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A spatio-temporel optimization model for the evacuation of the population exposed to natural disasters

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Abstract

The importance of managing the crisis caused by natural disasters, and especially by flood, requires the development of an effective evacuation systems. An effective evacuation system must take into account certain constraints, including those related to network traffic, accessibility, human resources and material equipment (vehicles, collecting points, etc.). The main objective of this work is to provide assistance to technical services and rescue forces in terms of accessibility by offering itineraries relating to rescue and evacuation of people and property. We consider in this paper the evacuation of an urban area of medium size exposed to the hazard of flood. In case of inundation, most people will be evacuated using their own vehicles. Two evacuation types are addressed in this paper, (1) a preventive evacuation based on a flood forecasting system and (2) an evacuation during the disaster based on flooding scenarios. The two study sites on which the evacuation model developed is applied are the valley of Tours (Fr, 37) which is protected by a set of dikes (preventive evacuation) and the valley of Gien (Fr, 45) which benefits of a low rate of flooding (evacuation before and during the disaster). Our goal is to construct, for each of these two sites, a chronological evacuation plan i.e. computing for each individual the departure date and the path to reach the assembly point (also called shelter) associated according to a priorities list established for this purpose. Evacuation plan must avoid the congestion on the road network. Here we present a Spatio-Temporal Optimization Model (STOM) dedicated to the evacuation of the population exposed to natural disasters and more specifically to flood risk.

1 Introduction

This paper addresses the problem of the evacuation of people exposed to risk of flooding. Arranged with a specific urban data bases (flooding scenarios, census of population, transport network, etc.), the model developed here enables to compute the evacuation routes to be taken by the affected population while minimizing the total evacuation time (Te). This optimization model must take into account several constraints such as accessibility (Geurs and Wee, 2004; Chapelon and Leclerc, 2007; Mathis et al., 2007), roads capacity, capacity of safe areas, vulnerability of the population exposed to risk (lists of priorities, scheduling), vulnerability of transport network (roads cut during floods) (Fuchs et al., 2007; Plattner, 2005; Matisziw and Murray, 2009; Caloz, 2011).

The occurrence time of a flood event is known in advance, at least 48 h before, period during which the population concerned should exit the area (Patouillard et al., 2013). The evacuation process must be prepared i.e. fixing for each family the departure date and its escape route to the safe area associated.

The evacuation of issues (inhabitants, nuclear centers, hospitals, etc.) exposed to natural hazards (floods, earthquakes, tornadoes, volcanoes, tsunamis, etc.) was and is a problem that occupies a high position in the hierarchy of priorities of governments of multiple countries. The US Department of Homeland Security (DHS) defines the evacuation of an area as:

> The organized, phased, and supervised withdrawal, dispersal, or removal of civilians from dangerous or potentially dangerous areas, and their reception and care in safe areas (National Incident Management System, December 2008, p. 139).

The evacuation of areas prone to natural (floods, etc.) or technological (nuclear risk, etc.) hazards can be one of the measures for the protection of urban issues. It requires systems and decision aids tools allowing mainly to protect the lives of people. The reorganization of routing traffic in densely populated areas is a very important element for a massive emergency evacuation. Safety, minimization of delays and of total travel time are the main aspects to be taken into account during an evacuation. This reorganization of the traffic can be modeled and solved by tools of Operations Research (Bretschneider and Kimms, 2012).

The total evacuation time can be defined as the time needed for an evacuation process and which includes the warning time, preparation time, travel time between dangerous and safe areas, and evacuation verification time (Bretschneider and Kimms, 2012; Hamacher and Tjandra, 2001). Stepanov and Smith (2008) show that the complex process of evacuation includes several consecutive phases (see Fig. 1).

Missions and necessary tasks are needed to be coordinated among government and nongovernmental organizations (Bretschneider and Kimms, 2012). The realization phase itself consists in evacuating the affected population through the network prepared for this purpose. This latter includes the paths computed from areas to be evacuated (buildings, neighborhoods, etc.) to safety areas (shelters, assembly points, etc.). Transportation planning that includes the design and the evaluation of transport infrastructure (highways, streets, public transport routes, etc.) is required to ensure that the entire population exposed to hazard has the opportunity to leave safely the danger zone. This includes the planning of routing and the organization of traffic circulation on evacuation routes. As only a part of the population is evacuated using their own vehicles, adequate transportation must be provided for the other part of the population (e.g. nursing homes, hospitals, prisons, etc.).

Since 1960, many researches have been conducted in the fields of optimization and evacuation planning. Those works can be grouped into two families: the optimization approaches of an evacuation plan with specific objectives, and the evaluation process of existing evacuation plans in view to check and validate them. While the validation approaches are usually of microscopic type, the optimization approaches are rather macroscopic (dynamic network flow) or microscopic (traffic assignment) and manage the evacuees movements over time. Contrary to microscopic models (Naghawi, 2010; Lammel et al., 2010; Powell et al., 1995), the macroscopic methods (Yusoff et al., 2008; Bretschneider and Kimms, 2011; Saadatsresht et al., 2009) do not take into account human behavior. Indeed, evacuees are treated as a homogenous group where only common characteristics are considered. These methods tend to minimize the total evacuation time. Between the two previous levels (macroscopic and microscopic), the mezoscopic methods (Naser and Birst, 2011; Dixit, 2005; Bormann et al., 2012) allow to follow in real time the trajectory of each vehicle (its position in the network). However, these methods do not take into account neither the behavior of evacuees nor the interaction of vehicles with their environment.

We are interested in STOM[1] to develop a two-stages mezoscopic model combining between dynamic network flow and traffic assignment models. The first stage concerns the development of an evacuation scheduling system based on a priorities list established, where we evacuate at each time slot (one hour, half hour, etc.) and by priority order the maximum number of vehicles from each building not yet totally evacuated. Roads capacity, evacuation paths predetermined and destinations capacity must be respected during the assignment of flow. Based on this result, a vehicles pursuit model (VPM) is also developed in order to first, convert the discrete process (time slots) to a continuous one (time intervals), and second, to avoid overlap between successive time intervals. This overlap may occur on network roads because the sources from which flow is outgoing (incoming to network roads) at each time slot vary over time. VPM minimizes the evacuation departure times of buildings. The flow-dependent travel time on roads is computed using a polynomial traffic model (Ardekani et al., 2011; Trani, 2009) which is also used to compute the capacity (maximal flow rate) on roads based on the free-flow speed, jam density and number of lanes of roads.

2 Evacuation model reformulation

At time of evacuation, inhabitants of site exposed to risk must be evacuated through the transport network to the assembly points equipped for this purpose (Southworth, 1991). This operation must be based on a plan computed by an evacuation model under certain constraints (hazard, accessibility, vulnerability, etc.). A definition of the evacuation plan, applied to the case of the tsunami, but easily applied to the case

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of the flood, was given by the IOC (Intergovernmental Oceanographic Commission of UNESCO)

> The primary aim of an invoked tsunami evacuation plan should therefore be to guide all affected persons along the evacuation routes towards safe places (which are primarily supposed to be outside the reach of tsunami waves but could also be inside the flooded area), also called assembly facilities or emergency shelters; and in time (time span between alarm and arrival of first wave taking into account for each person the distance to the next emergency shelter) – SCHEER, VARELA, EFTYCHIDIS, 2012.

The flowchart in the Fig. 2 shows the steps of the evacuation model STOM developed. The first step is the formation of the input spatial database which includes an urban network database, buildings to be evacuated (Sect. 3) and safety points (Sect. 4). The next step includes the formation of groups of buildings by network nodes (Sect. 3). Then the third step concerns the reconfiguration of network according to the preferences of decision makers (reservation of few specific ways to rescue forces, authorization of no entry, etc.). The fourth step of the model consists in associating with each group of buildings one or more shelters (Sect. 4). Then, the fifth step calculates the K-best paths between each group of buildings and each safety point associated. The sixth step computes an evacuation plan based on an evacuation scheduling system and a vehicles pursuit model (VPM). While the next step simulates and checks the evacuation plan. Finally, a mapping of the final evacuation plan is proposed.

The construction of the database (network, buildings, shelters, population) required for the evacuation model are not addressed here. We focus in this paper on showing only the veritable steps for constructing an evacuation plan.

3 Grouping of buildings

The first step is to assign each building to the nearest network node. This assignment results in the formation of groups of buildings by network node. Note that we don't work here neither on a microscopic scale (buildings) nor on a macroscopic scale (neighborhood, area, etc.) but on an intermediate scale, that is to say mezoscopic (group of buildings). The Fig. 3 shows this step on a part of the valley of Tours, where buildings that are assigned to the same network node have the same color.

This assignment can be a source of difficulty in traffic if the distance between the centroid of buildings and the nearest network nodes is relatively large. The diagram in Fig. 4 shows that this distance (per interval classes) is low for the majority of buildings in the valley of Tours.

Henceforth we denote by building a group of buildings assigned to the same network node.

4 Safety points

Safe points, shelters, or assembly points are spaces equipped to receive evacuees before or during floods and for a long or short time (Lindell and Prater, 2007). They are determined on the basis of a multi-criteria analysis (vulnerability, bridges, etc.) and with the support of local actors (Departmental Directorates Territories, prefectures, etc.) (Stage, 2011, 2013). Thus, safe points should provide sufficient reception capacity in terms of people and vehicles, be located in areas providing a rapid response medical assistance and humanitarian aid, etc.

As for buildings, assembly points are also assigned to the closest network nodes. From these assignments, we can divide network nodes into three categories: (1) nodes grouping buildings: nodes-buildings, (2) nodes associated with assembly points: nodes-shelters and finally (3) all the remaining nodes.

It should be noted that a node-buildings can be a crossing node for vehicles incoming from other nodes-buildings. In other words, those vehicles are not authorized to stay in intermediate nodes at the evacuation (Lim et al., 2012).

The last assignment related to the construction of evacuation network corresponds to the association of each building with one or more safety points according to the following criteria: (1) distance to hazard "as the crow flies" (2) proximity of buildings from safety points "shortest path", (3) reception capacities of assembly points in terms of vehicles and people, and (4) existence of at least one escape route: assignment of buildings to safe points is changed according to flood evolution over time (road cuts).

The Fig. 5 shows the assignment of buildings of the valley of Tours to two safety points (north and south).

5 Determination of evacuation routes

The last step to build the evacuation network is to determine the evacuation routes to be taken by the concerned population. These paths can be provided as an input data for the evacuation model STOM. Otherwise a paths computation method is applied to compute a set of K-best paths between each building and each safety point associated (see Alaeddine et al., 2014c). It should be noted that the transport graph excludes certain routes reserved for rescue forces, firefighters, etc., or/and for the evacuation of major particular issues (nuclear infrastructure, hospitals, retirement homes, etc.). Moreover a polynomial traffic model is adopted here to compute the capacity (maximal flow rate) of each road link basing on jam density, free-flow travel time and number of lanes of roads. This traffic model enables to compute the flow-dependent travel time on roads.

In case of evacuation during disaster, egress routes change over time. Anticipating the state of network can be helpful to manage traffic and to determine the safest access paths to the impacted areas for rescue services (Versini et al., 2010). We show in the

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last section of this paper and on a real site (valley of Gien) the consideration of the aspect “roads cut” in our model STOM.

6 Evacuation priorities list

At time of massive evacuation, transportation network does not allow a simultaneous evacuation of all persons located in danger zone. This requires a complex organizational system allowing to minimize the total evacuation time according to a priorities list established.

Lim et al. (2012) identified several factors that influence this priority as the distance of regions from the hazard (hurricane center), the flooding extent and the population density. Based on this priorities list, the authors assigned a score per region defining the level of vulnerability. This level of zonal vulnerability is established also for each building identified by its gravity center or centroid. However, using this method, all buildings in the same area or region have the same vulnerability level.

In this paper, evacuation of buildings is based on a priorities list similar to that developed by Lim et al. However, in addition to criteria of distance from hazard, flooding extent and population density, we take into account other factors including age of the population to be evacuated, distance of buildings from both dikes and shelters.

In addition, our priorities list also depends on the spatial scale (region, city, area, building). Indeed, at each level or scale, a building has its own priority established according to priorities of higher levels and influenced by one or more factors. A combination of factors can be set to determine the priority of buildings at each level.

We present here one of the evacuation priorities lists. It is based on the most vulnerable areas which need to be removed at first. These are the areas which lie just behind the dykes. The map in Fig. 6 shows dyke failures and potential damage (in red) on the site of the valley of Tours. The dyke failures represented are only those who have been experienced since it is impossible to predict where a rupture could occur.

We divide each evacuation zone (two evacuation zones, see Fig. 5) into three sub-zones $[0,300[$, $[300,900[$ and $[900,\text{and}\ +]$, where for example $[0,300[$ is the area that lies between 0 and 300 m from the river (see Fig. 7). Moreover, for reasons of organization and behavior of people, it is desirable to evacuate people per neighborhoods according to their vulnerabilities. Priority evacuation of two buildings located in the same neighborhood at the same level (sub-zone) is defined according to their distance to rivers. In other words, the priority building is that the closest to the river. The neighborhood with the largest number of buildings located in the level [0,300[will be evacuated first, then the second priority neighborhood of level 300 and so on until the last one. After evacuating the maximum number of buildings (depending on network capacity) located in the first level 300, we turn to the following levels 900 and 900+ repeating successively the same procedure. We repeat these three steps (levels 300, 900 and 900+) until the evacuation of all buildings in all neighborhoods at all levels. Planning the evacuation of buildings at risk requires therefore the construction of priority lists specifically tailored for each treated area.

7 Flow and routing optimization

The construction of an evacuation plan is the result of two-stages model combining between discrete and continuous process. The first phase in this model is to schedule the evacuation of buildings based on a priorities list established. The model assigns, at each time slot (one hour, half hour, etc.) and by priority order, the maximum number of vehicles from each building not yet totally evacuated. This model is subjected to roads capacity, evacuation paths predetermined and destinations capacity (see evacuation scheduling system, Fig. 2). The second phase of this model focuses on the conversion of the discrete process (time slots) to a continuous one (time intervals) using a developed vehicles pursuit model (VPM). This model which is based on a polynomial traffic model enabling to compute flow-dependent travel time on roads, aims to minimize the departure times of vehicles while avoiding overlap between successive time intervals (see vehicles pursuit model, Fig. 2). This two-stages model was presented in a previous papers (see Alaeddine et al., 2014a, b, d).

8 Applications and results

Tests and experiments, as we mentioned before, were performed on two selected study sites: valley of Tours (Fr, 37) and Valley of Gien (Fr, 45). The first site protected by a system of dykes, as mentioned previously, is subjected to a precautionary evacuation only due to several factors, among them the relatively high hydraulic flow in case of flood dykes break. In a complementary way to the first site, we perform on the second site (the Valley of Gien) an evacuation during a possible crisis.

It should be noted that our evacuation model STOM can be applied and adapted, if necessary, to any other site requiring an evacuation whether preventive or during the crisis. To apply a pedestrian evacuation (Chalmet et al., 1982; Hamacher and Tufekci, 1987) (stadiums, ships, etc.), STOM requires a traffic model enabling to compute a pedestrian travel speed according to the number of pedestrians crossing the arc (corridor, passage, etc.). In general, a given evacuation problem (preventive or during the crisis) requires determining the evacuation network (fixed or progressive depending on time), the issues to be evacuated and the safety points to which evacuees will be directed and distributed Kaisar et al. (2012).

The size of the transportation graph is not limited to a certain threshold in STOM due to the dynamic implementation of data structures. All figures in this section, unless otherwise stated, are generated by *STOM Evacuation Software* developed as part of this project[2].

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[2] The tests are performed on an HP Pavilion dv6, Windows 7, 4GB RAM, Intel CPU (R) Core (TM) i5-2410M 2.30 GHz CPU@2.30.

8.1 Descriptive indicators of the network

In this section, we provide the size of graphs of the two study sites as well some descriptive indicators on the transport network of the site of valley of Tours.

We represent the size of graphs of the two sites by their connectivity index β, that establishes the relationship between the number of links and the number of nodes[3].

$\beta = \frac{L}{S}$, where L: number of nodes, S: number of arcs.

- $\beta_{\text{Tours}} = \frac{44\,814}{19\,997} = 2.241$
- $\beta_{\text{Gien}} = \frac{5813}{2567} = 2.264$

Capacity or maximal flow rate on roads is a very important element to build an evacuation plan. It is computed by a polynomial traffic model based on the free-flow speed, jam density and number of lanes of road links. The Fig. 8 shows the capacity (number of vehicles per hour) computed on the site of valley of Tours.

8.2 Preventive evacuation of the valley of Tours

The scenario of dams failure is not considered, as we mentioned previously, in the valley of Tours because of the very high flood flows on this site. Given the impossibility of estimating cuts roads for load shedding during the flood, we focus only on the preventive evacuation. The simulation of the evacuation plan presented here is based on a priority list which is in turn based on the vulnerability of people per districts (see Sect. 6). The preliminary steps and the evacuation scheduling per time slots are respectively illustrated by the two Figs. 10 and 11. The part (a) in the Fig. 10 shows the four levels of hazard on this site while the the part (b) illustrates the vulnerability

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[3] Many nodes of the graphs only serve to describe the geometry of road (curves). In a graph where edges are straight lines (crow flies), the number of nodes must be reduced. However, it should be noted that these intermediate nodes have helped us a lot to build groups of buildings by assigning each building to the nearest network node.

of original buildings based on the destruction zones relative to historical dam failures (see Fig. 6). The grouping of original buildings (by assigning each original building to the nearest network node) and the association of each building to one shelter is given in part (c). The part (d) shows the evacuation network constituent of the 3-best paths computed between each origin-destination. The evacuation priority of buildings per districts based on destruction zones is given in part e (see also Sect. 6 and Fig. 7).

In the Fig. 11, the different colors of each assembly point (rotation in the direction of clockwise) show the evacuation order of buildings associated to it.

This visualization will be strengthened in the following by another representation showing the importance of the evacuation based on the vulnerability of people per districts.

Evacuation scheduling based on vulnerabilities of districts

For illustration purposes, we focus only on the evacuation of the center of the valley of Tours: city of Tours. The Fig. 12 shows the evacuation of buildings per districts according to the priorities list established (see Fig. 7). The buildings are arranged in descending order of evacuation priority and each color corresponds to a district.

The Fig. 13 shows more clearly the evacuation of neighborhoods by their levels of vulnerability. We note that, at each time slot, the neighborhoods located in the first level of danger (band of 300 m located directly behind the dike, see Fig. 7) are first removed (Beaujardin, etc.), then those of the second level (La Fuye Velpeau, etc.) and finally the neighborhoods of third level. The three different colors (red, yellow and blue) represent the three areas of vulnerability (see Sect. 6).

This Fig. 13 shows that the evacuation of all neighborhoods is not consecutive (Beaujardin, Rabelais, etc.). However buildings with the same level of vulnerability (destruction zones) in each neighborhood were evacuated in an almost sequential manner (Beaujardin, Febvotte, etc.).

8.3 Evacuation during the flood of the valley of Gien

The evacuation of the valley of Gien can take place during a flood crisis since it is concerned with a slow-flooding. In this section, we test the evacuation model STOM during the crisis management on the valley of Gien complementing its application in the Valley of Tours (preventive evacuation).

8.3.1 Dynamic of hazard

The dynamic of hazard over time on the second site is illustrated in Fig. 14. We note the continued accessibility of certain network roads even after 107 h from the beginning of the flood allowing for a possible evacuation of some buildings not yet evacuated.

8.3.2 Simulation of the evacuation of the valley of Gien: network almost submerged

This section is devoted to the simulation of the evacuation of the valley of Gien for two time periods (beginning of the flood and 125 h later[4]).

The evacuation in real time during the crisis is not simulated in STOM because of the lack of dynamic information on the network status. However, this simulation does not seem necessary on this site since it is not a mass evacuation. The time slot chosen to illustrate the scheduling of the evacuation is of one minute and a half because the total evacuation time computed being less than 30 min (Figs. 16 and 18). This duration is justified by the relatively low number of buildings to be evacuated dispersed along this site. The evacuation paths of buildings do not share many arcs (parallel evacuation per sectors).

The part (a) in Figs. 16 and 18, represents two cases of buildings: the remaining buildings to be evacuated and the buildings considered isolated. These latter are the buildings that can not be evacuated (we assume they were evacuated earlier) after

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[4] Data base provided by Dreal-Centre, Orléans, France 45.

a certain time from the beginning of the flood, because the area to which they belong is already submerged[5]. The area shown in blue on the network corresponds to HKW[6] and not to the progress of the level of water over time. We are interested to represent primarily the isolated buildings (eg at $t = 127$ h) to show the dynamics of the hazard. Thus, part (b) illustrates the assignment of buildings to safety points with an initial percentage of 50 %. This threshold (50 % of the total number of evacuees) probably is not met due to network disconnection (areas submerged). Part (c) shows the 3-best paths computed between each origin-destination pair. This number may suffer a reduction over time for the same reason evoked previously (network disconnection). Finally, part (d) shows the evacuation scheduling per time slot (1.5 min).

The assignment of buildings to safe points is performed based on the proximity of these latter and the priorities list established is based on the distance of buildings from assembly points (from far to near). We note that evacuation routes computed before or at the beginning of flooding change depending on the evolution of the flood. Part (c) in Fig. 18 shows evacuation paths of some buildings (bottom left) much longer than that of the same buildings at the beginning of flood (see part (c) in Fig. 16).

Moreover the capacity of shelters is not identical after 125 h from the beginning of the flood because the network disconnection as mentioned above (see parts (b) for comparison). In other words several buildings that are closer to the shelter in south must be evacuated to the north because there is no available path.

8.4 Scenarios and validation of evacuation plan in case of incidents

The two curves in the Fig. 19 show the total evacuation duration of the two study sites according to a potential reduction in network capacity. For reasons of graphical representation, the total evacuation time of the Valley of Tours with a fall equals to 99 %

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[5] A network road is considered submerged (not applicable for evacuation) if the water level is higher than or equal to 30 cm.

[6] Highest known water. Provided by the Prevention Plan Flood Risk.

is set to 100 h although it is more than 500 h in reality. The analysis of these two curves shows that the total evacuation time of the Valley of Tours remains reasonable with a fall of capacity less than or equal to 80 %, while that of the Valley of Gien remains reasonable with a fall less than or equal to 99 %.

9 Conclusions

The feasibility of an evacuation plan still faces two challenges related to the behavior of evacuees: respect for evacuation routes and departure dates. Simulation of several scenarios such as delay departure, non-respect of roads, accidents, etc., allows to verify to what extent this plan remains robust in terms of total evacuation time. Such simulations should update the evacuation model itself by establishing new constraints to be respected.

Such simulations could also be used to inform people about this risk and compliance with evacuation instructions. In addition, a higher number of safety points will result in the diversity of K-best paths which in turn enables to minimize the total evacuation time and to guarantee a high acceptance level for evacuation plan by the concerned population. In this case, the evacuation plan is similar to a parallel evacuation of several urban areas (neighborhoods, islands, etc.).

As for the evacuation priorities, it was carried out several tests according to different priorities lists established. Those were based on a combination of several criteria such as proximity to the hazard of flooding, the age of the population, etc. Total evacuation times provided remain very close for the various priorities lists. This would give the crisis management actors more flexibility in prioritizing the evacuation order of the population and neighborhoods.

Of course, the validation of an evacuation plan, by theoretical definition, can not be complete without realizing of real evacuation exercises by policymakers. From a scientific point of view, these exercises should validate not only the provided results but also the model input data. The total evacuation time, a measure among others of the vulnerability, should meet the deadlines of a preventive evacuation. If this condition is not achieved and in order to minimize the total evacuation time, decision makers can apply strategies to change direction of movement, to increase speed on certain network roads, to open an additional safe areas etc. Finally, the construction procedure of evacuation plan should be regularly updated according to the evolving of issues located in flood areas.

At last, mapping of evacuation plan carried out by STOM evacuation software requires further development in order to make it more operational (Meyer et al., 2012). Research on this topic is ongoing.

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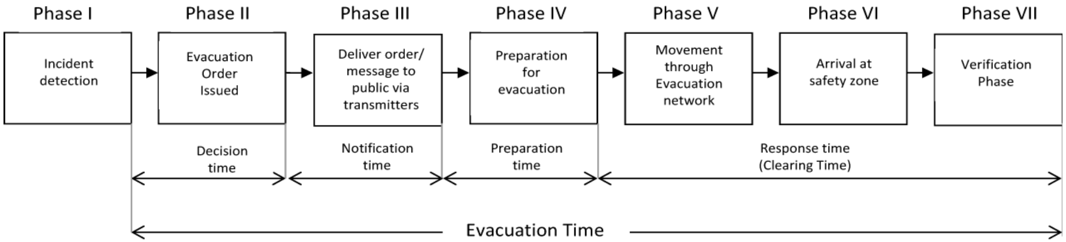


Figure 1. Phases of the evacuation process (Stepanov and Smith, 2008).

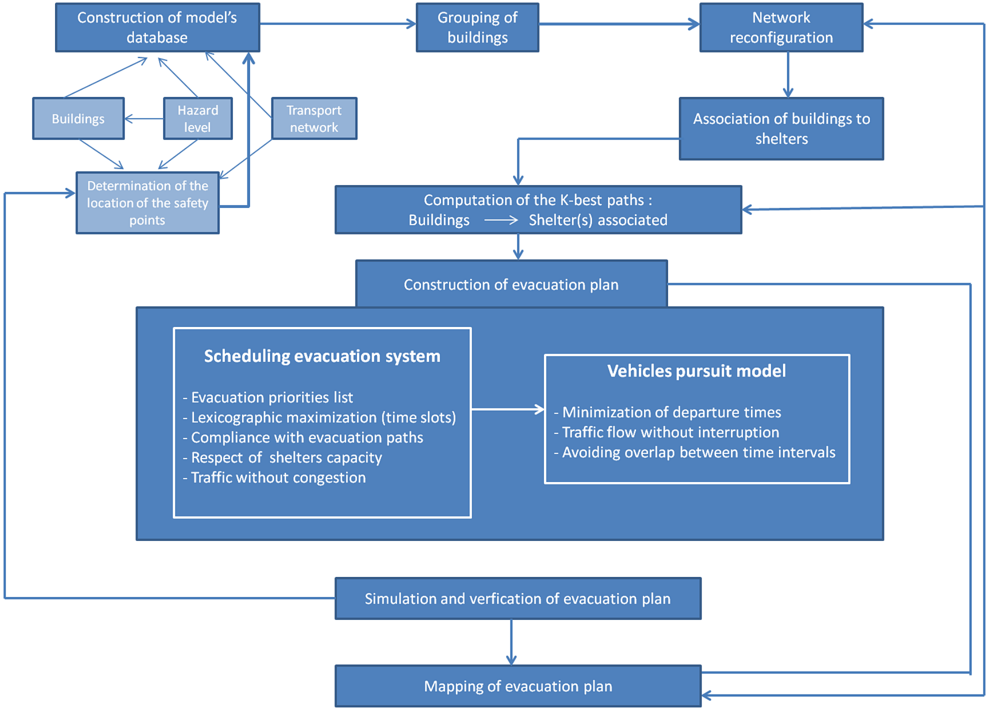
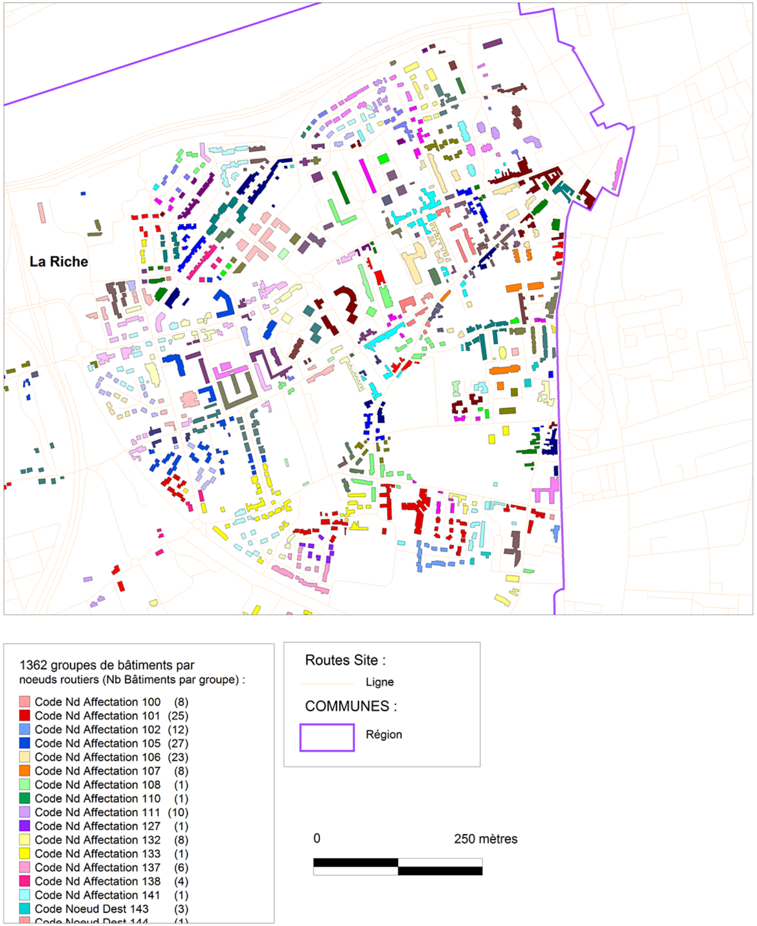


Figure 2. STOM evacuation model.



Source : BD TOPO IGN
Réalisations : K. Serrhini et H. Alaeddine, mai 2014

Figure 3. Assignment of buildings to nearest network nodes.

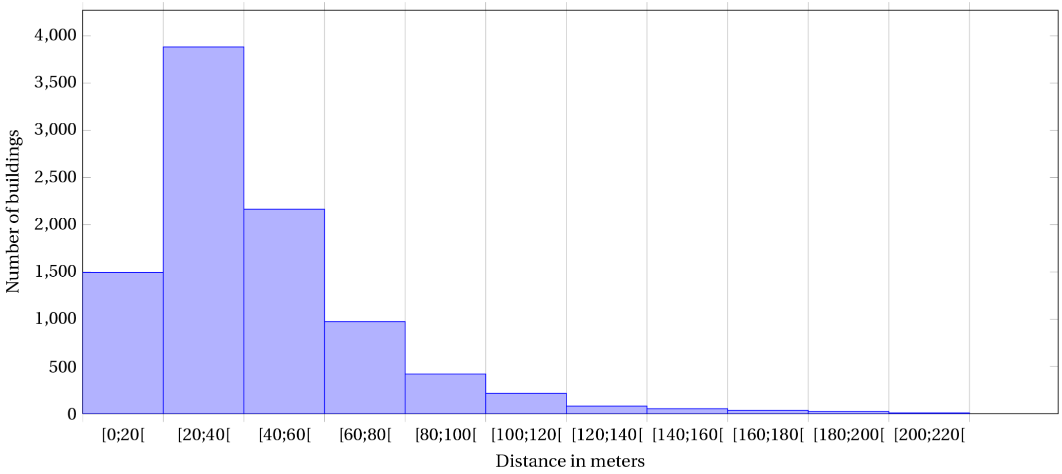


Figure 4. Number of buildings according to their distance from the nearest network nodes.

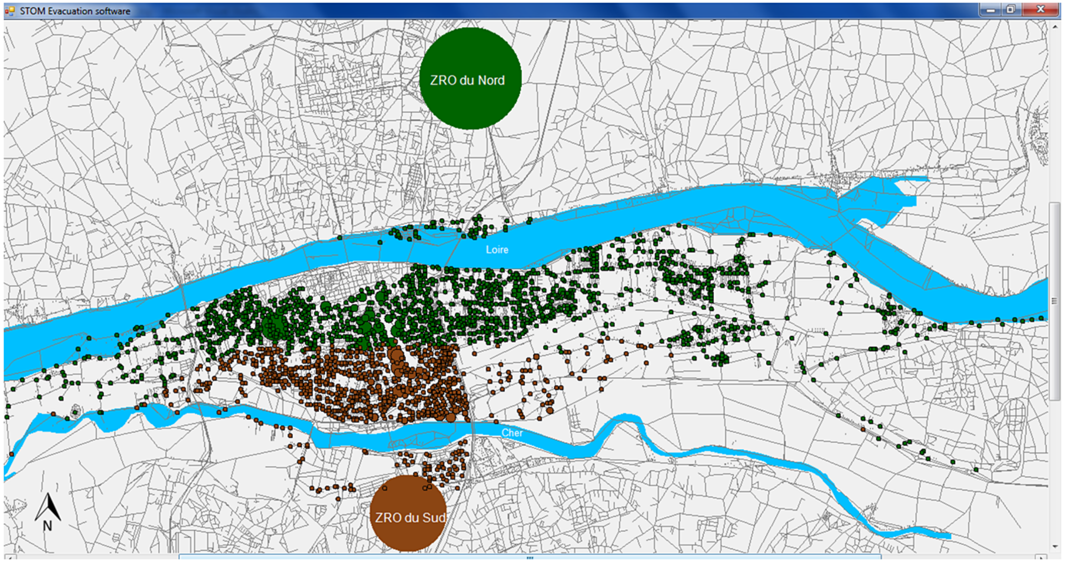


Figure 5. Assignment of buildings to safety points.

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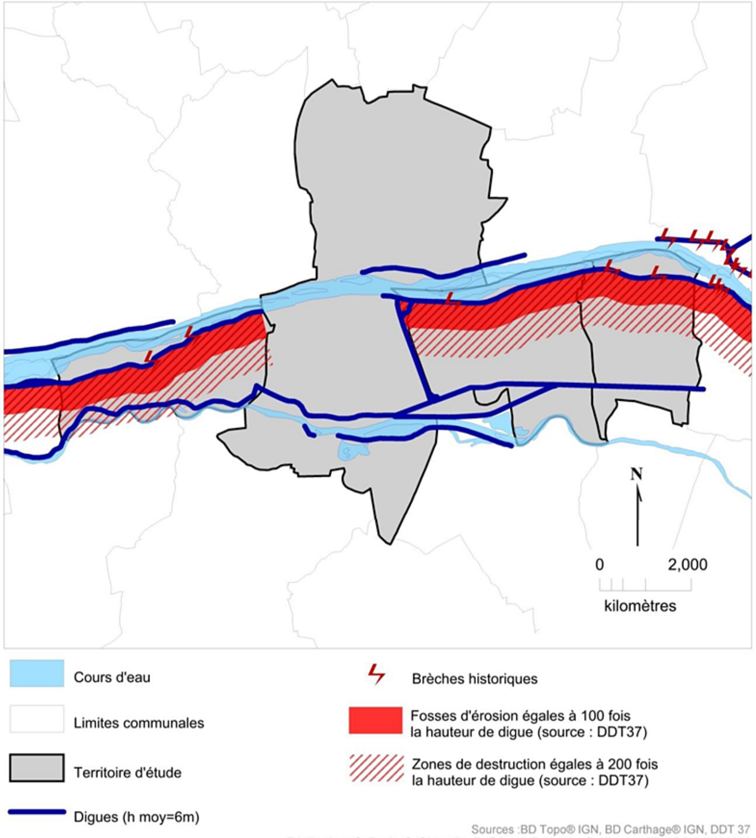

Sources :BD Topo® IGN, BD Carthage® IGN, DDT 37
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Figure 6. Break levees and potential damage on the Valley of Tours.

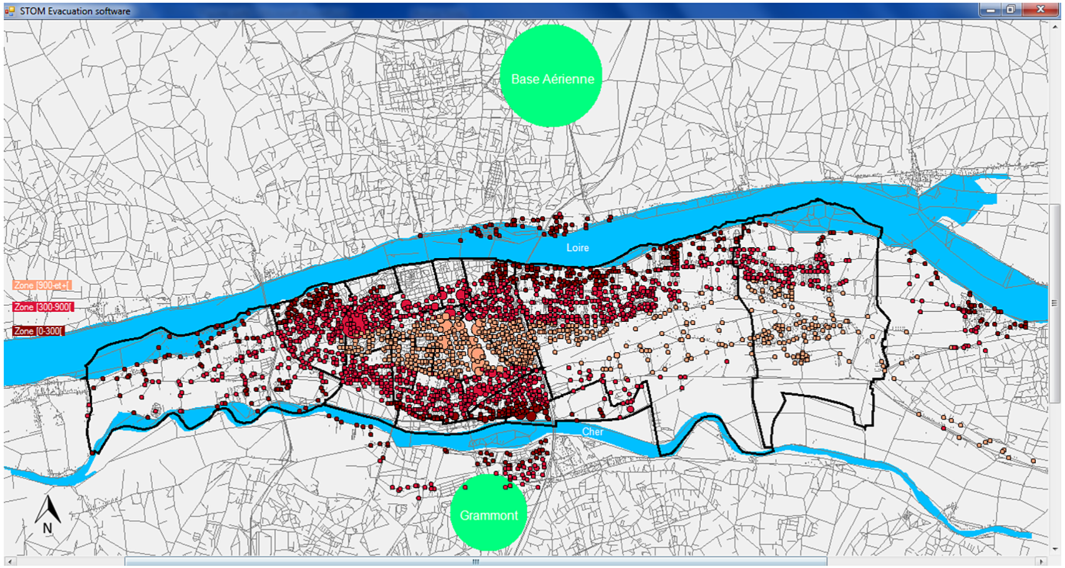
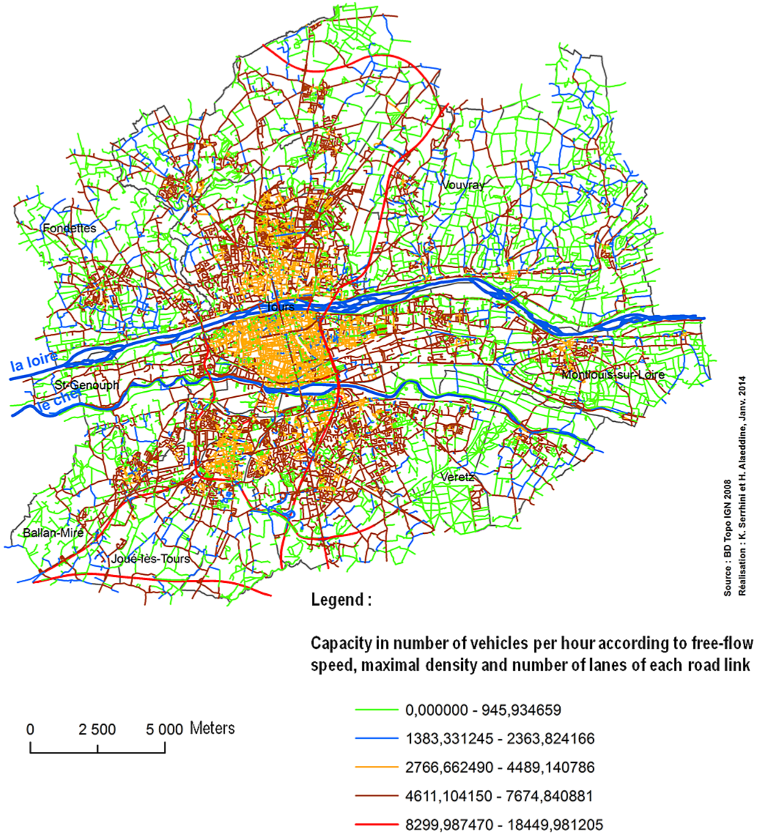


Figure 7. Division of zones, each into three sub-zones.



Source : BD Topo IGN 2008
Réalisation : K. Serrhini et H. Alaeddine, Janv. 2014

Figure 8. Capacity of roads according to free-flow speed, jam density and number of lanes on roads.

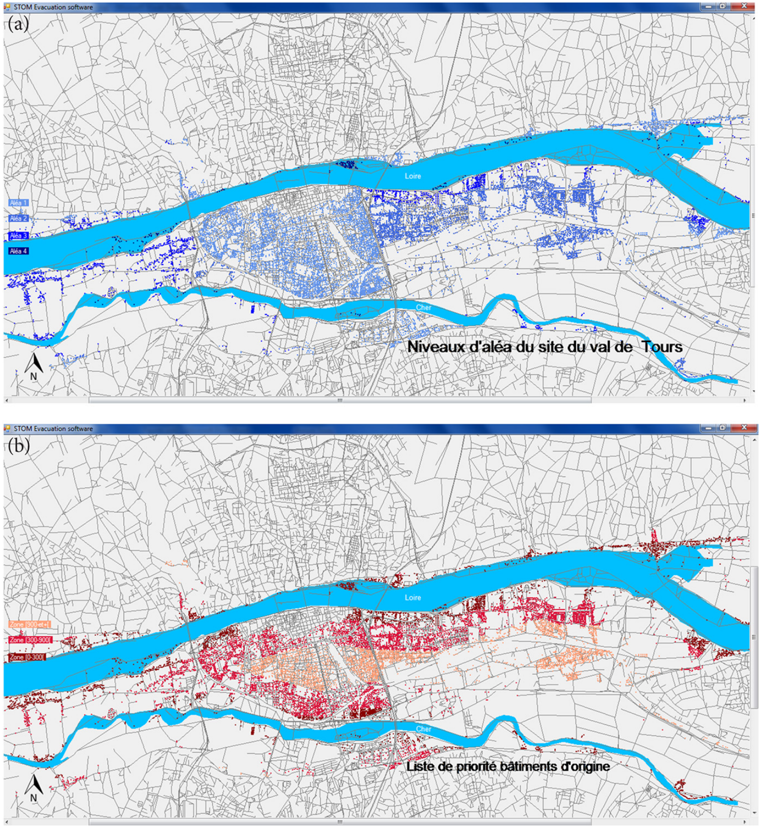


Figure 9. The preliminary steps for the construction of evacuation plan: I. **(a)** Hazard levels, **(b)** destruction zones and assigning priority.

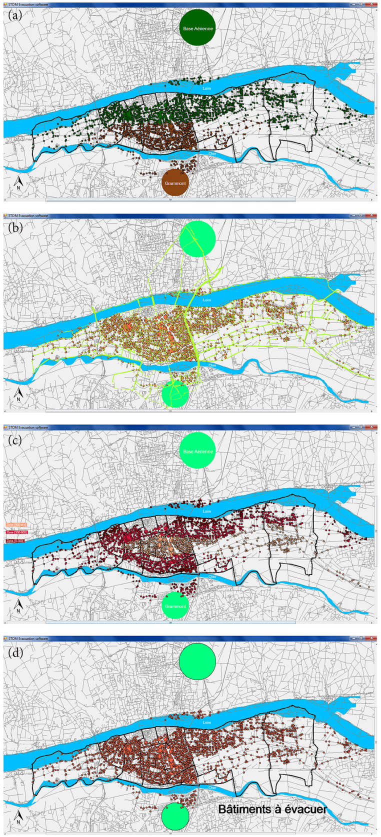


Figure 10. The preliminary steps for the construction of evacuation plan: II. **(a)** Grouping of original buildings and association of buildings (groups of original buildings) to safety points, **(b)** calculation of 3-best paths between buildings and safe points, **(c)** establishment of priorities list: destruction zones + districts, **(d)** buildings to be evacuated.

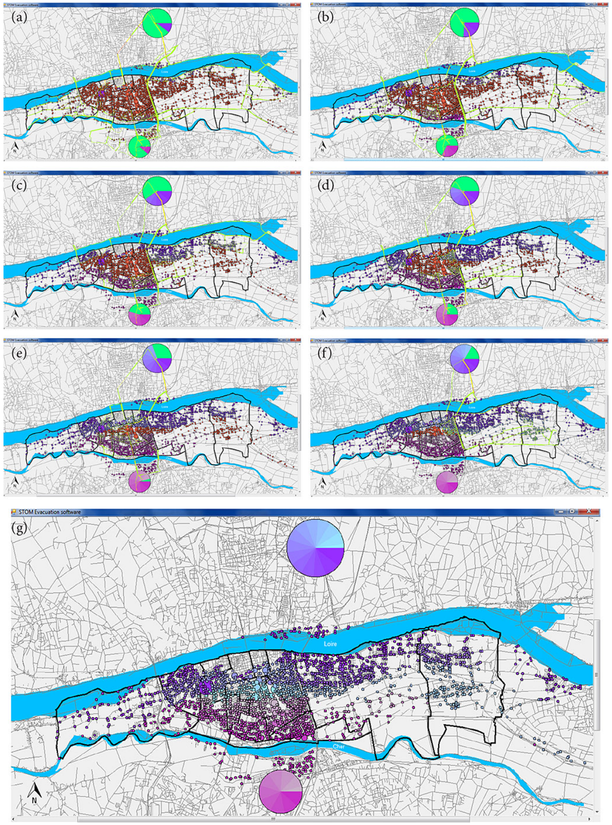


Figure 11. Evacuation scheduling of the valley of Tours. **(a)** Time slot 1, **(b)** time slot 3, **(c)** time slot 5, **(d)** time slot 7, **(e)** time slot 9, **(f)** time slot 11, **(g)** valley of Tours is completely evacuated.

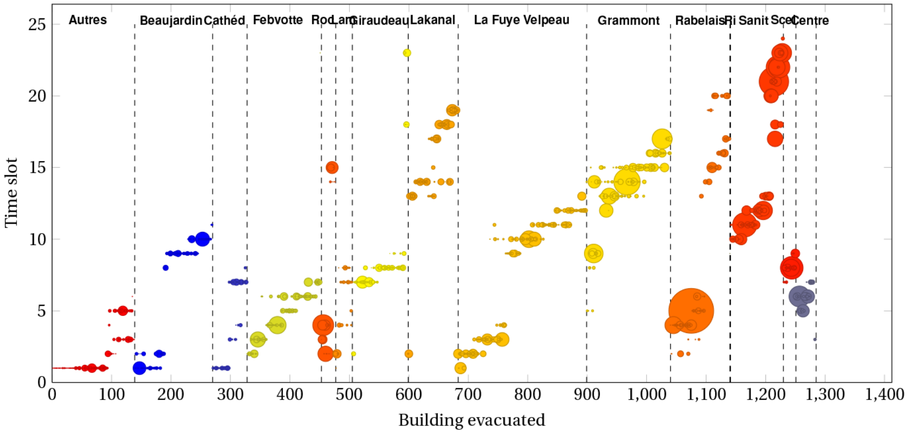


Figure 12. Evacuation of buildings of the districts of the city of Tours; priorities list (vulnerabilities of districts according to destruction areas).

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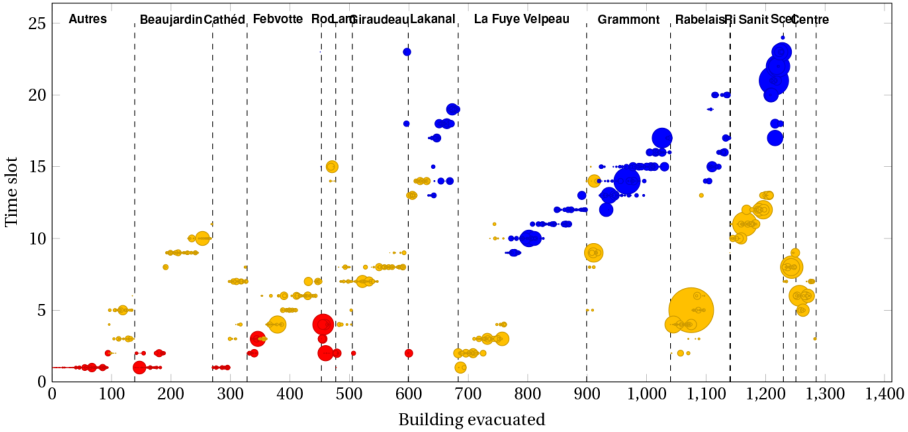
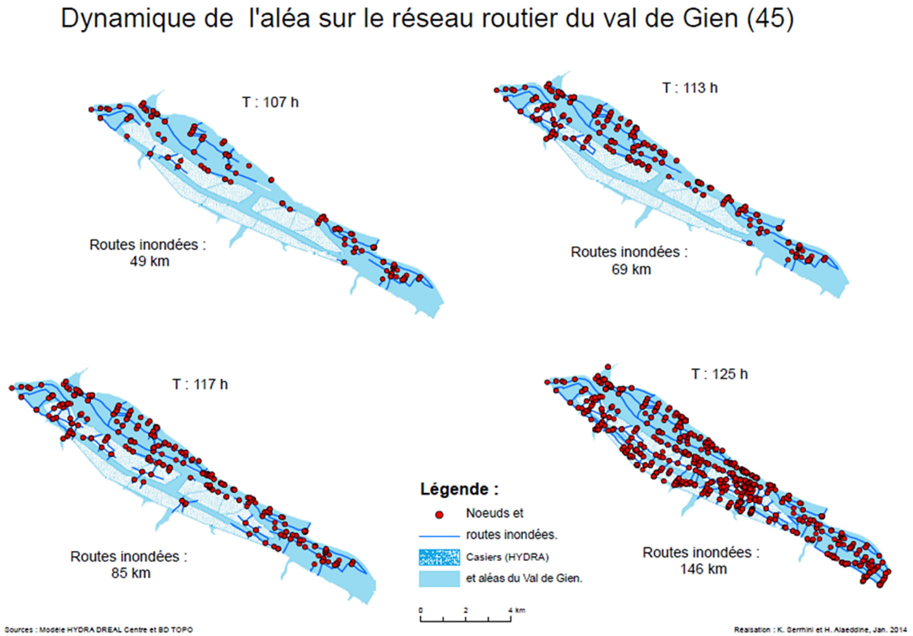


Figure 13. Representation of the evacuation of neighborhoods of the city of Tours based on their vulnerabilities.



Sources : Modèle HYDRA DREAL Centre et BD TOPO

Réalisation : K. Serrhini et H. Alaeddine, Jan. 2014

Figure 14. Dynamics of the hazard on the valley of Gien's road network.

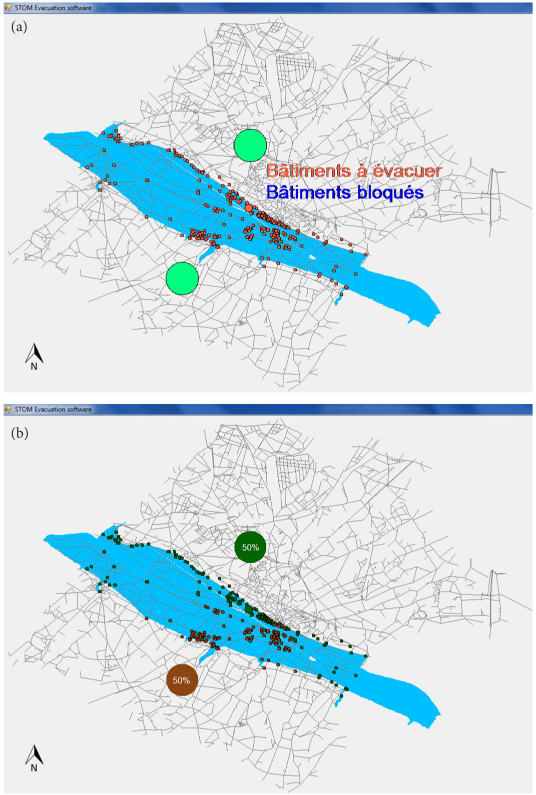


Figure 15. Construction of the evacuation plan: beginning of the flood. **(a)** Buildings to be evacuated (in red) and isolated buildings (in blue) at the beginning of the flood, **(b)** assignment of buildings to safety points.

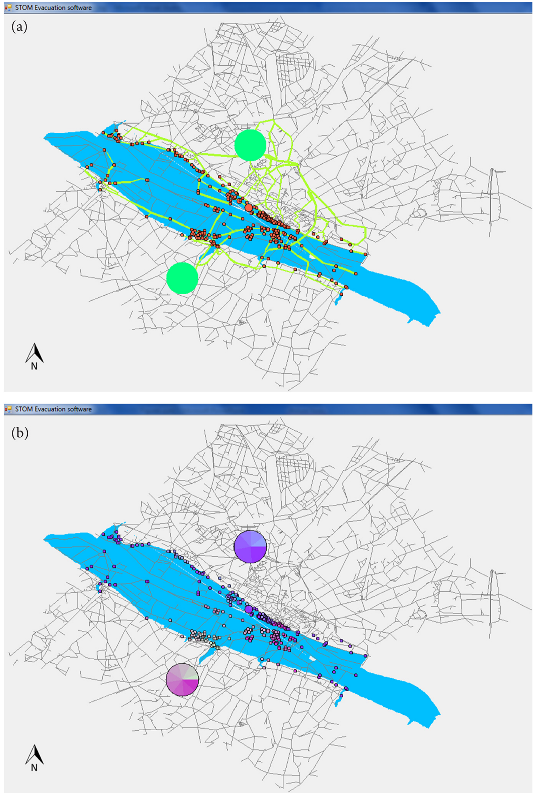


Figure 16. Construction of the evacuation plan: beginning of the flood. **(a)** The K-best evacuation paths among buildings and shelters, **(b)** evacuation of the valley of Gien.

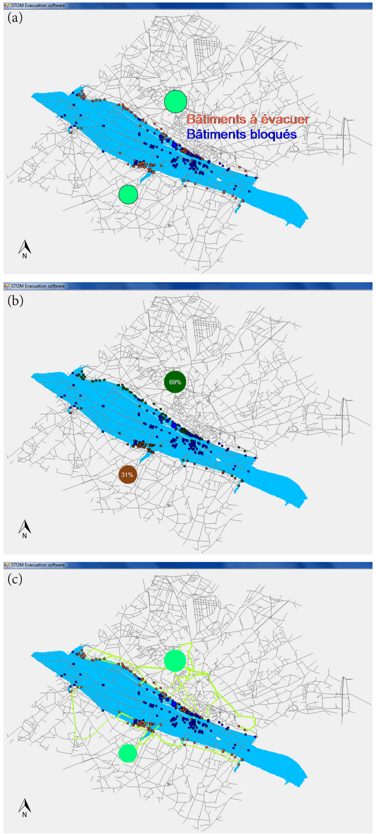


Figure 17. Construction of the evacuation plan: 125 h after the beginning of the flood. **(a)** Buildings to be evacuated (in red) and isolated buildings (in blue) 125 hours after the beginning of the flood, **(b)** assignment of buildings to assembly points, **(c)** the K-best evacuation paths among buildings and safety points.

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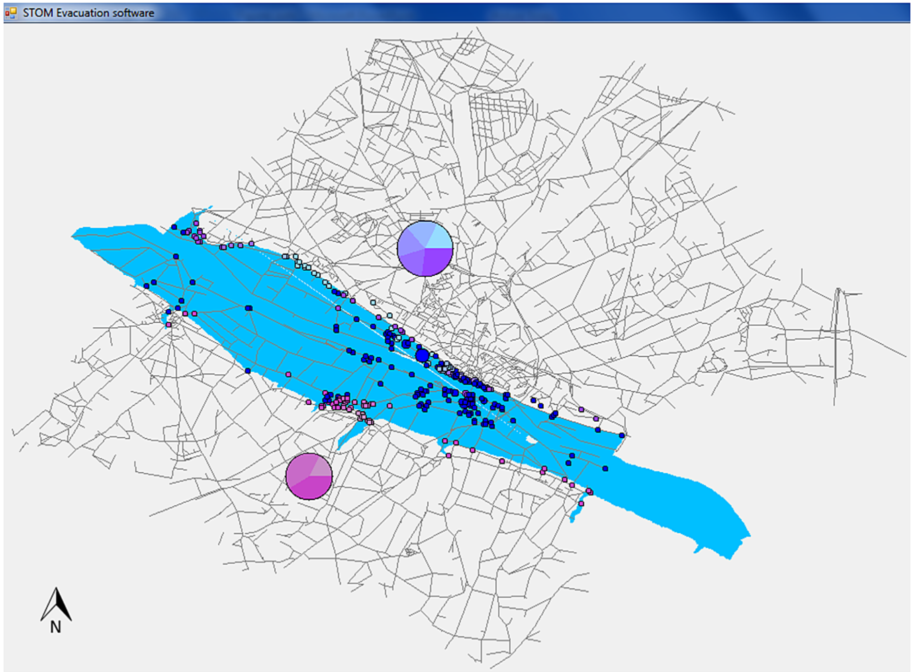

Figure 18. Construction of the evacuation plan: 125 h after the beginning of the flood, evacuation of the site of valley of Gien.

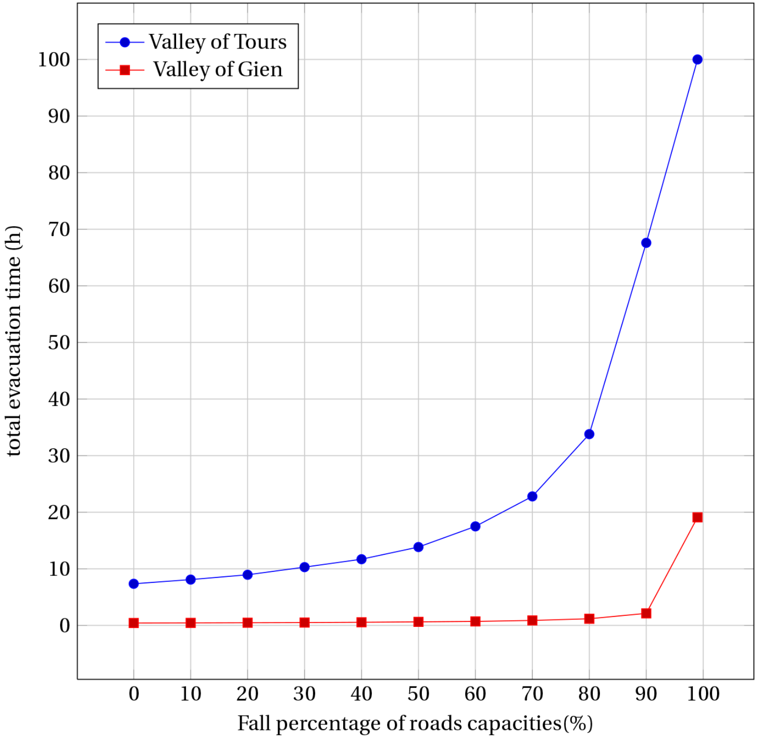

Figure 19. Evacuation scenarios in case of fall of network capacity.