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An agent-based model of flood risk in Mexico City

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With best regards,

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An agent-based model of flood risk in Mexico City

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Abstract. Risk modeling is becoming increasingly important in order to avoid disasters, particularly in large cities. In this study, flood risk was simulated in Mexico City by using an agent-based model. The model dynamics include simulating precipitation randomly distributed throughout the city map, taking the elevation from the open MEC (Mexican Elevation Continuum) data set into account. Flooded areas emerge from the simulation as a result of global and local interactions between rain and land elevation. When we compare the model results to the Mexico City flood risk atlas, we see a fairly good correspondence between the flooded areas and the high flood risk zones obtained from the simulation. Among other things, this research could lead to better planning for rainwater harvesting and strategic sewer installation.

Keywords: Agent-based modeling · floods in Mexico City · risk modeling.

1 Introduction

Floods are the most common type of natural disaster, according to the World Health Organization [1], and they occur when an overflow of water submerses a portion of land that is normally dry. Depending on the purpose of the analysis, floods are studied using a variety of approaches: susceptibility [2], risk [3], or vulnerability [4]; information availability, as well as the nature of the phenomenon, can all be considered.

Water management research can be extremely challenging, especially in large cities such as Mexico City. An integrated management strategy that takes into account demand, supplies, and sanitation services, as well as the intricate socio-environmental relationships, is required [5].

The lack of flood data is a major issue when modeling these types of phenomena, so developing models is critical in order to understand their behavior. This data problem is one of the reasons why it is difficult to study and forecast the basin's behavior and the risk of flooding in Mexico City.

The use of private software (e.g., MIKE SHE) and deterministic heuristics to generate flood risk maps is one solution to this problem [6]. In contrast, using open source software can help to reduce costs associated with this research.

Nevertheless, some authors use machine learning algorithms to investigate the hypothesis that incorporating some factors into the modeling of a river's rise in water level can improve the accuracy of a flood susceptibility map [7]. They conclude that using additional factors in the modeling, such as LiDAR data, elevations, slope, curvature, current power index, topographic wetness index, topographic roughness index, and sediment transport index, does not always ensure a high degree of precision in the model and that the modeling method can significantly alter the results.

The agent-based modeling approach has been used successfully to predict flood risk in a variety of contexts, including coastal areas vulnerable to sea level rise and cities. The case studies [8], [9], [10] agree that this alternative approach provides useful knowledge that can be applied to better manage public policy and prevent flood disasters based on simulations and the properties that emerge as a result of the local interactions between the agents considered in the models.

An agent-based model was developed to simulate the interaction of biophysical processes, residents' decisions and water authorities in Mexico City [11] (model available in [12]). It simulates Mexico City's vulnerability to sociohydrological risk by taking into account decisions made by Mexico City's water authority regarding infrastructure investments. To validate the assumptions about residents' decision-making, a role-playing game was created, which facilitated a discussion with residents about the game's potential further development as a learning and communication tool [13].

The agent-based modeling approach has not been used specifically to assess the risk of flooding in Mexico City. As a result, the goal of this research is to make a contribution to a flooding model in the study area.

2 Materials

2.1 Agent-based modeling

The origins of agent-based modeling can be traced back to the study of complex systems [14], [15], [16] and artificial life [17]. An agent is an autonomous individual or object with particular properties, actions, and possible objectives. There is an environment, which is the setting where the agents interact among themselves. It can be geometric, network-based, or data-driven by the real world, with extremely complex interactions between agents or the environment.

A complex system is composed of autonomous components that interact with one another [18]. Complex systems, on the other hand, have an additional feature: the agents are adaptable at multiple levels, including individual and population. The goal of complex systems research is to discover universal principles governing these systems (self-organization, emergent behavior and emergent phenomena, and natural adaptation origins).

Furthermore, the central concept of agent-based modeling is that many (if not most) phenomena in the world can be effectively modeled using agents, an environment, and relationships between agent-agent and agent-environment [19].

An agent-based model is made up of, essentially, three elements [20]:

1. A set of autonomous agents: each agent has an attribute set that describes its state and a behavior set (rules that describe the agent's behavior) that defines how agents react to changes in their environment and, most likely, how they pursue their goals or objectives.
2. A set of relationships between agents: each relationship defines how each agent interacts with the others and with their environment. It implies that each agent is linked to the others.
3. The agent's environment is the "world" where agents exist. It is a minimal set of global variables or structures that are needed to define how agents react to their environment.

2.2 Rainfall agent-based model

This model simulates rainfall over a geographical area, taking elevation into account in order to have an emerging behavior from raindrops, i.e., flooded zones because the model has no drainage, so the rain will be concentrated in some zones. Rain can fall at random or on areas selected by the user. The original model can be found in NetLogo's model library [21] (see Figure 1).

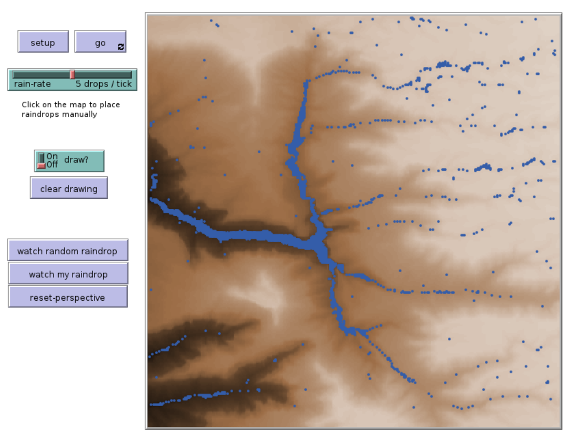

Fig. 1. Grand Canyon rainfall agent-based model interface.

2.3 Elevation continuum

The Mexican Elevation Continuum 3.0 (MEC) [22] was chosen to generate simulations from the agent-based model. It is a product that depicts the Mexican country's elevations. We only considered the Mexico City area (see Figure 2).

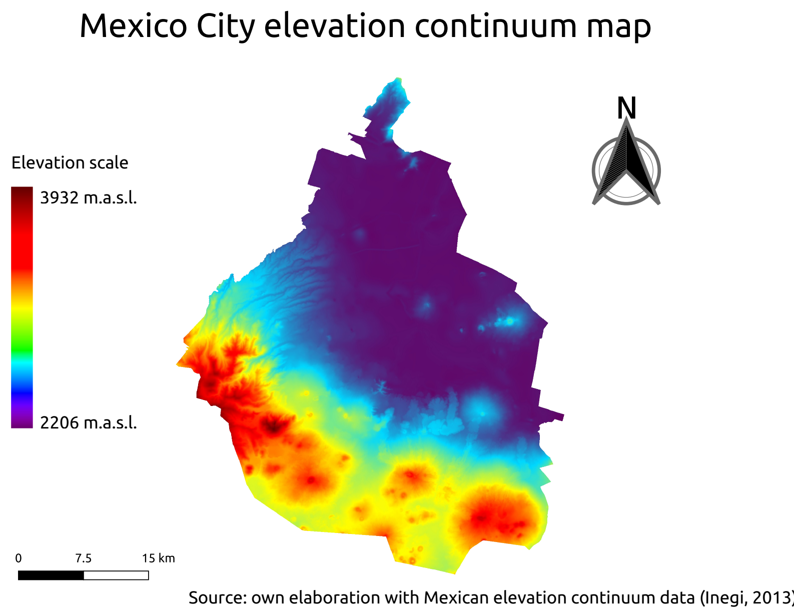

Fig. 2. Mexico City elevation continuum map.

The Mexico City elevation continuum raster image is 3921 rows by 3057 columns in size. Each pixel is worth 15 m × 15 m area. The extension of the raster image in Figure 2 is shown in Table 1.

	Minimum	Maximum
Longitude	$-99.36492\,^{\circ}W$	$-98.94034\,^{\circ}W$
Latitude	$19.04823\,^{\circ}N$	$19.59281\,^{\circ}N$

Table 1. Mexico City elevation map extension.

Table 1's geographical coordinates are based on the GRS 1980 ellipsoid (see details in [23]).

2.4 Flood risk atlas

The goal of the Mexico City flood risk atlas is to calculate flood danger using the flood risk index computed by the National Center for Disaster Prevention (Cenapred), its Spanish acronym, the floodability index map from the National Commission of Water (Conagua) and historical flood data [24].

The flood risk atlas' information is organized by Basic Geostatistical Area (BGA). This terminology comes from the National Institute of Statistics and Geography (Inegi). Each BGA is assigned a risk category (see Figure 3).

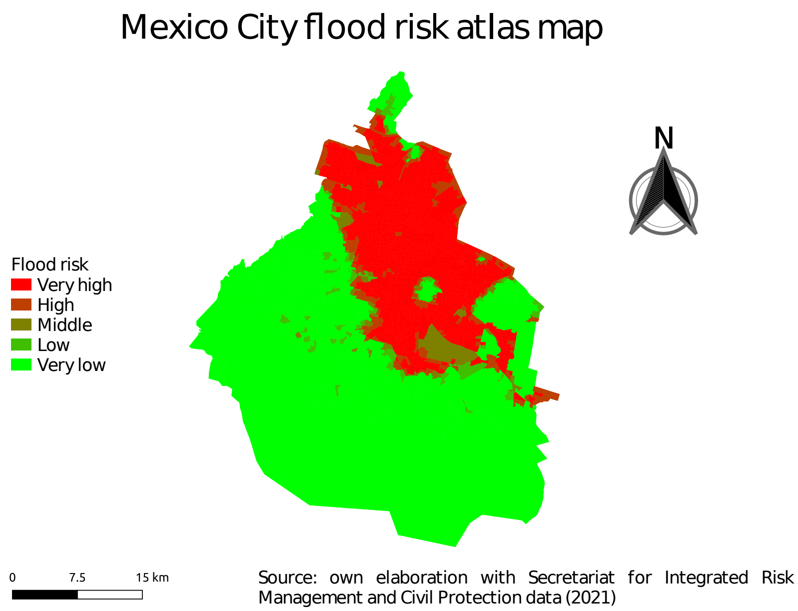

Fig. 3. Mexico City flood risk atlas map.

3 Methods

Following a review of the relevant literature, it is clear that a study using Mexico City's open data to analyze the precision of the flooding information in order to evaluate the known hazard flood zones is required.

The model was developed in the NetLogo programming environment [25]. The model's assumptions are that raindrops fall in random locations and it excludes drainage and any other type of water removal.

The model's world is composed of two layers, namely, elevation continuum raster image and atlas flood risk. The elevation continuum raster image was converted to ASCII format using the Geographic Information Systems open source software QGIS [26]. It has 490 rows and 382 columns. Therefore, in the model's world, each pixel represents an 8×8 square of pixels from Figure 2. As a result, each patch in the world is 120 m $\times$ 120 m in size. The flood risk at each BGA, on the other hand, was addressed as well as a patch attribute. Every patch, in summary, has two attributes: elevation value and risk category.

The agents in the model are raindrops that follow a set of rules. This set of rules enables system-wide emergent behavior to emerge from local interactions among raindrops.

The model dynamics are as follows: raindrops are generated at random, flow along the elevation continuum, and are killed when they reach the borderline. We have the following detailed description:

go procedure

```
go
 create raindrops at rain-rate
 with raindrops do {
    flow
 }
 with border do {
    die
 }
end.
```

Where `raindrops` are a `breed` in the NetLogo model, `rain-rate` is a user-selected parameter, `border` is a subset of patches with fewer than eight neighbors, `flow` and `die` are procedures, the latter is a NetLogo native procedure.

The essential procedure in model dynamics is `flow`. It allows raindrops to interact with one another on a local scale. Given a patch, this procedure seeks the neighboring patch with the least amount of water. In that case, the raindrop will move on to this patch. Otherwise, the raindrop will become a puddle.

flow procedure

```
flow
 target := the lowest neighboring patch considering how much
           water is on each neighbor patch
 if (target != empty) {
    ifelse (elevation + water's target < elevation + water's patch)
       {move to target}
       {set waters}
 }
end.
```

`water's target` and `water's patch` depend on `water-height`, a user-selected parameter (see Figure 4). This is in charge of determining the level of raindrops so that they form puddles.

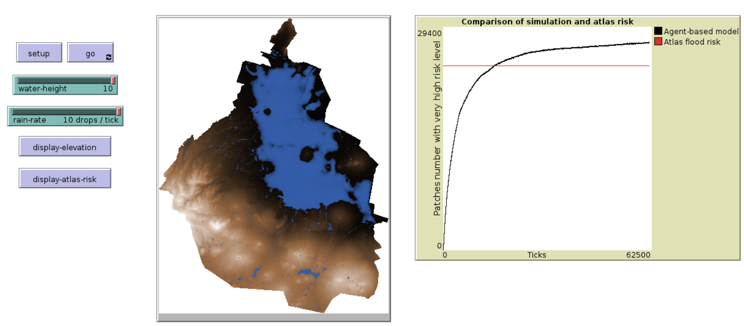

Fig. 4. Agent-based model interface.

4 Results

The simulation results are shown in Figure 5, with blue marks indicating potential flooding areas, whereas the risk from the atlas is displayed with the same scale color as in Figure 3.

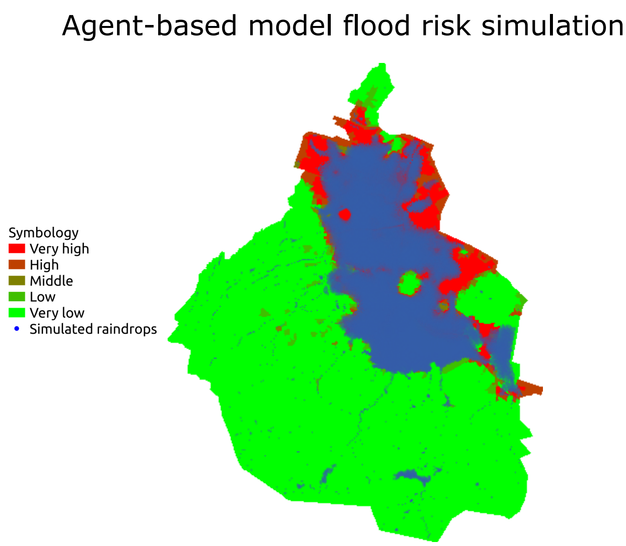

Fig. 5. Agent-based model flood risk simulation.

The comparison of the model's simulated risk and atlas risk is shown in Figure 6. It takes into account the number of patches with a very high risk level for slightly more than 60 000 simulation ticks. Patches with more than zero raindrops are recognized as very high risk.

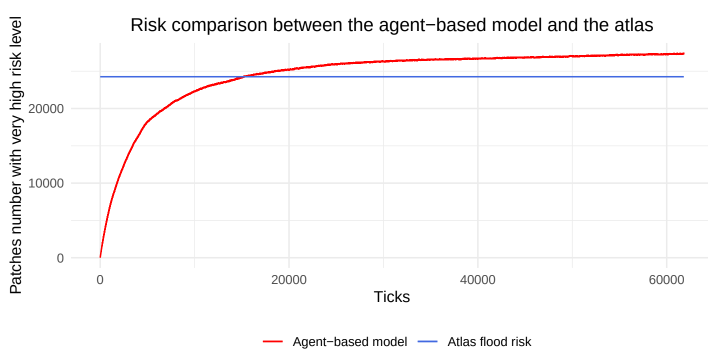

Fig. 6. Comparison of risks between the atlas and the model.

5 Discussion

In most areas with a high risk of flooding, we found pretty good correspondence with the atlas flood risk (see Figure 5). Nonetheless, the simulation did not cover some areas, particularly along Mexico City's northwestern and northeastern borderlines.

We hypothesize this is because the elevation outside of Mexico City was not considered, so it may be necessary to consider the continuum elevation around Mexico City in order to obtain the "missing" potential flood areas.

Even though cumulative water in the borderlines behaves differently than in the inner areas, the study area could be delineated to directly improve the obtained results.

The number of patches with a very high risk level obtained from simulation appears to have an asymptotic behavior around a fixed bound, which is greater than the number of patches with a very high risk obtained from the atlas (see Figure 6).

6 Conclusions

The approach we used, agent-based modeling, has been demonstrated to be appropriate for modeling the flood risk caused by precipitation puddles in the Mexico City area.

We can conclude from the results (see Figures 5 and 6) that the agent-based model approach, like the flood risk atlas methodology, has the potential to produce interesting results.

Clearly, the model requires significant improvement in order to accurately represent reality and gain a better understanding of complex phenomena such as floods.

7 Prospectives

As previously stated, the model could be improved by putting into consideration, for example, the Mexico Basin elevation continuum. It appears more appropriate than focusing solely on the Mexico City elevation continuum.

Taking into account variables like historical rainfall data and hydraulic infrastructure could significantly improve the agent-based model used here.

Water harvesting in Mexico City is another intriguing topic that could be addressed from this perspective. Data from Mexico City's water harvesting infrastructure could be analyzed to help with water resource management and make recommendations for more catch points with higher rainfall levels.

Appendix

The developed model and needed files are available in the following repository: https://github.com/LuisMunive/ABM-of-flood-risk-in-Mexico-City

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