Assessing the impact of crisis cell decisions during flash flood

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Abstract. Catastrophic weather-related events, such as flash floods, require efficient decisions to reduce people's exposure while avoiding unnecessary decisions. To provide efficient decisions, a crisis management cell composed of decision-makers and experts must be able to centralize information and make relevant choices. Our study proposes an agent-based model which can be used to assess various strategies for flood crisis management. Our study focuses on the application of several decisions taking into account both their interactions and the time of their implementation. We model people's behaviors during their daily activities and their adaptation to flooding and to the authorities' decisions with the GAMA platform. Preliminary results indicate that the time of decision implementation impacts people's exposure to flooding and that combining specific decisions enhances the efficiency of crisis management. This approach helps limit ineffective decisions and select those that provide a trade-off between flood exposure and daily activities' disruption.

Keywords: Agent-based modeling · Crisis management · Flash flood · Decision timing

1 Introduction

Flash floods are weather-related hazards that are difficult to anticipate and whose frequency is increasing [8]. To deal with a flash-flood event as it occurs, a crisis management cell made up of decision-makers, experts, and communication professionals gathers, centralizes information on the situation, assesses the risk, makes decisions, and defines a communication strategy.

However, crisis management cells often lack tools to measure the effectiveness of alternative decisions. Individual reactions are difficult to predict as they vary according to personal constraints, available information [13] and decisions from the official authorities. Agent-based models (ABMs) are particularly relevant to the evaluation of emergency strategies for their ability to simulate dynamic decisions in a spatial environment with heterogeneous individuals. Agent-based simulations provide a testing bench for analyzing how social dynamics evolve under crisis management scenarios that are unsafe or expensive to approach in real life [1, 19]. Simulations often study the implementation of different decisions individually but they rarely examine the interaction between several simultaneous decisions or the dynamic aspect of applying decisions at different times [6].

Our study proposes to use ABM to assess the impact of different decisions on individual behaviors during a flash flood. This work is conducted through a case study that occurred in the town of Trèbes (France) between October 14 and 16, 2018. Based on empirical knowledge gained from post-event interviews, the model simulates realistic population heterogeneity by incorporating individual characteristics, activity chains, and individual or family adaptations to warnings and official advice. The model is designed to support a serious game called ANYCaRE [17] where the decisions are made by players who take on different roles within a crisis management cell and must make decisions based on different predictions. The model enables (1) to observe the effect of combining different decisions and (2) to analyze the impact of the time of decision implementation with a focus on individual exposure and the impact on their daily activities. We illustrate our approach by quantifying the impact of different emergency management decisions on people's flood exposure.

The article is organized as follows: Section 2 reviews key contributions in ABMs for crisis management. Section 3 details the model. Section 4 presents preliminary results. Finally, Section 5 summarizes the main contributions of this study and outlines future directions.

2 Related work

ABMs enable to vary the hypotheses of the tested event (time, amplitude, uncertainty) and crisis communication towards the population by confronting the range of available official protective options with the dynamics of the hydro-meteorological and human behavioral patterns [2]. In the last decade, several ABMs have been developed to simulate long-term adaptive behaviors and risk mitigation decisions related to flood hazards [1]. A recent review of ABMs for flood risk management [1] found that only 33% of the 39 reviewed studies looked at evacuation during flood events. Evacuation ABMs simulate the various residents' emergency behaviors during the evacuation phase with the aim to explore relevant strategies in evacuation planning [19]. Taillandier et al. [15] proposed a model that integrates emotions, social norms, and social relations with information sharing and risk knowledge to simulate evacuation strategies during a flood in La Ciotat city (South France).

Although some evacuation models integrate the behavioral reaction of individuals to flood warnings [4], holistic models that explore the effect of flood alerts, warning messages, and emergency decision-making on human losses remain rare [18]. Existing models rarely explore the impact of the time of decision implementation and how combining various decisions could impact the efficiency of a crisis management strategy. The next section presents a model that allows one or multiple decisions to be applied at any time during the simulation in order to assess the impact of the decision on individuals.

3 Model

The model is implemented in the GAMA platform [16] and described using the Overview, Design concepts, and Details (ODD) protocol [5].

3.1 Overview

Purpose. The model simulates the daily mobility of the inhabitants and represents the flash flood that occurred in the Trèbes city (France) between October 14 and 16, 2018. It is used to evaluate different decision combinations and implementation times and to identify those that minimize the individual's exposure. The model is intended to be used in a serious game where various experts must choose decisions to implement during the crisis.

Entities. The main kind of agent models an inhabitant with his own characteristics: age, sex, level of study, socio-professional category and occupation. Each agent has its own agenda which is a sequence of activities and trips over the day. The agents are geolocalized and belong to a household. A household gathers one or more agents and is associated to a residential building. A trip entity contains the starting and the ending time of the trip, a destination zone, and the activity both at the origin location and at the destination. Buildings and roads are the two main spatial entities of the model. Roads are the support of agents' trips and buildings are places for agents' activities. A building may be considered as a shelter if it has more than one floor or if it is an official shelter. At the beginning of the simulation, each household is randomly assigned a residential building within its residential zone and each agent is assigned with a building for its primary activity: a workplace for working adults or a school for students. Buildings for other activities (such as shopping or leisure) are randomly allocated in the destination zone for each new agent's activity. Roads and buildings have a flooded state that depends on the water level: safe, disrupted or dangerous (see Section 3.3). A road or building is safe when it is not affected by flooding, disrupted when the water level hinders movement, and dangerous when there is a risk of physical injury and loss of life. A flooded road can be closed by the authorities with a delay that depends on the decisions applied (Tab. 1). Finally, buildings are located in a zone and a municipality. A municipality is the smallest administrative division in France often centered around a town. A zone is a small-scale geographical unit that includes at least 130 households and 160 individuals [12]. This segmentation ensures both statistical representativeness and data confidentiality.

Scales. The studied area comprises three municipalities of the Carcassonne urban area (South-West of France). The three municipalities are populated by around 14200 inhabitants and cover an area of around 100 km^2. This area is often exposed to flash floods. As we aim to assess the total exposition to the flash flood we take into account all the people that may be in the flooded area during the event. We thus extended the simulated area to the whole Carcassonne urban area. We simulate 16 hours from 6 a.m. to midnight on October 14, i.e. the day of the flooding, with a simulation step of 1 minute.

Scheduling overview. The model has three different time scales: one for individuals, one for the flooding and one for crisis decisions. Individuals' behavior is computed at each simulation step. Flood propagation is updated every 15 minutes as water level information is provided by raster files available at the same interval (see Section 3.3). The model is designed to support a serious game where a crisis management cell can apply decisions at three predefined game times: 11 a.m. (30 minutes after the start of the flash flood), 2 p.m. and 4 p.m. These timescales were chosen because managing a flash flood requires short decision times.

A time step is as follows: if it is one of the three predefined game times, new crisis decisions can be applied (Table 1). Every 15 steps, the roads and buildings' flooded states are updated based on the water levels. The individual agents then execute their behaviors according to the activity diagram in Fig. 1 (the decision trees mentioned are shown in Fig. 2 and Fig. 3).

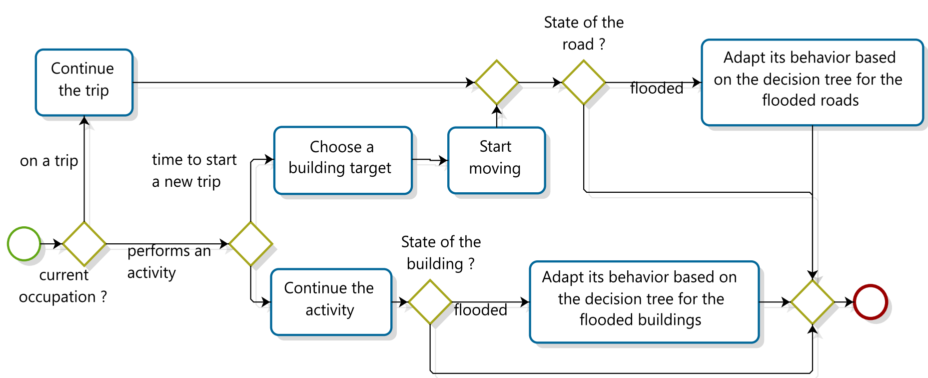

Fig. 1: Individual decision-making process at each simulation step

3.2 Design concepts

Basic principles. Individuals' behavior is described using an activity-based model. Each individual follows an agenda composed of a set of activities and trips. Agents perform activities in buildings selected from those available in their trip's destination zone (see Section 3.1). Agents move from one building to another using the road network either by walking or by car. The simulation is only run during the water-rising period.

Adaptation. We make the hypothesis that inhabitants' reactions to a hazardous situation depend on their individual and social characteristics. Their behavior is also altered by the crisis management cell's decisions and the condition of the surrounding road or building. Behaviors of agents located in a flooded building or on a flooded road follow the decision trees in Fig. 2 and 3. Agents' behavioral adaptation to a crisis management cell's decision is described in Tab. 1.

Objectives. Agents have two implicit objectives embodied in their rule-based behavior: 1) follow their agenda; and 2) ensure their safety and avoid flooded (disrupted or dangerous) roads and buildings.

Sensing. Individuals perceive the flood-related state of the road on which they are moving on and of the building in which they are located. When they plan their trips they know the location of their next activity and the roads that are closed by the authorities (cf. decision 4 in Tab. 1). Finally, individuals know the nearest unofficial refuge (building with more than one floor) and official refuge.

Interaction. The main interaction between individuals is the escort activity between individuals of the same household. For example, parents have to pick up their children from school if they cannot return on their own. Interactions between the flood and the inhabitants are limited to the water level recorded in buildings and roads.

Stochasticity. Individuals' behaviors are impacted by several random factors. They randomly pick a building in the destination zone as target for their current trip. Their adaptation behavior to flooded buildings and roads follows random distributions which will change depending on the crisis cell's decisions. Finally, some decisions are not followed by all individuals. The individuals who follow instructions are randomly selected from the population with the required characteristics according to the proportions and conditions specified in Tab. 1.

Collectives. Individual agents are gathered into households sharing the same residential location (e.g. a family). Grouping of individual agents into households can impact their behavior as their agenda may contain escort activities.

Observation. The evolution of the simulation can be monitored in real-time through several indicators: number of individuals exposed to flooding (in buildings or on roads), total exposure duration (cumulative time spent in contact with the flood for the entire population), number of changes in activity caused by exposure. These indicators can be observed for specific population groups or for the entire population.

3.3 Details

Initialization. The initialization of the simulation follows two main steps: 1) creation of the spatial entities (buildings, roads, zones, municipalities) from the input shapefiles; 2) creation of the demographic entities (individuals, households, trips) and links between them from the Time Survey dataset: an agent has an agenda of trips, a household has a set of individuals, and a home building. All individuals start the simulation at their home place at 6 a.m.

Input Data. The temporal evolution of flooding (spatial extent and water levels) is obtained through a processing pipeline [3] that incorporates observed rainfall fields (Antilope J+1 [9]). The pipeline output is a set of raster files (one every 15 minutes) with a spatial resolution of 5 m. Instead of using flood data directly, these files map flood information onto roads and buildings. For each building and road, we record the times at which their status changes first to "disrupted" and then to "dangerous". A road is considered as "safe" when the water level is below 30 cm, "disrupted" when the water reaches 30 cm and "dangerous" when it reaches 50 cm. The states are the same for buildings but the thresholds are 10 cm and 40 cm. These thresholds have been provided by experts. Flood dynamics in the case study have been shifted by 8 hours in simulation so that flooding occurs during the day rather than at night. The first road is flooded at 10:30 a.m. (instead of 6:30 p.m.) and the first building at 11:30 a.m. (instead of 7:30 p.m.).

The spatial description of the buildings is provided by IGN BD TOPO Version 3.0, the reference French database [7]. The river network comes from the French Catchment National Database [11]. The road network comes from OpenStreetMap [10] and includes only the major roads.

The synthetic population is generated from the 2015 Time Survey dataset on the Carcassonne urban area [12]. This dataset provides data about a sample of the urban area population with 5924 individuals in 2726 households and their daily trips. Each household's home and each activity's place is located in a zone. The dataset has missing data: in some households, there are individuals with unrecorded agendas. To complete missing agendas, we relied on [13] which provides a clustering of the agendas (using similarity metrics) and a decision tree depending on individual characteristics: age, gender, education, professional status, household composition. However, this work only considers individuals older than 16 years old. To complete the agendas, the population has been split into 3 sets: non-studying individuals, studying teenagers ($>$ 11 years old), and pupils (children between 3 and 10 years old). For adults without agendas, we copy the agenda of an individual randomly selected from the corresponding group (using the decision tree [13]). For teenagers, we copy the agenda of a randomly selected teenager in the same age range (11-16, 16-18 or $>$18) with an equal probability for each selection. These three ranges correspond to different kinds of French schools (secondary school, high school, and university). In the dataset, parents or relatives bring pupils to school in the morning and bring them back home in the evening (plus some trips back home at noon to eat). However, some pupils are brought to school but never brought back home, and vice versa. To prevent blocking situations, we completed pupils' agendas with the missing trips.

Finally, we filtered the synthetic population to keep only individuals that could be impacted by the flood, i.e. individuals having their home or activities in the study area. The final synthetic population consists of 855 individuals in 381 households, i.e. around 9% of the actual population that could have been impacted by the real flood. We created a complete synthetic population by duplicating (x11) individuals to obtain a full population of 9405 individuals. Simulations have been performed with 9% and 100% of the population for the scenario 1 (Section 4) in which the individuals adapt when they face flooding but no decision is applied by the crisis management cell. These simulations produced identical results in both cases when analyzing different indicators such as the number of individuals exposed to the flood or the number of individuals with disrupted agendas. The results obtained with the population from the Time Survey dataset are thus representative of the entire population. To reduce simulation time all simulations were executed with the 9% population sample.

Subprocesses. An agent follows its agenda throughout the day. The agent stays at home and when the departure time arrives, the agent starts its trip to go to its next activity. Once at a destination the agent remains there until the next trip starts. Some adults have escort activities meaning they do the trip and activity with a child.

Individuals do not react uniformly when facing hazards: Fig. 2 (resp. Fig. 3) presents the decision trees that agents follow in flooded buildings (resp. on flooded roads). This formalization enables to adapt the proportions of each behavior according to the flood situation [14].

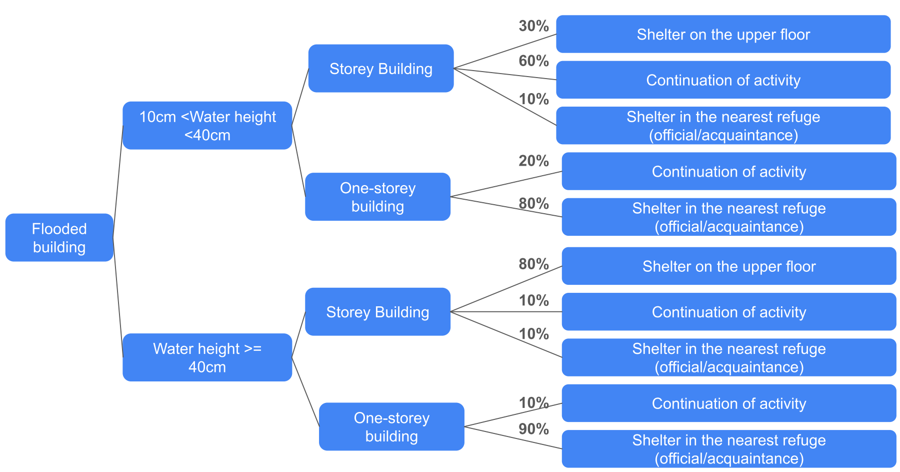

Fig. 2: Decision tree for the reaction of individuals in a flooded building

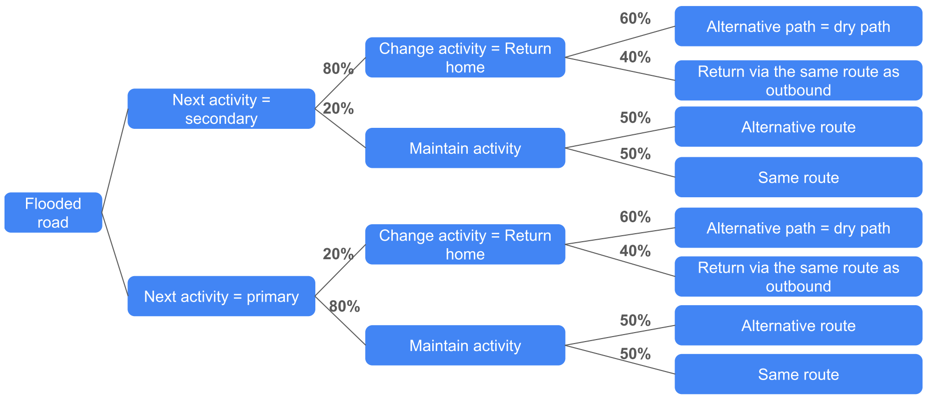

Fig. 3: Decision tree for the reaction of individuals on a flooded road

Fourteen authority decisions provided by experts can be applied during the simulation (Table 1). For a given decision only a proportion of the individuals will adapt, selected according to the conditions in Table 1 (e.g., if schools have to be closed, only students and parents are impacted).

4 Preliminary results

Calibration. The model used to obtain the temporal dynamics of flooding has been calibrated separately from this study. The trips performed by individuals are those from the Time Survey and their displacement speed has been calibrated to match the departure time and arrival time given by the Time Survey.

Experimental setup. The model allows to explore all the decisions presented in Table 1. In this paper, we focus on exploring strategies impacting schools and the closure of flooded roads (decisions 2, 6, 7, and 8). More strategies will be explored in future work. Three kinds of scenarios were simulated:

- **Scenario 0**: agents follow their agenda regardless of the flood. For example, if they are in a flooded building they stay there and continue their activity;
- **Scenario 1**: agents follow their agenda but adapt when they face flooding.
- **Scenario 2**: agents follow their agenda but adapt to both the flooding situation and the decisions issued by the crisis management cell (Tab. 1).

Each simulation was repeated 100 times. All the results presented are average values and standard deviations of 100 simulations.

Baseline scenarios Scenarios 0 and 1 are used to verify that the model behaves as expected. Comparing the results of these two scenarios confirmed that in Scenario 1 (where individuals react to the flood) the agents are less exposed to the flood: the cumulative duration of individuals' exposure to dangerous roads

	Decision	Effect of the decision
1	Implement flood **control measures**	Delay the flood time
2	**Anticipate school leaving time**	70% of households pick up their children
3	Evacuate to the **nearest shelter** (if you do not have a floor)	100% of the population apply the measure
4	Pre-position teams to **anticipate road closures**	Roads closed within 15 min of flooding
5	Pre-position **intervention columns**	Reduces the evacuation time by 1/2 if decision 6 is applied
6	**Evacuate facilities** in flood zones: campsites, health facilities, schools	Evacuates people from buildings in 1 hour
7	**Confine students** to the school to prevent parents from picking them up	50% of households apply the measure
8	**Close flooded roads**	Selected roads are closed in 1h
9	**Evacuate vulnerable populations** in flood zones	50% of people over 75 are taken to a shelter
10	Be vigilant a **orange rain-flood vigilance** is in progress	20% of people who have planned a leisure activity during the day do not realize it
11	**Avoid travelling** and inquire before you travel	30% of the trips to school or work are cancelled and 80% of other trips
12	**Stay home** and follow the advice of the appropriate authorities	70% of men between 18 and 40 years and 90% of the rest of the population apply
13	**Do not use your car**	80% of the trips to school or work are cancelled and 100% of other trips
14	Take **refuge** in the floors	Multiplies by 2 the number of people who go to the floors (Fig. 2)

Table 1: The different possible decisions

is 140 minutes in Scenario 1 compared to 4099 minutes in Scenario 0. This is expected as individuals in Scenario 1 adapt their agenda when faced with flooding: 205 individuals out of 855 changed their agenda to be safer.

Evaluation of the effectiveness of a decision. Applying only one decision at a time and comparing results with those from Scenario 1 enables to assess the decision's impact. Results obtained with decision 2 which was applied at 11 a.m. show that anticipating school leaving time did not significantly reduce individuals' exposure (Fig. 4) while impacting 81 agendas on average: 205 agendas are disrupted in Scenario 1 compared to 286 with decision 2. (Fig. 5). An explanation is that only 6 of the 15 schools are flooded with only 3 schools impacted before the end of the school day. Two are impacted at 3:30 p.m. and one at 4 p.m. In contrast, decision 8 helps to reduce individuals' exposure to flooded roads; 130 agents are exposed to dangerous roads in Scenario 1 compared to only 15 agents when decision 8 is applied at 2 p.m.. Decision 8 also limits the agendas' disruptions: only 98 people changed their agendas (Fig. 5) compared to 205 when no decision is applied. As flooded roads are closed, individuals are less exposed to flooded roads and therefore less likely to give up their planned activity.

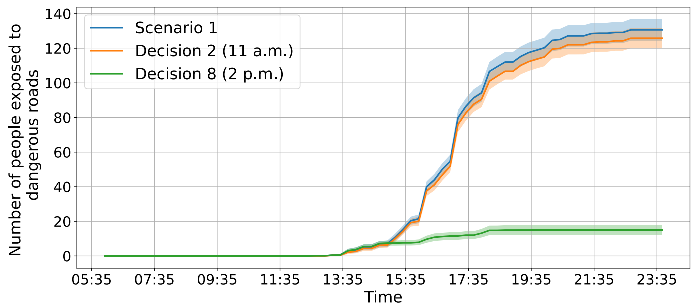

Fig. 4: Comparison of the number of people exposed to dangerous roads

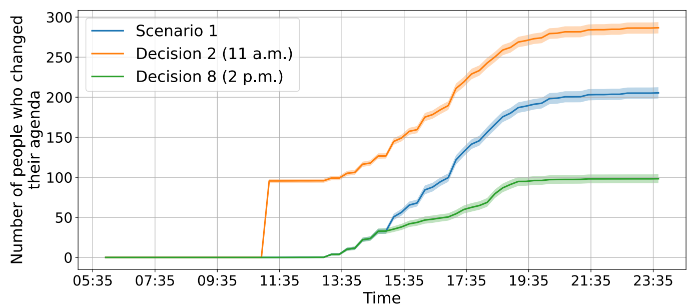

Fig. 5: Comparison of the number of people changing their agenda

Impact of implementation's time. The time of decision 8 affects the decision's effectiveness. When applied at 2 p.m. it reduces people's exposure to flooded roads and agendas' disruptions compared to its application at 4 p.m.: 15 agents were exposed to dangerous roads compared to 57 and 98 agents had their agendas changed compared to 141. As roads are closed earlier, fewer people face flooded roads and thus change their agenda. When more people are exposed to flooded roads, more agendas are disrupted. This explains why delaying road closures increases agendas' changes.

Interaction between different decisions. Applying only decision 7 (confining students to school) has no impact on either individuals' exposure or agenda changes. Applying only decision 6 (evacuating facilities in flood zones such as schools) slightly reduces children's exposure. However, if we couple decisions 7 and 6 and apply them at the same time the strategy becomes more effective. It reduces children's exposure but requires significant agendas adaptations: on average 143 additional individuals change their agenda compared to Scenario 1. Yet, applying decision 7 at 11 a.m. and decision 6 at 2 p.m. worsens the situation compared to Scenario 1: more children are exposed to flooded roads (Fig. 6) and 132 additional agendas are impacted. This indicates that both the time of implementation and the combination of decisions should be considered.

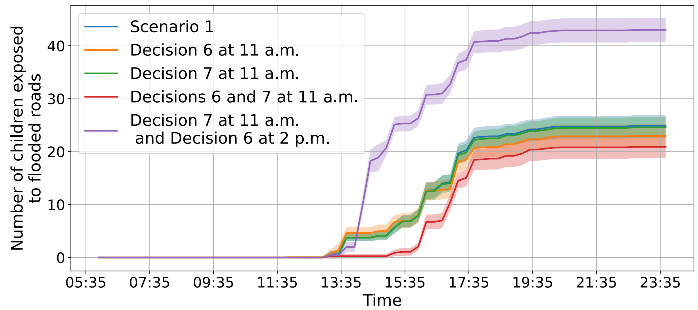

Fig. 6: Comparison of the number of children exposed to flooded roads

5 Discussion and conclusions

The proposed model enables the analysis of strategies by exploring both the decision's implementation time and the combinations of multiple decisions.

Eight strategies have already been explored. Preliminary results show that some combinations and implementation times are more effective than others in reducing both people's exposure to floods and the impact on their daily activities. Anticipating school leaving time does not reduce individual exposure and disrupt agendas while closing roads reduces individuals' exposure and minimizes schedules' disruptions. The decision to close flooded roads is more effective when applied at 2 p.m. than at 4 p.m. Keeping students at school to prevent parents from picking them up is effective only if authorities evacuate students to a shelter at the same time. Combining these two decisions limits parents' trips and reduces their exposure while preventing students from staying in a school that may become flooded.

We plan to further explore the model by implementing additional strategies, testing new decision combinations, and applying them at different times. The model will be integrated into a serious game allowing experts to validate it. The goal is to provide a tool that assesses the decisions made by the crisis management cell formed for the game by identifying those that minimize damages, i.e., the number of exposed people and the number of people whose agenda is disrupted.

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