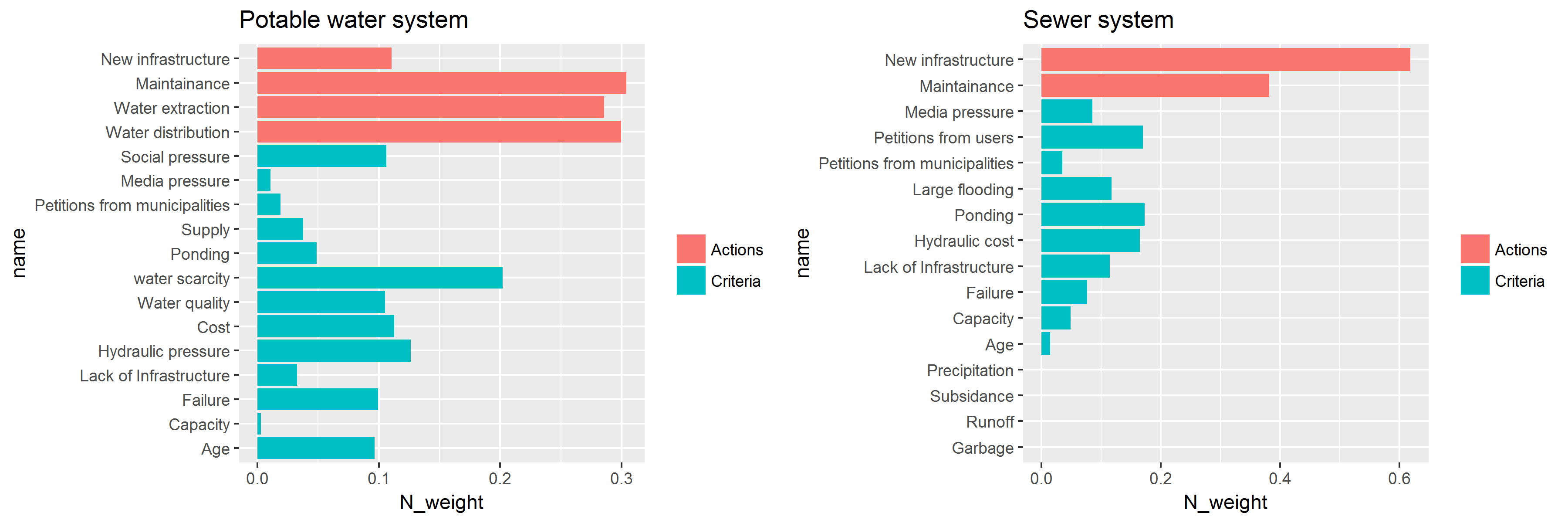


Figure 2: MCDA model of Water infrastructure manager of Mexico City (SACMEX). The model includes criteria, actions, and criteria and action weights. The bar plots synthetize the input data needed for the model to define socio-institutional and socio-political agents. The example shows the case of the water operator of Mexico City water infrastructure systems (SACMEX), and the policy scenario to operationalize the interaction between criteria, actions and infrastructure systems performance. In red the actions and in blue the criteria. The length of the bar show the importance SACMEX give to each criteria and action.

**Site Selection**

Every year site selection is invoked by the water authorities for choosing investments , in action in system ,in a specific number of census blocks, established by budgetary constraints . Formally, this involves using a 0-1 (or binary) programming model (Dykstra 1984) in which the objective function maximizes . In this way, the model simulates a preference for investing in the census blocks where investment in infrastructure of system is most needed. Formally:

(2)

Subject to

where is the number of census-blocks where investment related to action can take place; is the 0-1 decision variable for action for system in census block at time (, if census block is selected for investment, or 0 otherwise). An implementation of other forms of maximization with more complete set of constrains is underway.

Budget represents a total capital or resources divided among census blocks. Thus when there is a limited among of resources to be divided in the city. The budget can be aggregated or disaggregated according to institutional rules. For instance in Mexico City the budget for drainage is separated from the budget for potable water system, and within each system the budget is divided in actions. The optimization of the objective functions were done using a non-dominant sorting assessment (NDSA) that find solutions near the Pareto frontier. The results from the NDSA was then used to constrain a genetic algorithm that find the best alternative in for investments each spatial unit (See [optimization](optimization.docx)).

**Standardized score functions**

This procedure standardizes each criterion using normalization functions needed to evaluate the distance to the ideal point of each census block related to each action and system . This procedure is called in every decision cycle to update in a standardized scale the value of the criteria.

##### Different procedures are implemented to capture different functional forms. Generally, the procedures take the following notation:

(3)

where is the perceived magnitude of stimulus defined by the value of attribute in census block at time , and a set of control parameters to ensure that , given the scale of the attributes and it relevance to each agent.

In the Netlogo version, the code also includes a procedure to compute using step-functions that take as argument the value of the attribute and a set of cut-off values, such that

(4)

where are cut-off values that follow a progression for increasing and decreasing functions. Parameter represents the maximum value of the attribute , which will set the range of the value function.

**Add new functional form after consultation with sacmex**

**Actions of Socio-institutional agent SACMEX**

Once the model computes the distance metric for each census block and the selection procedure is activated, a set of actions are invoked. These actions change specific attributes of the landscape. Here, we explain the actions and their consequences on the census block attributes. Table 2 summarizes these actions and the original explanations contained in the matrix input files.

**Maintenance**

Maintenance reduces the age of infrastructure system , at a rate proportional to its effectiveness:

(15)

where is the effectiveness of maintenance.

**Creation of New infrastructure**

The provision of new infrastructure influences the proportion of the population in census block covered with infrastructure system , such that:

(16)

where is the effectiveness of the action “new-infrastructure” in providing system to the proportion of houses that lack coverage, .

In addition, we assumed that when the action “new-infrastructure” is invoked, the wells in census block , , with , are replaced by new ones such that

.

The new well is located in the same census block and inherits the same extraction rate as the old one.

**Water extraction**

The action “water extraction”, , represents the yearly increment in the system of wells . We assume that in each year census blocks can receive a maximum of one new well. Thus, when the procedure “water extraction” in invoked, the number of wells per census block, , increases according to:

**Water distribution**

The action “water distribution”, is the action of supplying water to neighborhood by the system pipes . When the water distribution procedure is invoked, a probabilistic model simulates the number of days a census block receive water in a week (see risk module water provision model).

**Policy Scenarios**

Currently the model includes the policy scenarios of the two water operators. Figure 3 and Tables 2 3 and 4 summarize the information.

**Socio-Political Module**

The module simulate Mexico City residents. An resident agent is a group resident from a spatial unit or census block. Residents can invoke actions that either influence the attributes of the census block can demand action from socio-institutional actors, and action labeled “protesting”.

**Representing residents and their actions**

Based on interviews and focus groups a mental model of resident from three different neighborhood was implemented. These mental models elicited the alternative for actions of the residents and the exposure variable connected to the actions (Shelton et al., in review). Based on this information, simple decision procedures were built for the resident agents to respond with specific actions to the level of exposure to hazard (simulated in the risk module). These decisions implies considering also the level of sensitivity, or tolerance, to exposure, and the perceived response from the authority. Currently two actions are implemented for the socio-political resident agents. House modifications and Protests.

**House Modifications**

House modifications are actions that resident takes to reduce the effect of exposure to influence the sensitivity of the house to hazard events. Two key modifications were identify by Eakin et al.: Modification to storage water, by adding systems to capture, store and maintain fresh water for long periods. Another modification is associated to modifications to reduce the exposure to flood water. These modifications implies stopping water from coming inside the houses. In the model these two house modification actions are implemented: The house modification for water storage influence the storage capacity of the residents of a census block, and the house modification for flooding preparation reduces the sensitivity of houses to flooding of different magnitude. The sensitivity of the houses to flooding is calculated as incremental changes based on the accumulation of actions. Formally, we assume that sensitivity is defined by

(23)

where

(24)

is the accumulated number of times that the action “house modification for flooding” was invoked by the residents of census block .

in the effect that the magnitude of hazards has on the threshold , assuming that modifications are cumulative, but saturated, meaning that there is a limit to adaptation and a rate at which these changes influence the sensitivity.

### **Protests**

The procedure “protest” if activated generates a single event of protest in a census block per week. A protest, which is defined by the symbol , is triggered when the level of exposure residents suffer is higher than the tolerance level of the residents. Per consultation with residents and stakeholder, the model implement here simulate protests in Mexico City related only to water scarcity. According to information collected from workshops, we obtain information to parametrize the tolerance of residents to days without water that would trigger a protest in their neighborhood (Shelton). Accordingly, our model simulates this socio-political process using:

(25)

where is the value of the attribute in the landscape associated to the exposure variable that triggers the action of protest . is the level of tolerance that triger the decision to protest. For instance, interviews with residents of Mexico City have reveal that protests are triggered after 14 days without water. In our simulations therefore . I is the sensitivity of the people to water scarcity. It is assume therefore that house modifications to storage water changes the tolerance of the residents to the scarcity in the supply of water.

**Risk module**

**Water provision model**

**Flooding event model**

The risk module simulates the frequency of flooding events per census-block per year using a regression based method that simulate the frequency of flooding to the effect of the infrastructure management. The model chosen for the dynamic simulation with the ABM is the zero-inflated negative binomial (ZINB). This model is composed of a logistic link function to represent a binomial process, which accounts for the zeros in the data, and a negative binomial component, which includes a regression function of the form

where is the exposure time, which in this case is 1 year, are the set of parameters to be estimated for each predictor. The predictor variables that best explain the variance in the frequency of flooding in Mexico City are: the age of the spatial unit , the average rate of subsidence , the daily rate of garbage production per capita , the average capacity of the sewer system within each census-block and the mean annual rainfall .

**Infectious diseases model**

The risk module includes a model to simulate the incidence of water borne diseases and the effect of flooding and infrastructure deficiencies in Mexico City (Baeza et al., 2018). The model is implemented as two separate spatial regression models that simulate the expected number of incidences for two different geomorphological regions of Mexico City: the lowlands and the highlands.

For the lowlands, a regression model of the form

(14)

was used to incorporate the full set of predictors and the spatial dependency observed in the data. is the number of incidences observed in year in census block . is a vector of observations of the dependent variable, with one observation for every census block, is the number of flooding events in census block , and is a parameter that relates the number of flooding events to the risk of gastrointestinal diseases. is a vector of disturbance terms, where is assumed to be independently and identically distributed for all , with zero mean and variance of . In order to capture the spatial dependency observed in the incidence data, the model incorporates an additional regressor in the form of a spatially-lagged variable,(Anselin, 2001). This variable captures the “neighborhood effect” as cross-section dependencies, in which a covariance structure exists in specific locations from the geographic space (Anselin, 1998; Anselin, 2001). The term is the unknown spatial lag coefficient, and *W* is the contiguity matrix.

The model for the highlands of Mexico City have the following form:

Where ..

This model differs from the model for the lowland in two ways: First, in the highlands, the explicative variables are different that in the lowlands. Notable is the negligible effect of flooding. Second, the neighborhood effect in the highlands is also not important (Baeza et al., 2018).

**Outcome variables**

The indicators obtained at the end of the simulation period are described in the sections below.

**City average age of infrastructure systems**

This indicator corresponds to the average age of the infrastructure in the city over the last years of the simulation. formally,

where is the average age of infrastructure system , and the total number of census blocks in the urban landscape.

**City average flooding event and number of days without water**

These indicators are calculated using

for scarcity, and

for flooding, where and are the annual number of water disruption and flooding events, respectively, in census block at year . is the final time-step of the simulation and . is the total number of census blocks.

**Census block average exposure**

The total number of events in the 10 years of simulation in each census block was calculated using:

and

**City average level of socio-political pressure**

This index is calculated using the number of accumulated protests over the last time-steps of the simulation, divided by the total number of census blocks :

**Vulnerability index**

The vulnerability of a census block is calculated using the “surface of vulnerability” definition by (Luers 2005). In this framework, the vulnerability index is summarized as the ration between the product of exposure *E* and sensitivity *S*, and the adaptive capacity of the census block. Formally:

where is the vulnerability in census block at time . is the exposure, defined as the level of flooding or scarcity of water. represents the sensitivity of census block to hazard events . We measure this by keeping track of the number of decisions that involve house modifications and water storage. The more these actions accumulate in a census block, the less sensitive it would be to the exposure. Parameter represents the adaptive capacity of the census block. We assume that

(48)

where is the income index of census block . Thus, we explicitly assumed that census blocks with more resources have higher adaptive capacity than poor census blocks. That is, wealthy areas are less vulnerable because they have more access to resources to take action. We use purchase power as an indicator of adaptive capacity.

**Inequality in Exposure**

This index is obtained by calculating the Gini coefficient. The Gini coefficient is a measure of dispersion, often used to measure dispersion in income and wealth in a population. We use it here to evaluate the dispersion in combined exposure to flooding and scarcity. The Gini coefficient is an index between 0, completely equal, to 1, completely unequal. Thus, the larger the value of the index, the higher the inequality in exposure. The Gini is effectively calculating by

(49)

where is the population of census blocks.

is the sum of exposure to flooding and scarcity at time t, where , are the values of the vulnerability index of census blocks, indexed in increasing order (). The inequality index is then the average of the Gini coefficient over the last yearly decision cycle:

(50)

**Key Concepts (from ODD protocol)**

**Emergence**

From the interaction between the agents’ actions and modifications to the attributes of the census blocks, we expect an emergence of spatial patterns in investments that in turn should influence the spatial pattern of vulnerability of census blocks to infrastructure-related hazards.

**Observation**

The agents observe the attributes of the landscape that are considered to be criteria in the decision-making process. The observer can evaluate the vulnerability of the city using different indicators of performance and a metric of vulnerability. We compute the average age of the infrastructure, the numbers of day in a year without water, and the number of actions taken by the water operators. These observations are computed by census block and aggregated by municipality.

**Adaptation**

Residents in each census block can modify their local environment to reduce their sensitivity to exposure to flood and scarcity hazards. Thus the action “modification of house” reduces the sensitivity of the census block to flooding, whereas the action “water storage” reduces the sensitivity of a census block to suffering exposure to water scarcity (see Details). These processes over time can be considered as adaptations to the local environment.

**Interactions**

The water operator and resident agents interact with the census blocks and the infrastructure systems by modifying their attributes. The attributes of the census blocks in turn influence the risk of infrastructure failures, which will influence subsequent decisions made by water operators and residents. There is also interaction among actors that influence decisions. Specifically, the protest actions of the residents generate social pressure, which is one of the criteria that is used by the water authorities when engaging in the decision-making process.

**Stochasticity**

The model has procedures that generate stochastic events of hazards related to flooding, scarcity, and health. Currently, the model incorporates a regression model that generates an expected number of events per year using a set of infrastructure-related, and biophysical independent predictors. Water distribution by pipes is simulated using a Poisson distribution model that generate as outcome variable a number of days census blocks do not receive potable water. Finally, the model includes a regression model that generates incidences of infections associated to waterborne pathogens.

**Tables**

Table 1: Attributes of the census blocks of Mexico City.

|  |  |  |  |
| --- | --- | --- | --- |
| Variable | Description | Symbol | name variable in netlogo |
| Census block ID | Numerical key to identify each census block |  | ID |
| CVEGEO | Unique national identifier | - | CVEGEO |
| Estate | Administrative units |  | CV\_estado |
| Municipality | Units |  | CV\_mu |
| Aquifer | The aquifer that is below the census block |  | Aquifer |
| Aquifer zone | The zone of the aquifer below the census block |  | zona\_aquifera |
| Region | The geomorphological region the census block belong to (lowland or highland). |  |  |
| Altitude | Meters above sea level |  | altitude |
| Group cluster ID | A classification of the census blocks of MC based on socio-economic and environmental similarities (appendix) |  | group\_kmean |
| Weekly water supply | Days in a week water was supplied by system |  | scarcity |
| Flooding | Number of flooding events per year |  | flooding |
| Protests | 1 if a protest occurs in a given week; 0 if otherwise |  | protests |
| Health | Annual incidences of gastrointestinal diseases |  | salud |
| Social pressure | Number of protests per year |  | Presion\_social |
| Media pressure |  |  |  |
| Wells | Set of wells within a census block |  | Pozos\_neighborhood |
| Infrastructure coverage | % houses connected to infrastructure system |  | Houses\_with\_*v* |
| Age infrastructure | Age of infrastructure system |  | Antiguedad-infra\_v |
| Condition | An index of the state of the infrastructure system in census block |  | condicion |
| Hydraulic load | Average volume of water per unit of time received by the sewer system in census block in a year |  | Gastro-hydraulico |
| Capacity | Index of the capacity of the pipes of system |  | capasidad |
| Rainfall | Total annual rainfall in census block |  | precipitation |
| Subsidence | Rate of subsidence per year |  | hundimientos |
| Income index | The purchase power by census block |  | Income-index |
| Potable water | Volume of water supplied to the census block by system at time |  | Water-in |
| Garbage | Garbage produced in each census block |  | garbage |
| Water quality | Index of the quality of potable water |  | water\_quality |
| Urban growth | Percentage of census blocks considered to be urbanized |  | urban\_growth |
| Water deviated | Number of wells multiplied by the days without water in census blocks with indigenous communities |  | desviacion\_agua |

Table 2: Actions of actors water authority and residents.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
|  | Actions | Symbol | Definition | Attribute changed | Decision cycle | Action weight |
| Water Authority | Distribution |  | Refers to the water distributed by government |  | Weekly |  |
| Extraction |  | Harvesting water from aquifers by investing on more wells |  | Annual |  |
| Maintenance |  | Repair infrastructure systems |  | Monthly |  |
| New infrastructure |  | Build new infrastructure |  | Monthly |  |
| Residents | Water storage |  | Modification to reduce exposure to water scarcity |  | TBD |  |
| House modification |  | Modification to reduce exposure to flooding |  | Annual |  |
| Mobilization/protests |  | To express dissatisfaction with the public services of water delivery and sewage |  | Monthly |  |

Table 3: Criteria used in residents’ decision-making.

|  |  |  |
| --- | --- | --- |
|  | |  |
| Criteria | Definition | Attribute associated |
| Urbanization | Percentage of area urbanized  (driver of change from simulations of urban growth model) |  |
| Waste of water | Dummy |  |
| Water deviación | The perception of local people that live close to wells that water is being distributed to other census-blocks |  |
| Service efficiency | related to efficiency of infrastructure system |  |
| insuficient infrastructure | Represented by the percentage of population in each census-block not connected to sewer system |  |
| Contaminación de agua/water quality |  |  |
| drainage system cloGged | accumulation of garbage connected to the failure of the sewer system (in the layers folder says it is still dummy) |  |
| water scarcity | Number of days of water disruption |  |
| Flooding | Number of flooding events per year |  |
| Health risk | Number of incidences per pear |  |

Table 4: Criteria used in water supply operators’ decision-making.

|  |  |  |  |
| --- | --- | --- | --- |
| Criteria for calculating THE decision metric OF THE water supply operator | | | |
|  |  | Definition | unit |
| Infrastructure | Age of infrastructure | Average age of infrastructure per census block | years |
| Capacity | Capacity [in length of pipes] of the infrastructure to supply water or to discharge | Mts/area |
| Failure | An index of the number of infrastructure-related hazards per year (e.g., pipes break) | [events/year] |
| Lack of infrastructure | The lack of connection to potable water ans sewer systems | % houses not connected to infrastructure system |
| Hydraulic pressure | Pressure in pipes TBD | ? |
| Budget | Amount | The importance of the budget received from central authority | ? |
| Risks to the population | Water quality | TBD | ? |
| Water scarcity | Number of weeks in a year without water supply by system or | [weeks/year] |
| Flooding | Represented by the number of flooding events per year | [events/year] |
|  | Health | Represented by the number of gastrointestinal incidences per year | [events/year] |
| Socio-institutional | Supply | Represented by the requirements of the population on the infrastructure system | [pop \* need/pop.] |
| Petitions from census blocks | Demand of population funneled by politicians at the level of the municipality, representing the collective level of response from each municipality. |  |
| Social pressure | Represented by the number of protests per year | [pop \* need/person] |