Agent-based model Mexico City

ODD Protocol

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# Introduction

This document describes the implementation of the agent-based model of the MEGADAPT project. The model simulates the coupling between biophysical processes, the decisions of residents and the water authority of Mexico City. The aim of the model is to investigate the consequences of this coupling on the spatial distribution of socio-hydrological vulnerability in Mexico City. The model simulates decisions on investments in infrastructure by the water authority agents, which is done by evaluating the condition of the landscape across the census-blocks. These investments in turn trigger actions in selected census-blocks. These actions then influence the condition of the socio-political and physical attributes in the landscape that in turn modify the biophysical condition that influence the risk to infrastructure hazards and the exposure to flooding, disruption of water supply, and gastrointestinal diseases.

The decision making process of the water authorities involves the identification and selection of census-blocks that need investments. This prioritization of census-blocks for investments is rooted in computing a multi-criteria metric in which the water authority evaluates the landscape based on a set of criteria that are weighted differently based on the priorities of the actors. To compute the multi-criteria metric the model relay heavily on empirical data derived from mental models and translated into a multi-criteria decision framework, which are inputs to the model. The decision-making process of the residents is also done via a multi-criteria decision metric, but in this case the evaluation is only in their local census-block and the action taken modifies only those local attributes. Figure 1 shows an overview of the basic processes included in the model.

The current version incorporates stochastic simulations of weekly water supply, annual production of floods and annual cases of gastro intestinal incidences. The model were constructed using available empirical observations of these hazard events.

With the model we aim to investigate the dilemmas and spatial patterns of vulnerability to infrastructure hazards that emerge due to the actions and decision-making process of the agents.

The current version of the model is constructed in Netlogo V 6.2.1. The advantage of Netlogo is its versatility to develop agents as objects, which allow to define actors their actions and the infrastructure systems as separate computational entities.

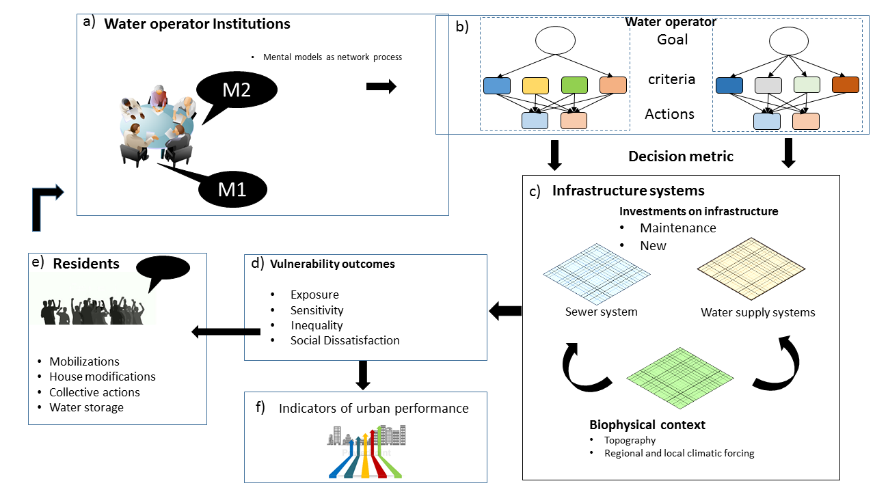


Figure 1: Overview of the Agent-based model

# Agents, actions, scale (and notation)

Three types of agents are incorporated in the model: Water operators, residents and infrastructure systems. Resident are located in census-blocks. Each census-block is indexed using symbol and the total number of census-blocks by symbol . Each census-block contains a set of attributes, . Infrastructure systems are also considered as agents when they are defined as object, with properties and methods similar to those of other agents.

Water operators make investments on different infrastructure systems, in selected census-blocks. These investments are related to the set of actions, : 1) repairs and maintenance,, 2) construction of new-infrastructure , 3) distribution of water , extraction of water, . Residents, can take different actions as well. These actions are: 1) house modification , 2) collective actions, , and 3) protesting, .

The decisions to invest by the water operators and to modify the local environment by residents, are evaluated based on a multi-criteria metric. This metric is calculated based on set of criteria, and each criteria is weighted with values specifically related to the actor and the actions they take. This information and the actual actions of the agents is derived from empirical data from the actor’s mental models, and is derived information collected during focus groups, interviews and workshops with the managers and operators of the water system, and residents. This information was pre-processed and transformed into an analytical network process (ANP) to derive the criteria weights and the weights of the actions.

Infrastructure systems are labeled with the symbol . The current version of the model includes as infrastructure systems the wells for water extraction, , the system of pipes for potable water distribution, , the sewer system , the system for water distribution (trucks) . In the current version the system of pipes and sewer system are represented as a set of attributes in each census-block, such as coverage, average age, condition, and capacity. The system of wells on the other hand, is modeled as a set of agents, with particular attributes. The model associated the set of wells with the census block, based on the location of both the wells and the census blocks.

The model also contains procedures to represent the stochastic production of hazard events related to the risk of flooding, , disruptions of water supply , and gastro intestinal disease incidences, . These models are defined based on the empirical information about pass events in Mexico City. In all these submodels, the frequency of the hazards are assumed to be related to failures in the provision of services by a particular infrastructure system. These failures are in turn associated to the local conditions of the system, local biophysical conditions in the census-blocks, and importantly on the actions of the water operators and residents.

The actions the agents take modify the attributes of the census-blocks that in turn will influence the stochastic production of hazards. These changes in events in turn inform subsequent decisions by the actors. Therefore the model simulates the feedback loop between actor’s decisions and biophysical changes in a dynamics and spatial explicit platform.

The spatial resolution of the model is the census-block, represented in the model by 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 belongs to.

The temporal resolution of the model is 1 week. Depending on the action and agent different period in a year can represent different evaluation of the priorities. We call this period a cycle of decision *T*. A year in the model represent a cycle of decision while a month would be cycle of decision . for the water operators for action maintenance and new-infrastructure. Each cycle of decision this agent re-evaluate the census-blocks selected for investments for action maintenance, new-infrastructure, and extraction. For the action water distribution the cycle of decision is . For the residents the cycle of decision is as well. Actions are independent from the evaluation in the sense that they can occur in different periods. These are cycles of actions, . The actions of the water operators occur in monthly cycles, for maintenance, extraction and new infrastructure, and weekly for water distribution. For residents, cycles of action are weekly for the action protest, and monthly for the actions water storage and house modification.

# Process Overview and scheduling

The model currently is 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 and set values for global variables, and the agents and their attributes. It also contain procedures to read the information that will define the decision making process of the agents. Namely, their actions, the criteria set, criteria weights and action weights. Finally, in setup, the GIS layers are loaded from which the value census-block attributes are defined.

The file value-function contains the procedures to update the information needed for the actors to calculate the multi-criteria decision metric. Specifically, these procedures update the standardize values of the attributes of census-blocks that are criteria for decision, and calculate the distance metric.

The code file contains the procedure call “GO”. Procedure “GO” involves the suitability assessment and site selection procedures, which define the census-blocks that will be selected for investments by the water authorities. Once the census-blocks have been selected, the model invokes the actions of the different agents, which will in turn modify the attributes of the landscape.

Inside the code file, there are also procedures to calculate indicators of performance at the scale of the census-block, municipality and city.

To run the dynamic part of a single simulation, the observer needs to invoke the procedure “GO”, which will trigger a set of processes related to the stochastic simulation of water allocation, flood and health models, the decision-making process of actors, the action of the actors, and the changes that those actions caused to the attributes of the census-blocks. The decision making process of the water authorities includes procedures to a site selection process and suitability of census-blocks In the case of the residents this involve a selection of actions. Within in each cycle of decision, the actions will modify the attributes of the landscape associated to each action in each census-block. Details about these processes are provided in the section “sub-models”.

# Design concepts

## Basic principles

The model aims to represent the decisions of important actors in Mexico City water management system to invest in infrastructure systems in a geo-spatial and dynamical multy-agent system. The decision making process of the actors involves a multi-criteria decision procedure in which the actors evaluate a set of criteria they consider as important for decision (criteria), and they consider them with different importance (criteria weights). In the model each criterion is associated to an attribute of the landscape. Therefore the agents evaluate the attributes in the landscape to make decisions related to investments in the case of the water authority and adaptation in the case of residents. The attributes in the landscape change over time according to the stochastic variability generated by the statistical processes of hazard production, and, most important, due to the changes in the attributes made by the actors’ action.

Emergence

From the interaction between agent’s actions and the modification to the attributes of the census-blocks, we expect the emergence of spatial patterns of 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 as 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 made by the water operators. These observations are computed by each census-block and aggregated by each municipality.

Adaptation

Residents in each census-block can modify their local environment to reduce their sensitivity to the 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 suffer exposure to water scarcity. These processes over time can be consider as adaptation to their local environment.

Interactions

The water operators 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 subsequence decisions of the water operator and the residents. There also interaction between actors that influence their decisions. Specifically, the action of the residents to protest generate social pressure which is one of the criterion that is used in the decision-making process of the water authorities.

Stochasticity

The model has procedures that generate stochastic events of hazards related to flooding, scarcity and health. Currently, the model incorporate two different methods to generate flooding events: A linear regression model that generate expected number of events per year using a set of infrastructure-related and biophysical independent predictors from each census-block. The second method is based on contingency table using Bayes rules, where flood outcomes of certain magnitude are cross classified according to a finite number of states that are related to the condition of the infrastructure.

Water distribution by pipes is simulated using a Poisson process which generates number of days that census-blocks received water by the system of pipes, P. The model assumes that the mean of the Poisson process is driven by the condition of the infrastructure and its propensity to fail in the delivery of water by the pipe system.

## Details

Initialization

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” and 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 #) in 2) the model sets the type of agents or “breeds” in netlogo terminology, and in 3) their attributes. Procedure 4 contains methods to read 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 to read data to define the actions and the information to define the multi-criteria decision mechanism involve in the decisions of the actors. In 7) are the algorithms to define the infrastructure systems, . In 8) are methods to read 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 in 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 influenced each other. Which is needed to simulate the health model.

Input data

The setup procedure invoke a procedure that loads layers of geographic information to fill the attributes of each census-block that will define the criteria for decisions. Table 1 shows the attributes of each census-block. The model also loads data to define the actions, the criteria, criteria weights and action weights. This information is read csv files in procedure SETUP using the cvs-extension capability of Netlogo. Another type of input data is the average number of days without water by municipality, which is needed to simulate the days with water by the system of pipes, , using a Poisson process. Finally, the model contain procedures to read data to represent the probabilities of flood using Bayesian contingency matrix analysis () and regression analysis of health.

# Sub-models and components

## Water authority decision procedure

### Priority assessment

An assessment of the prioritarian census-blocks for investment is obtained through multicriteria evaluation of the distance of each census-block from an “ideal point” or utopian state, defined a set of decision criteria and how relatively important those criteria are for the decition makers. Formally we calculate a distance , such that:

(1)

where is the distance to the ideal point of census-block j with respect to decision and system ; is the criterion weight of criterion related to system ; is the normalize 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; , , , and are indices for criteria, census-blocks, action, time and infrastructure system, respectively. In Equation 1, the standardized score, , represents a judgment about the importance of an observable stimulus (census-block attribute value) for the water authority’s decision.

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).

### Site selection

Every year site selection is invoked by the water authorities for choosing a single investment on on system v,, in a specific number of census-blocks that is established by budgetary constraints, . Formally, this involves using 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 on 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);

### Normalization Functions

##### This procedure standardizes each criteria using normalization functions. This procedures is needed to evaluate the distance to the ideal point of each census-block related to each action , and system . This procedure is called every cycle of decision. The information will define the vectors of criteria and will update their representation in a standardize scale using the procedure report “value function”.  This steps is critical to quantify relationships between condition of the attributes in the landscape (e.g., age, capacity, etc) and the perceived response by agents. Formally this procedure takes the following notation:

(3)

Where is the perceived magnitude of stimulus defined by the state of attribute in census-block at time , . Parameter refers to the constant fraction (ref). Function is often represented by a logarithmic function:

In the current version of this model, the function is implemented using a set of cutoff, for such that:

(4)

Where are cut-offs, that follow the Weber-Fechner progression increasing functions and {0.937,0.875 0.725,0.5} for decreasing functions. Parameter represents the maximum value of the attribute, , which will set the range of the value function.

In the current Netlogo version of the model, this procedure is called in the context of actions, which are called in the context of the census-block.

## Exposure models

Exposure of census-blocks to infrastructure hazards is assumed to be related to the average risk of water supply disruption and flooding. Floods also influence the exposure of the population to waterborne pathogens.

In addition to the landscape (that is, exposure to water scarcity increases), the risk associated with these hazards depends on the condition of clean water and sewer systems, *c*; formally (ten Veldhuis, Clemens, and van Gelder 2011):

(5)

where is the rate of decline of the infrastructure system . is the infrastructure´s age at time in weeks. The function assumed a exponential decay in the condition related to the aging process of the infrastructure system, . refers to the effect of subsidence on the condition of the infrastructure associate to the rate of subsidence in census-block , with:

, (6)

Where is the subsidence rate [mm/year] in each census-block, and is the effect of subsidence to system . It is a conversion parameter that must be parametrized to ensure that .

#### Age of infrastructure

It is an attribute that tracks the age of infrastructure systems, , as they decline over time in the a census-block, ; We assumed that the age of the infrastructure system , in census-block , , changes weekly accordingly to:

(7)

where is a single weekly time-step.

### Exposure to water supply disruption

A census-block can have weekly disruptions in water supply. These disruptions are assumed to be caused by failures of the infrastructure system, . We also assumed that water supply can only be delivered within each municipality by either the pipe system, , or by distribution by mobile sources, , such as trucks. Formally, we define the weekly supply of water to census-block using system as,

Accordantly, the risk of exposure to water supply disruption from the network of pipes *P*, is assumed to be associated to the condition of the system. Formally we assumed that the average number of days in a week that a census-block is without clean water service from pipes is represented by:

(8)

Where is the mean number of days in a week without piped water, is the estimated average number of days without piped water in a municipality (A parameter estimated using available survey data). Parameter represent the local correction factor for altitude differences of census-block from the mean altitude of the municipality, such that:

(9)

Where, is the altitude in census-block, and is the mean altitude of municipality.

Parameter b2 represent the additional number of days without piped water due to specific disruptions associated with the condition of the pipes. To represent a specific disruption we use variable with such that

Thus, when the condition of infrastructure system is lower than a random number drawn from a uniform distribution, there are extra days census-block will suffer from disruption.

We simulate stochastic realization of days with water per week per census-block using a Poisson process, truncated between 0 and 7:

(10)

Thus, the amount of water delivered by the pipe system to census-block is

(11)

Where is the volume of water supplied to census-block by the pipe system, . is the number of people in census-block ,and is the proportion of population connected to the system of pipes . Parameter is the consumptive use of water per person, in units of volume, and parametrized using minimum water requirements per person. Therefore it is assumed that water is delivered by pipes is proportional to the population usage and the coverage of supply infrastructure system .

#### Infrastructure coverage

We define infrastructure coverage as the percentage of houses in a census-block with connection to infrastructure system ,. Thus, when all the houses in census-block are connected to system , and if none.

### Exposure to flooding

This sub-model simulates the number of events of flooding in a year in each neighborhood, given a probability. Three initial prototype had been explored so far to obtain these probabilities: 1) a contingency Bayesian matrix approach based on calculating the partial probabilities of number of events, given the amount of rainfall. The second model uses the same bayes contingency table approach, but divides the city in term of age, and define contingency tables a for an old city and a newer city. Instead of rainfall, these tables uses the capacity of the sewer system as a predictor. In this case the model calculates the partial probability that a census block would have a number of event in intervals, conditional to the capacity of the sewer system. Both variables show a relationship and therefore a new model that combines the effect of all variables was also include.

Bayes contingency matrix model using age and sewer capacity.

This model assumes that the risk of flooding associated with malfunctions of sewer system in a census-block depends on the condition of the sewer infrastructure system, which is influenced by age, capacity, and the effect of subsidence. Yearly number of flooding events were simulated using contingency matrix and Bayes rules, to calculate posterior marginal probabilities of the number of events, conditional to the condition of the sewer system. The first then was to separate the city between old and new. Thus we define the set of old census-blocks as

The probability of having more than f event of flooding is calculated using

The predicted posterior distribution of the number of events of magnitude m, given the observation of *F* events in a year, given the condition C and the observations, that is the likelihood, and is the prior information of the capacity, given the observations. Whenever the value of the risk associated with age and capacity is higher than a random number generated from a uniform distribution, :

(12)

The model also includes other procedures to simulate flooding events based on a linear regression model:

(13)

Where is the expected number of flood events in census-block at year . ,, are the regressor parameters associated to the independent variables age , capasity , and hydraulic cost, , of the sewer system, , respectively all of them evaluated at week .

### Exposure to gastro intestinal diseases

The health model is implemented as two separate regression models that simulate the expected number of incidences of gastrointestinal diseases in the lowland and in the highlands of Mexico City.

For the lowlands, a spatial regression model of the form

(14)

was used to incorporate the full set of predictors and the spatial dependency observed in the data. is an vector of observations of the dependent variable, with one observation for every census-block, is the number of flooding in census-block , is a parameter that relates the number of flooding to the risk of gastrointestinal diseases. is a vector of disturbance terms, where is assume to be independently and identically distributed for all , with zero mean and variance . 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 cross-section dependencies, in which exist a covariance structure in different locations derives from the geographic space (Anselin 1998, Anselin, 2001). The term is the unknown spatial lag coefficient, and *W* is the contiguity matrix. This equation was estimated empirically in (*Baeza et al. In review*).

For the highlands…TBC

## Water authority actions and changes on census-blocks’ attributes

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 its consequences on the census-block attributes. Table 2 summarize these actions and the original explanation contained in the matrix input files.

### Maintenance

Maintenance reduces the age of infrastructure system, , proportionally to its effectiveness, formally:

(15)

where is the effectiveness of maintenance.

### 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 of 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

(17)

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

### Water distribution

The action water distribution, is the action of supplying water to areas that had a disruption in the supply of water by the system pipes, . When the water distribution procedure is invoked, a set of census-blocks, defined by the site selection procedure and the budget , are scheduled to receive water by system of “trucks”, , such that the days with water delivered by trucks,, is formally defined as

(18)

Another way to represent this would be:

Thus, when the action water distribution,, is taken in a census-block, that is , the number of days water was delivered by trucks is set to the difference between the days with water by pipes and the max number of days in a week (7).

IF water is then distributed to this census-block (), then the total water delivered to the census-block by this mean is then:

(19)

### 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 new well. Thus when the procedure water extraction in invoked, the number of wells per census-block, , increases according to:

(20)

Subsequently, the subsidence rate, , is influenced by water extraction pressure. This is implemented by assuming that the rate of subsidence, , changes over time with:

(21)

where and are the total number of wells inside aquifer , at time , and time 1 respectively, and are formally calculated using:

(22)

Where , is the number of wells in census-block at time , and identifies the aquifer in which the census-block belongs to.

## Resident actions

Residents invoke actions that influence the local infrastructure of the census-block or change the socio-political landscape by protesting.

### House modification

House modifications influence the sensitivity of the house to suffer hazard events. We define the sensitivity of the house as the modulation of the perception of the magnitude of hazards. We assumed also that modifications are cumulative, but it saturates, meaning that there is a limit to adaptation and a rate at which these changes influence the sensitivity. Formally we assume that sensitivity is defined by

(23)

Where

(24)

Is the accumulated times that the action house modification was invoke by the residents of census-block

### Protests

When the procedure protests in a census-block, , are triggered when the valuation of the action protest exposure to infrastructure hazards, the response of the water authority, and the tolerance of local inhabitants to those hazards; accordingly:

(25)

where is the distance to the ideal point related to action protest, .

## Criteria for decision -Water authority

### Capacity

This refers to the perception of the capacity of the sewer system and the pipes network system, . Formally the criteria “capacity”, , is constructed by standardizing the attribute capacity, using , such that:

(26)

### Failures

The criterion failures, represents the perception of the authority about the propensity of the infrastructure system to failures. It is represented by the condition of the infrastructure such that

(27)

### Lack of infrastructure

Lack of infrastructure is a criteria, , that is represented by an increasing function, that takes as arguments the residual of the attribute “infrastructure coverage”, and a set of specific cut-off values for action ,. That is

(28)

Thus, census-blocks with more unconnected residents will be prioritized.

### Amount

This need to be define. (dummy layer now)

Water quality

This need to be included. (dummy layer now)

Water scarcity

This criteria is represented by the accumulation of disruption of water supply by systems and evaluated at yearly for cycle of decision, :

Where

Represent the number of days in a year census-block did not received water neither by pipes nor by trucks. are the days without piped water in a week, and the days that census-block did not received water in a week by system , either.

Flooding

The criteria flooding is represented by the variable with the same name, .Thus

(30)

Health

Health is represented by the annual number of incidences per year, such that

(31)

Supply

The criteria lack of supply represent the people without piped water infrastructure

(32)

### Social pressure

Social pressure, , is a measure that results from the accumulation of protests in a census-block in a period of time , formally:

(33)

(34)

Where, are the total protests in census-block and accumulated over the past yearly cycle of decision .

### Age of infrastructure

The criteria age of infrastructure represent the perception of the water operator about the age of the system. This is represented by the age,, such that

. (35)

## Criteria for decision -Residents

### Urbanization

The perception that green areas are being replaced by new urban areas. This is represented by the percentage of area urbanized in a census-block at the time of the re-evaluation of priorities. Formally,

(36)

### Drainage clogged

Drainage clogged represents a criterion about the perception of the residents that the problem of flooding relates to the lack of maintenance on drainage that get clogged with garbage. To represent this criteria geographically, we use in this implementation, the amount of garbage produced in each census-block,, such that

(37)

### Insufficient infrastructure

This criteria is represented by the lack of coverage in the census-block. Depending on the action this criteria refers to different infrastructure systems, therefore:

(38)

For instance, action “storage water occur water

Which the same function than for insufficient infrastructure from the perspective of the water authority actions.

### Water scarcity

The criteria scarcity residents, , is the perception of lack of water by the residents and is represented by the days without water in the last week.

(39)

### Flooding

Similar to the water authority, the criteria flooding is represented by the variable :

(40)

Health

The criteria health is represented by the variable incidence of gastrointestinal diseases :

(41)

Water deviation

This criteria refers to the perception by indigenous communities that water from local sources is being distributed to other census-blocks, and is represented by the attribute water deviated, :

(42)

Petitions from Census-blocks

TBD

## Policy scenarios

We define a policy scenarios as the set of parameters and variables associated to each actor’s action. These include the criteria name, the biophysical variables associated to each criteria, the set of criteria weights, the set of alternative weights, and the cutoffs of each value function. Currently the model includes the policy scenarios from the two water operators. Table # summarize the information.

## Indicators

At the end of the period of simulation, the following indicators were obtained:

### City-average age of infrastructure system

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.

### The city-average exposure to flooding and scarcity .

This indicators is calculated using

For scarcity, and

for flooding. Where and are the annual number of events water disruptions and to flooding in census-block at year respectivelly. is the final time-step of the simulation and . is the number of census-blocks.

Census-block-average exposure

This is the number of events in the 10 years of simulation in each census-block:

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

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

### Vulnerability index

The vulnerability of a census-block is calculated using the definition of “surface of vulnerability” 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 wealthy areas are less vulnerable because they can have more access to resources to take actions. We use the purchase power as 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, complete equal, to 1 completely unequal. Thus the larger the value of the index the higher the inequality in exposure we day. The Gini is effectively calculating by

(49)

Where is the population of census-blocks.

is the sum of exposure to flood 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 cycles of decision:

(50)

### Sensitivity to policy changes

To evaluate the sensitivity of each census-block to changes in the policy scenarios, we calculate the coefficient of variation in exposure. The coefficient of variation is measure of the variance in a sample relative to its mean as is calculated.

Where is the mean in exposure indicator in census-block at the end of a set of simulations, and is the standard deviation of the sampler of simulations. Thus, if census-block a) has higher coefficient of variation than census-block b, we say that census-block a) is more sensible to changes in policy.

## Appendix

### Extensions

The extensions needed to run a run of decisions are the GIS-extension, which allow to manipulate geographic information such as raster and shape files. Also, the csv-extension is needed to allow the read of coma separated values into Netlogo variables. Matrix-extension is used to update the criteria and action weights of the agents.

### Generating classes of census-blocks using a k-mean clustering classification

### GIS pre-processing information

### Instructions to create new type of agents and actions

#### Create actions as agents

#### Set value variables new agents

## 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 |
| Altitude | Meters above see 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 flood events per year |  | flooding |
| Protests | 1 if a protest occur in a week; 0 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 infrastructure system |  | Antiguedad-infra\_v |
| Condition | An index of the state of the infrastructure system in census-block |  | condicion |
| Hydraulic cost | 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 | A 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-block considered as 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 |  | Refer to the water distributed by government trucks to areas without connection to the supply network |  | Weekly |  |
| Extraction |  | Increase extraction by increasing number of wells |  | Annual |  |
| Maintenance |  | Repairing infrastructure system *v* |  | Monthly |  |
| New infrastructure |  | Refer to the action of providing new infrastructure in census-blocks that lack of coverage |  | Monthly |  |
| Residents | Collective action |  | Refer to the action of organizing to demand changes from the authority or to internally generate change locally | TBD | TBD |  |
| Water-storage |  | refer to the capture of water using storage devises |  | TBD |  |
| Purchase of water | TBD | refer to the action of buying water from private sources | TBD | TBD |  |
| House modification |  | Action to modify local condition of dwelling to reduce damage from flooding |  | Annual |  |
| Mobilizations/protests |  | To express dissatisfaction with the public services of water delivery and sewage |  | Monthly |  |
| Water Re-uso |  | the action of recycling and re-using water | TDB | TDB |  |

Table 3: Criteria residents

|  |  |  |
| --- | --- | --- |
| Criteria for calculating decision Metric of Residents | |  |
| Criteria | Description | 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 water operator supply

|  |  |  |  |
| --- | --- | --- | --- |
| Criteria for calculating decision metric water supply operator | | | |
|  |  | definition | unit |
| Infraestructura | Age of infrastructure | Average age of infrastructure per census-block | years |
| Capacity | Capacity [in length of pipes] of the infra to supply water or to discharge | Mts/area |
| Failures | An index of the number of infrastructure related hazards per year (e.g. pipes break) | [events/year] |
| Lack of infrastructure | The lack of supply and discharge connections | % houses not connected to infra 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 flood events per year | [events/year] |
|  | Health | Represented by the number of incidences per year | [events/year] |
| Socio-institucional | Supply | Represented by the requirements of the population to infrastructure system | [pop \* need/pop.] |
| Petitions from Census-blocks | Demand of population funneled by politician at the level of the municipality. It represents the collective level of response from each municipality |  |
| Social pressure | Represented by the number of protests per year | [pop \* need/person] |