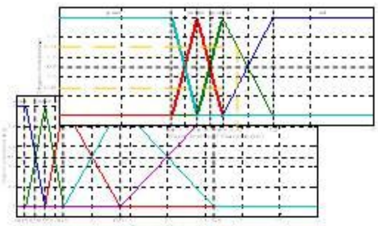
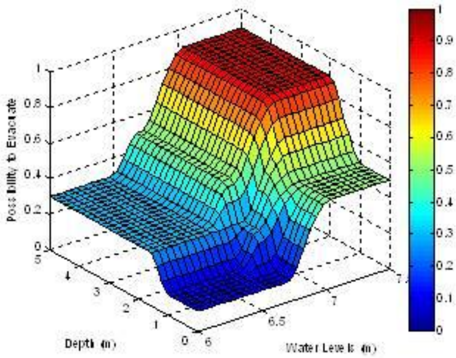
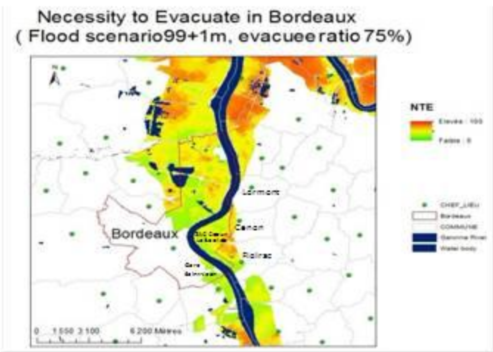
Par **Xiaojuan JIA**

Fuzzy logic based decision support system for mass evacuation of cities prone to coastal or river flood

Thèse présentée pour l'obtention du grade de Docteur de l'UTC







Type de décision	Nécessité d'évacuer (%)	
Pas d'évacuation	Très faible	(0, 15)
Vigilance évacuation	Faible	(15, 40)
Evacuation conseillée	Modérée	(40, 65)
Ordre d'évacuation ciblée	Forte	(65, 80)
Evacuation générale	Très forte	(80, 100)

Soutenue le 08 avril 2013
Spécialité : Mécanique avancée

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THESE

Pour l'obtention du grade de

Docteur de l'Université de Technologie de Compiègne

Discipline : Mécanique avancée

par

Xiaojuan JIA

Unité de recherches Avenues-GSU (EA 7284)

Thèse soutenue le 8 avril 2013 devant le jury composé :

G. HUBET	Professeur des Universités	Président
C. PRINS	Professeur des Universités	Rapporteur
D. SERRE	Enseignant chercheur, EIVP, HDR	Rapporteur
C. GUENON	Docteur, Ministère de l'Intérieur, Sécurité civile	Examinateur
J. GIROIRE	Professeur des Universités	Examinateur
F. HISSEL	Directeur Scientifique Adjoint, CETMEF	Examinateur
J.L. BATOZ	Professeur des Universités	Co-directeur de thèse
G. MOREL	Enseignant chercheur, UTC	Co-directeur de thèse

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RESUME

L’augmentation du risque d’inondation fluviale ou de submersion littorale est déjà visible à travers des événements récents comme la tempête Xynthia et les inondations du Var qui ont causé des dizaines de morts en France.

Ces événements dramatiques bien que d’ampleur limitée auraient justifié l’évacuation préventive des zones à fort risque, mais les conséquences pour la population seront bien plus importantes lorsque des agglomérations urbaines de plusieurs dizaines ou centaines de milliers d’habitants menaceront d’être partiellement ou totalement submergées par les flots. Cette possibilité est déjà d’actualité pour des grandes mégapoles mondiales comme Alexandrie et Bangkok, et menace en France des villes comme Tours, Paris ou Nice.

De plus en plus conscientes de cette éventualité, les grandes villes côtières, estuariennes et fluviales de France, d’Europe et sur tous les continents vont être amenées à préparer des plans de secours et d’évacuation de masse pour faire face à des événements exceptionnels. L’élaboration de ces plans s’avère extrêmement complexe et délicate aussi bien pour des raisons techniques, organisationnelles, sociologiques et même politiques.

La grande majorité des villes du monde soumises à un risque de catastrophe de grande ampleur ne disposent pas de ce type de plan et une recherche auprès de différentes sources montre qu’il existe peu ou pas d’outils opérationnels pour aider les responsables territoriaux à mettre en œuvre ces plans en phase de préparation et de gestion de crise.

Nos travaux visent plus précisément à contribuer à l’élaboration d’une méthode d’aide à la décision d’évacuation s’appuyant sur les plans d’évacuations réalisés en phase de préparation. Nous proposons pour cela d’adapter les outils de la logique floue à un ensemble d’indicateurs de synthèse sélectionnés à partir d’une méthode de planification des évacuations développée par ailleurs au sein du laboratoire Avenues-GSU. Ces indicateurs retenus intègrent des données classiques sur le niveau d’aléa (prévision globale et niveaux d’eau locaux), la vulnérabilité du territoire et des habitants, mais aussi et c’est plus innovant sur la capacité des autorités et de la population à évacuer dans un cadre sécurisé.

Le résultat final de cette méthode, appliquée à la dimension spatiale avec les logiciels MatLab et ArcGIS, est une carte de nécessité d’évacuation indiquant les zones les plus prioritaires à évacuer selon une analyse multicritères en logique floue. Elle a été expérimentée sur le site pilote de l’estuaire de la Gironde et la ville de Bordeaux, et les résultats théoriques comparés avec les inondations historiques de 1981 et 1999. On a également étudié un scénario prospectif tenant compte du changement climatique et des conséquences d'une élévation du niveau de la mer de 1m au cours du 21ème siècle.

Cette méthode et cet outil prototype devraient aider à termes les décideurs à mieux appréhender une situation complexe en phase de pré-alerte et à évaluer le besoin réel d'évacuation sur la base d'un ensemble limité mais représentatif d'indicateurs. La carte de nécessité d'évacuation représente une avancée qui prolonge et complète la cartographie officielle de la prévision inondation (vigicrue) et de ses conséquences en termes d'anticipation des impacts et de gestion de crise au niveau local.

Mots clés: Evacuation, inondation, aide à la décision, logique floue, Système d'information Géographique

ABSTRACT

The increasing risk of river flooding or coastal submersion is already visible through recent events like the storm Xynthia and the floods in the Var department, which caused several dozens of deaths in France.

These catastrophic events, even if their extent remains relatively limited, would have justified a preventive evacuation of high risk prone areas. However, the consequences for the population would be much more serious when large cities of hundreds of thousands of people will be partially or totally threatened by floods. This possibility is already an actual danger for large megacities like Bangkok and Alexandria, and also threatens French cities like Tours, Paris or Nice.

Being more and more aware of this possibility, big coastal, estuarine and river cities in France, in Europe and in all continents are incited to prepare emergency and mass evacuation plans in order to prevent and cope with exceptional events. The elaboration of these plans is extremely complex and difficult due to technical, organizational, sociological and even political aspects.

The great majority of cities in the world prone to large scale disasters do not already have this kind of plan at their disposal. Moreover, the existing state of the art shows that there are few operational tools to help territorial managers implement these plans in the phases of preparation and crisis management.

Our work aims to contribute to the development of a support method for the evacuation decision taken in a crisis management context. This method is partly based on the information included in the provisional evacuation plans produced in the preparation phase. To reach this objective, we propose to adapt the tools of the fuzzy logic approach and apply them to a set of synthesized indicators. These indicators or decision criteria have been first selected from a method of evacuation planning previously developed by the research team Avenues-GSU. These criteria integrate classic data on the hazard level (overall forecast level and local flood water levels), the vulnerability of the territory and population and, which is more innovative, some information about the ability of the organization to evacuate and the security or the risk of the evacuation itself.

The final result of this method, applied to the spatial dimension with the Matlab and ArcGIS software, is a map of the necessity to evacuate. This map shows the areas with the highest priority to be evacuated according to a fuzzy multicriteria analysis. It has been tested at the pilot site of the city of Bordeaux located upstream in the Gironde estuary, and the theoretical results were compared with historical floods of 1981 and 1999. A hypothetic flood scenario was also studied taking into account the potential climate change impact and the consequences of a 1 meter sea level rise during the 21st century.

This method and prototype tool should help policymakers to better understand a complex situation in pre-alert phase and assess the real need for urban zones evacuation on the basis of a limited but representative set of criteria. The maps of the necessity to evacuate represents an innovative proposal which extend and complement the existing official maps of flood forecasting (vigicrue) and its implications in terms of local impacts and crisis management anticipation.

Key words: evacuation, flooding, fuzzy logic, decision support, Geographic Information System

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Chapter I. General introduction

1. General context, stakes and background

Floods represent a major natural hazard in many countries in the world. They cause the greatest damage among all kinds of natural disasters all over the world and they affect the greatest number of people. According to the disaster data from the International Disaster Database (EM-DAT IDD), in the last decade (2002-2011), about 42% of natural disasters are caused by flood hazards (see Figure I-1), killing more than 50 000 people and affecting more than one billion people, and causing over 180 million US$ of damage (see Table I-1). Only in Europe, 213 flood events have occurred, killing about 1 000 people and resulting in more than 46 billion US$ damage (see Table I-1). While in France, according to the Ministère de l'Ecologie, de l'Energie, du Développement durable et de la Mer, there are 27 000 km^2 of flood-prone areas, where 5 million people are living (12 000 towns). In fact, as the major natural disaster (Figure I-2), flood events caused 75% of natural disaster damage in the period of 1970-2009 in France.

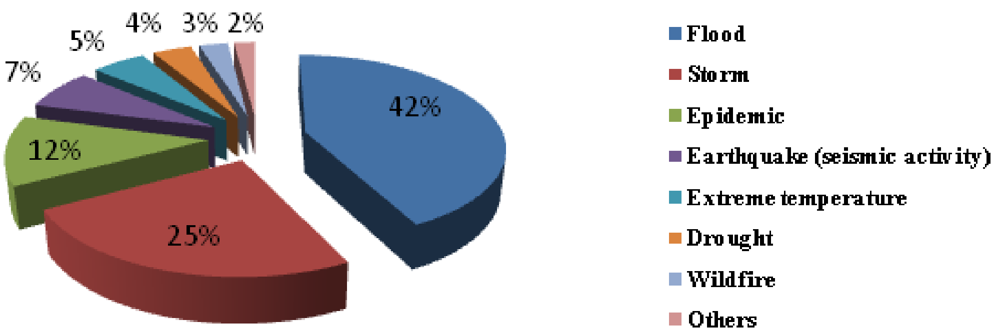


Figure I-1 Percentage of Natural disasters by occurrence times 2002-2011 (EM-DAT)

	Number of floods	Killed	Total affected(million)	Damage(billion US$)
Africa	407	5980	19.42	2.09
American	331	9391	26.82	26.83
Asia	639	36281	976.72	95.67
Europe	213	1002	2.74	46.27
Oceania	47	103	0.39	11.56
Total	1637	52757	1026.09	182.42

Table I-1 Summarized table of floods data by continent from 2002 to 2011 (EM-DAT)

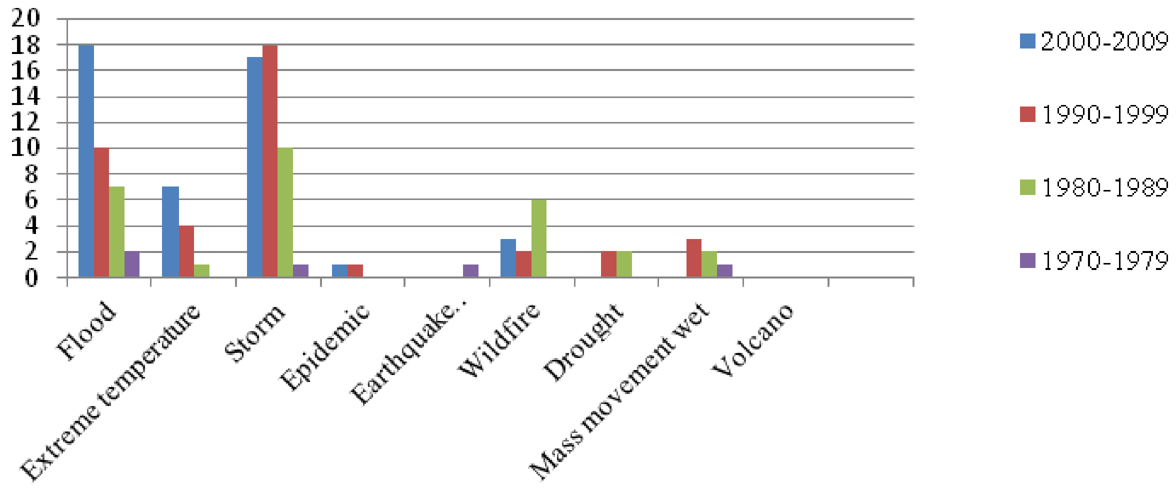


Figure I-2 Occurrence times of natural hazards in France 1970-2009 (EM-DAT)

Flood prone areas have been populated since ancient times because of fertilized land and transportation facilities. However, urbanization and climate change are increasingly worsening the natural disasters events and their consequences since the last century (Figure I-3). Extreme meteorological events occurred more often than ever. For example, the grim situation of the 2010 South China floods (Figure I-4) due to extreme heavy rainfalls made new damage records, and the persistent flooding is linked to unusual climate patterns, including an El Nino "Modoki'.

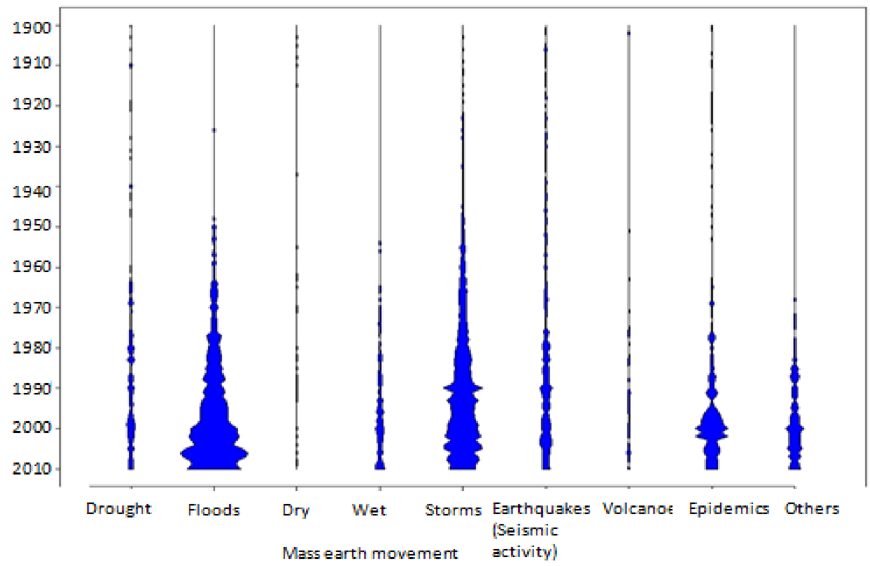


Figure I-3 Number of natural disaster reported 1900-2010 (EM-DAT: the OFDA/CRED - International Disaster Database-http://www.emdat.be/ - Université Catholique de LOUVAIN, Brussels-Belgium)

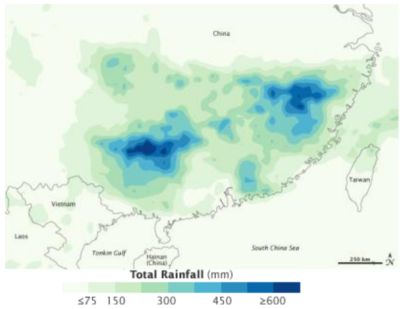


Figure I-4 Severe 2010 South China floods due to continuous heavy rainfall in southern China, June 15-21, 2010

Particularly, coastal areas are more often affected by severe storms than inland areas. In the context of climate change, the incidence of coastal flooding seems to be increasing with dramatic impacts requiring solutions (Jeroen et al. 2011). For example, flooding due to the storm Xynthia in France in 2010 (Figure I-5) has caused the most number of victims and important damage in France so far. Thailand severe flooding (Figure I-6) began at the end of July 2011, triggered by the landfall of Tropical Storm Nock-ten, and soon spread through 65 of Thailand’s 77 provinces, described as “the worst flooding yet in terms of the amount of water and people affected”.

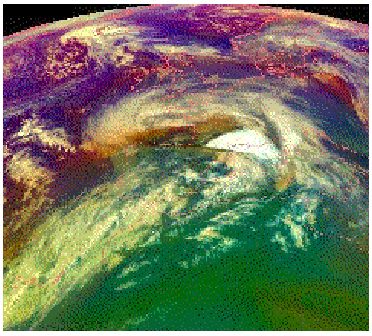


Figure I-5 Aerial view of flooded houses and streets due to storm Xynthia on the Atlantic seaboard between La Rochelle and L’Aiguillon-sur-Mer, western France, on March 1, 2010 (Frank Perry/AFP/Getty Images)

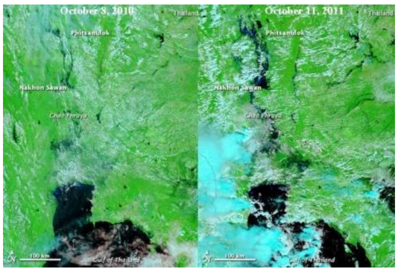


Figure I-6 Flooded areas in the outskirts of Bangkok on 22 October 2011(Source: Defense Video & Imagery Distribution System)

Flood disasters in coastal cities tend to be increasing because of the combination of climate changes, demographic growth and urban sprawl (IPCC 2007, the World Bank 2010, Jeroen et al. 2011). Moreover, the greater probability of extreme natural phenomena (sea level rise, flooding, storm surges, etc.), combined with high tides, increases the risk of loss of life, and significant economic losses during flood events in coastal cities.

To cope with the extreme events posing risk to life, health or well-being, preventive evacuations can be considered as an effective way to protect the potential victims by getting people at risk away from the dangerous area to safe places (Asselman & Jonkman 2003, Frieser 2004, Waarts & Vrouwenvelder 2004).

With a higher exposure to natural risks, some countries have a stronger risk awareness and management culture, and already have experience of mass evacuations. In the Netherlands, the severe winter floods in 1953 led to the evacuation of 72 000 people, and a massive evacuation of nearly 250 000 people was performed before the flood which occurred in 1995 (Bezuyen et al. 1998). In the United States, hurricane evacuations studies have accumulated much return of experience, particularly with recent events like the evacuation of the New Orleans (Hurricane Katrina, 1995) (Morel et al. 2011). In Japan, on March 11th, 2011, the Tohoku earthquake off the Pacific coast prompted the evacuation of 215 000 people (Morel et al. 2011). The most recent event causing a mass evacuation happened in New York City with 375 000 people evacuating low-lying areas on October 27th, 2012 (BBC news).

Compared with these countries, there have been few large-scale evacuations in France. Within the French institutional and legal frameworks for flood risk (PCS 2005), evacuation is so far generally not recommended and considered as a very last resort. Therefore, the preparation for such an eventuality is often lacking in crisis management plans, or is voluntarily avoided by the authorities, for it is difficult to tackle such a technically complex and politically sensitive problem.

Nevertheless, the major floods that occurred in a not-too-distant past (Paris in 1910, the Loire valley in the 19th century), the increasing catastrophic floods and storm tides over the last ten years (in the south of France and the Atlantic coast) and the perspective of the sea level rise suggest that some of France's large urban areas are likely to be severely impacted by major flooding (thus endangering the lives of thousands of inhabitants) in the coming decades. Therefore, this perspective should prompt national and local authorities to set up evacuation plans.

However, mass evacuation management is so complex that it requires the coordination of government agencies, local authorities and members of the civil society to ensure that clear instructions are given and followed by the population and to ensure an effective and safe evacuation. Therefore, a successful evacuation requires effective plans as well as suitable decisions taken during the crisis to save lives and reduce damage. Evacuation studies within the FP7 THESEUS project emphasize on supporting evacuation planning in the preparation phase through a rational guideline, a catalog of classified data and planning criteria (Morel et al. 2011). Nevertheless, this kind of planning approach is necessary but not sufficient to support the decision to evacuate in real-time, in the pre-alert phase of the event.

Furthermore, a mass organized evacuation is rarely used as one among many other emergency responses, because preventive evacuation is quite a drastic and risky measure that often affects many people. It can be costly in time, money, and credibility (Bezuyen et al. 1998, Friser 2004). Thus, it is necessary to decrease the occurrence of unnecessary evacuations in order to measure their relevance.

This objective requires the development of methods and tools to better understand the numerous factors involved in the evacuation decision making and to help decision makers to evaluate critical situations that can lead to a mass evacuation.

2. Definition, problematic and assumptions for evacuation decision support

2.1. Typology and nature of evacuation

According to the literature, different types of evacuation can be distinguished in terms of the moment of the disaster onset and the destinations of the evacuees (Quarantell et al. 1980, Sorensen et al. 2004, Kolen et al. 2012). The transfer of the evacuees outside the potential exposed areas is defined as horizontal evacuation. The movements to upper levels or safe places inside the potential exposed areas are considered as vertical evacuations (Kolen et al. 2012).

Before the arrival of the disaster:

- Preventive evacuation (horizontal evacuation): people move from an exposed area to a safe location outside of this area before the disaster occurs. Preventive evacuation can be organized in case of an event which benefits from an adequate forecast and warning and sufficient preparation time. Disasters due to hazards like floods, cyclones, and storm surges are generally preceded by a warning which ranges from several hours to several days, thus giving to the authorities and the population a time delay for an evacuation. This kind of evacuation can be considered as pre-warned and preventive evacuation (Wolshon et al. 2005a).
- Sheltering: people move to a location (shelter or refuge) inside the potentially exposed area. Shelters or refuges must be high and strong buildings or/and elevated and dry areas. This locations offer some kinds of protection.
- Sheltering in place (vertical evacuation): people move to higher levels (e.g. upper floors) of multistory buildings within the flooded areas (before the disaster impacts, or also after the onset of the disaster).

After the arrival of the disaster:

- Rescue: movement of victims with the help of safeguard services to get out of the endangered areas after being exposed.
- Escape: movement by victim themselves to get out of the danger after being exposed.

For our research purposes, only preventive evacuation is considered, in order to really ensure people’s safety, in case of large a scale flooding, particularly in coastal urban areas before the arrival of a submersion.

Evacuation management and activities can vary depending on the type and scale of the disaster. Flooding past events showed us some characteristics as follows: (1) the time allowance of forecast and warning: there are hours or days when flood hazards signs are perceived before a possible disaster occurs; (2) uncertainty of both impact time and location: it is hard to know exactly when and where it will happen. Yet, high risk locations can be anticipated thanks to forecast and simulations; (3) severe floods often affect a large area and a great number of people in urban endangered areas.

However, preventive evacuation in case of an immediate or forecasted threat of flooding can be a risky management strategy. It exposes people to risk of injuries, casualties and even the loss or stealing of goods or properties. Mass evacuation generally involves thousands of people moving from their house or business location to remote safe locations, out of the flood risk area, and the coming back of these people after the disaster also has to be organized.

2.2. The importance of experience in evacuation management

As for the recurring nature of floods, experience learned from historical events is precious and should be used for the next one. In the past decades, professional risk management methods and techniques have been developed for better managing flood disasters. Flood risk management mainly focuses on reducing the vulnerability within the social, economic and environmental setting. Flood risk management involves a wide range of actions and activities, generally in four stages (Lumbroso et al. 2008): prevention & mitigation, preparation, response and recovery. Flood risk management is hence a cyclic process which can benefit from return of experience after each crisis (see Figure I-7).

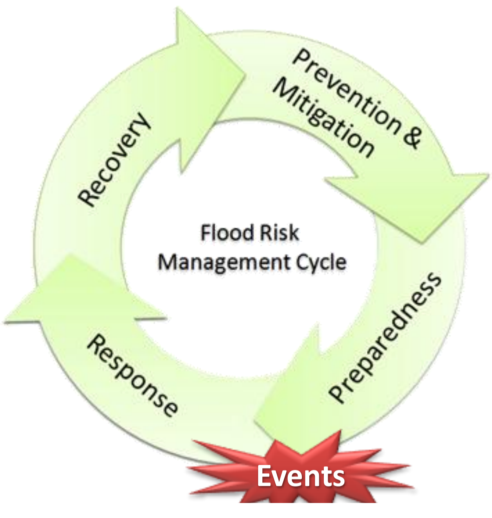


Figure I-7 Flood risk and crisis management cycle (adapted from Lumbroso et al. 2008)

As an integrated part of flood risk management, evacuation is considered as an important element of emergency response to protect the victims against the flood threat (Lumbroso et al. 2008). Evacuation decision making should be cautious and respect experience learned from past events.

Figure I-8 Steps of crisis management (adapted from Lumbroso et al. 2008)

Once an event occurs, the crisis management is unfolded, which involves every step of the procedure (see Figure I-8). In this way, each preparation and management action is tested in reality, and organizations like governments and civil protection authorities expand their experience and knowledge each time a disaster occurs. With the experience learned in reality, shortcomings and bottlenecks can be discovered and improved, so that experience learned from the latest disaster influences the management of the next one. Therefore, decision support methods for evacuation decision and management should incorporate and interpret the experience of experts and officials.

2.3. Evacuation process and decision making

A mass evacuation in an urban area is a very complex process taking place in the spatial and temporal dimensions. Despite the different definitions of the evacuation stages, the essential process includes 1) the vigilance, 2) the decision, 3) the warning and alert, 4) the evacuation itself, 5) the sheltering and 6) the return back home (Shaw et al. 2011, HR Wallingford 2006, Frieser 2004, Quarantell et al. 1980).

The evacuation process is initiated by receiving the forecast and warning of a possible disaster. Once a threat for the population is predicted, local authorities can decide to trigger an evacuation and first disseminate an evacuation alert. Then, individuals and groups of persons respond to the evacuation alert in order to leave dangerous areas towards shelters in safe locations out of the reach of the hazard. After the disaster has passed away, the evacuees must go back to their homes when all the conditions permit their come-back. Figure I-9 illustrates the sequence of the main phases of the evacuation process.

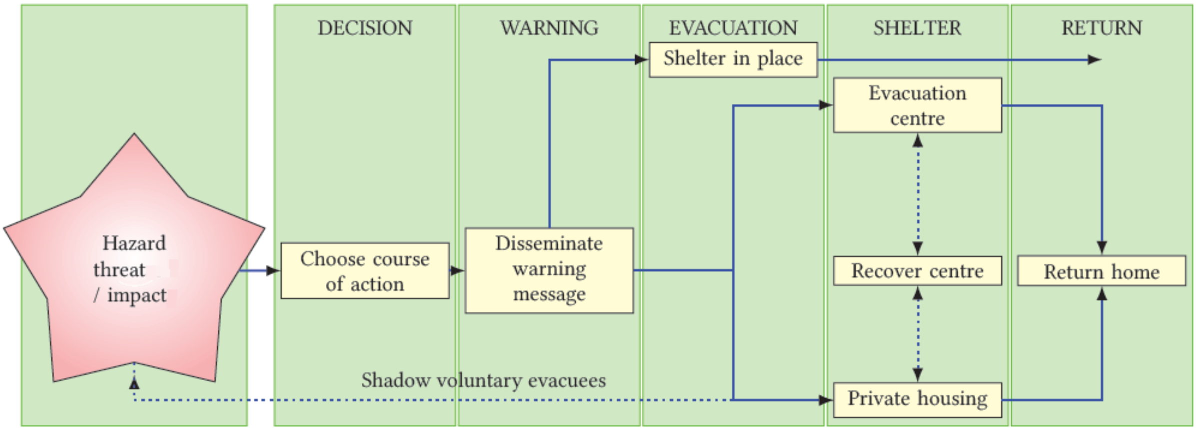


Figure I-9 The main steps of the evacuation process (Hissel 2011)

Actually, the evacuation decision making does not only depends on the hazard forecast but can be linked to the characteristics of the entire evacuation process, like the choice of evacuation areas, routes, shelters, etc. Moreover, the evacuation process involves different stakeholders and heterogeneous populations, and the final decision must take into account both the individuals' level and the officials/organizations' level.

In the case of a mass and preventive evacuation, the evacuation official decision is the first phase of the evacuation process, taken in the early crisis. The evacuation decision can be considered itself as a process to interpret and combine a set of various information, resulting into specific evacuation actions (e.g. no evacuation, advisory evacuation, evacuation order etc.). The aim of this evacuation decision process consists first to analyze specific event information and secondly to make an assessment on the necessity to evacuate or not areas at risk.

2.4. Evacuation decision difficulties

The highest priority given to forecast and early-warning is essential in a flood crisis management because the better authorities are informed, the better they can prepare. Thus, geographers, meteorologists, climate scientists, hydrologists, and decision-makers work together to improve the observation, analysis, and forecasting of floods, especially through the development of numerical simulation models.

Given the existence of a forecast and early warning system, and in order to ensure the safety of people in flood-prone areas, the central question is to determine what evacuation strategy is required in critical situations.

However, the single hazard forecast is not sufficient to take the decision to evacuate, because numerous and various other information must be included in the analyses of the situation and the decision process such as transportation ability, population characteristics, building sheltering ability etc. Hence, it is necessary for managers to have clear indicators and a framework to prepare for evacuation decision making.

The passed flood evacuations such as in the Netherlands in 1995, and hurricane evacuation studies in the United State (Frieser 2004, Kolen et al. 2010, Litman 2006) have underlined the importance of making timely evacuation decisions in advance of a catastrophic event. However, such events also remind us of the difficulties resulting from the multifaceted aspects of the problems that officials have to face in making the evacuation order:

- As natural disasters are often difficult to predict precisely enough, it is hard to decide which situation actually requires an evacuation. This is often the case with floods. Officials will be aware that water could rise to a certain level, but the uncertainty of the forecast might result into a situation quite different to the one expected. That's why the decision making process must integrate this uncertainty.
- If an evacuation is acted, authorities have no guarantee that everyone can actually reach secured zones, due to the reluctance to leave, the lack of resources, the too short delay…
- Since mass evacuation in dense urban areas is much difficult to achieve, an unwell-organized evacuation management might be catastrophic. Severe weather conditions during the evacuation might increase this risk.
- Decisions are often made within a social and political environment that seeks to balance needs and resources (Quarantell et al. 1980). Evacuation is one among many protective options available for dealing with floods but not the only one.
- The penalties for making the wrong decision can be severe in terms of lives lost economical costs, but also in public faith in the government which may compromise future emergency responses (Wolshon et al. 2005a).
- The hazardrisk levels constantly fluctuate during the event as do the uncertainty of evacuees' behavior itself (Shaw et al. 2011).

- From the technical perspective, because there are so many factors resulting from the emergency situation, (psychological, social-cultural, economical and political aspects), the information available to local officials is often incomplete or ambiguous, which increase the difficulty of decision making (Tiglioglu 2001).
- Last but not least, complicated and even potential conflicting information should be frequently dealt with in the decision process (Frieser 2004, Kailiponi 2010).

It becomes clear that these difficulties raise some challenges described below.

Firstly, factors to evaluate decision situations refer to environmental, social, economic and political criteria. It is thus a difficult challenge to define reasonable decisional thresholds and indicators for such various and numerous criteria.

Secondly, how to integrate those multiple criteria, when some of them are conflicting, into a comprehensive way is even a more complicated problem. The combination of the criteria is nevertheless necessary to suggest rational decision strategies (e.g. evacuation orders, recommended evacuation, no evacuation etc.).

Thirdly, uncertainty of information is unavoidable. Thus, uncertainty tolerance is required in decision making.

Finally, past experience and judgment relative to the severity of storms/floods can greatly help decision making. Therefore, fusing experience and expert knowledge is an essential component of decision-making.

2.5. Evacuation criteria and levers of action

In a previous work and in the framework of the FP7 EU THESEUS project, an operational methodology was developed to help local authorities to elaborate evacuation plans in case of submersion in the context of preparation crisis (Morel et al. 2011). This method proposes a task model with seven progressive steps, and the first six steps which aim to build the evacuation plans outside a crisis have been developed. In the logical continuation of this work, our study aims to propose an approach for the development of a method and a tool that implement the seventh and last step which aims to support the evacuation decision process in real-time and then implement these provisional plans during a real event.

In addition to the process modeling and explanation, the planning method includes a complete catalog of data needed to implement the plans, classified in six categories: forecast and hazard, buildings, networks, population, organization and actors, and finally real-time data (for the seventh task). To move on from crisis preparation to crisis management, it seemed interesting to extract a subset of decision criteria and data from this catalogue, which decision makers should take into account in the decision process of evacuation in real-time, when an alert is triggered. Our proposal aims to select and process these initial raw data in order to provide a support for the final evacuation decision.

3. Research objectives

Governments in different countries have some experience and guidelines for planning mass evacuations (US Army Corps of Engineers 1995, Emergency Management Australia 2005, Ministry of Civil Defense New Zealand 2008) and to address the factors associated with catastrophic events (e.g. the nature of the threat, the number of people to be evacuated, the time available for response). However, there remains big issues and major challenges to evaluate complex situations in the perspective of triggering an evacuation, due to numerous, various and uncertain information, sometimes conflicting, in the decision process.

In order to handle these incomplete and imprecise information in the multiple dimensions (geography, demography, roadway, time etc.), the general objectives of this thesis are to structure the decision problem and process for mass evacuation, to help decision makers better analyze event specific information (including the flood hazard and the evacuation event) and finally to assess the necessity to evacuate at the global and local level. The necessity to evacuate can be defined as a ratio or a qualitative level that indicates evacuation needs and preferences (the greater the value is locally, the more the area is a priority for evacuation). Through the proposed method, the value of the necessity to evacuate changes continuously in space and time with the changing input factors, thus avoiding sharp changes and discontinuity in decision making that could result from uncertainties. Decision support methods are expected to integrate empirical experience (learned from historical events) and expert knowledge, as well as to mitigate the impact of imprecise prediction and incomplete information on the final decision. Another objective is to provide a rational basis for prioritizing the decisions in flood evacuation management. Our proposal (see Chapter III and Chapter IV) is developed in the context of life-threatening floods involving multifaceted factors such as hazard forecast of a severe maritime storm and high tide, local danger level, land characteristics, evacuee characteristics and behaviors.

This dissertation is structured in five chapters. This Chapter I has introduced the context and the stakes of mass evacuation decision support and general research objectives. Chapter II gives an extensive literature review covering the general evacuation problem and specific evacuation decision approaches and methods. Chapter III presents the development of a fuzzy logic oriented method for modeling the decision making process under uncertainty. In addition, this method is combined with a GIS tool to provide necessity to evacuate (NTE) maps. Chapter IV describes the application and evaluation of the fuzzy logic method in the French city of Bordeaux prone to a submersion coming from the Gironde estuary and/or the river Garonne. With the NTE maps, different scenarios are analyzed and compared. Chapter V summarizes our proposal and results, and put forward some recommendations to improve them in future developments.

Chapter II. Literature review

1. Introduction

Evacuation as a critical response to a life-threatening situation due to natural (e.g. hurricane, flooding, etc.) or technical (e.g. nuclear accident, chemical accidents, etc.) incidents can mitigate the negative impacts of an incoming disaster on a community. Since a mass evacuation of population at risk in urban areas is a rather complex process, planning and preparedness ahead of a crisis are important to ensure an efficient and successful evacuation. As a crisis unfolds, decision makers become involved in the evacuation decision. Once an evacuation decision is taken, evacuation plans must be implemented and well managed. Therefore, the evacuation preparation and management can be divided into three main steps: 1) planning, 2) decision making and 3) implementation and management. In this chapter, we attempt to present a survey of various approaches, research studies and technologies mainly for the evacuation planning and decision making, whereas the implementation phase is only briefly mentioned.

At present, the following approaches and techniques are widely used to support evacuation planning and decision:

- Forecast and warning levels of hazard for analyzing potential risk;
- Hazard assessment model/methods for analyzing danger in a specific location;
- Evacuation models for estimating evacuation time;
- Optimization approaches for evacuation strategies, evacuation routes etc.
- Multicriteria decision analysis for evaluating evacuation alternatives;
- Geographical information system (GIS) for locating and visualizing evacuation routes, shelters, evacuation maps etc.

Since unnecessary evacuations are expensive, disruptive, and unpopular, it is important to make accurate evacuation decision analyses. However, decision makers face challenges to comprehensively assess decision circumstances taking into account multiple factors and uncertainties during a crisis. The researches on composite methods and models of evacuation decision-making to evaluate local situations associated with numerous information at the beginning of an incoming severe disaster have not been explored so far.

This chapter focuses on the literature on evacuation planning, modeling and decision making. Firstly, section 2 gives a survey of the existing methods/tools to support the evacuation planning and modeling. In section 3, it gains insight into evacuation decision making tasks, considerations and existing support methods and models. Section 4 briefly introduces the evacuation plans implementation and management in real-time. Section 5 points out the limits of the existing methods/models that support the evacuation decision. Section 6 introduces some applications of the fuzzy logic method for crisis management. Finally, section 7 summarizes the literature review.

2. Crisis preparation and evacuation planning

2.1. Objectives and components of evacuation planning

From the perspectives of disaster management and civil safety, governments and institutions across the world are increasingly engaged in evacuation planning to safeguard the populations from major disasters. These guidelines for evacuation planning and management have been written either for specific hazards like flood (European Community FP6 FLOODsite project, ERGO project), hurricane (USA hurricane evacuation studies) or for multi-risk purpose (Emergency Management Australia 2005, Ministry of Civil Defense Newzealand 2008).

In order to facilitate evacuation operations management, evacuation plans are designed and elaborated outside any crisis, in the preparation phase. Evacuation planning involves actions, strategies and resources that are needed during the evacuation process. It is a very complex process because numerous and various factors and stakeholders are involved both in space and time: transport means, human resources and organization, routes management, security etc. Different methods and tools have been reviewed to support an efficient evacuation planning (Wolshon et al. 2005a, Shaw et al. 2011, Lumbroso et al. 2008). However, evacuation planning lacks both a generic model and a consensus on specific parameters to be integrated as inputs.

As often struck by hurricanes, the United States began earlier studies and researches on evacuation planning. The US Army Corps of Engineers (1995) emphasize five major topics for hurricane evacuation studies including the analyses of hazards, vulnerability, population behavior, shelters, and transportation. More precisely, these analyses include technical data concerning areas to be evacuated, the number of people located in the threatened area, how the public respond to evacuation advisories, sheltering needs, and timing of evacuation for a range of hurricane threat situations.

In the FLOODsite project, the flood evacuation planning is classified into eight topics (Lumbroso et al. 2008) corresponding to stages in the crisis management: 1) organizing the planning for the stakeholders involved in the crisis management; 2) designing the plan for distributing tasks, available resources and activities in diverse evacuation scenarios; 3) identifying main evacuation routes, shelters and people behavior through analyzing the level of flood risk in certain situations in the pre-flood awareness stage; 4) evacuation decision analyses in the flood emergency stage; 5) communication in evacuation (leaving home) stage; 6) management of shelters and suppliers of materials 7) the return after the event; 8) debriefing the results of the evacuation in order to update and to improve the evacuation plans. According to these eight aspects, requirements of users involved in the crisis management are listed for evacuation planning. Several evacuation models (e.g. Evacuation Calculator, INDY, ESCAPE DSS etc.) have been developed to estimate the evacuation time and to support evacuation planning.

The evacuation studies in the USA and the FLOODsite project mainly focus on the identification of the evacuation components and the development of some methods and tools to support planning. The evacuation decision information is implicitly listed in the plans. However, it still lacks a method for evaluating the overall detailed information about the evacuation situation in real-time to support the evacuation decision.

The ERGO (the Evacuation Responsiveness by Government Organizations) project aims to examine and develop methods used by government organizations to prepare both themselves and their public for mass evacuations. The framework of evacuation planning focuses on six parts (Shaw et al. 2011): 1) preparing the public for mass evacuation; 2) understanding and defining the evacuation zone (e.g. car usage, number of people, building structures etc.) based on spatial data; 3) making the evacuation decision; 4) disseminating and evaluating the warning message; 5) evaluating transportation management policies and their consequences on the evacuation time; 6) shelters management. The evacuation decision is firstly systemically analyzed and quantified based on the managers' objectives. In order to optimize the multiple objectives, a cost-benefit approach has been proposed to reach the appropriate decision.

Evacuation studies led within the EU FP7 THESEUS project by the AVENUES-GSU research group (Morel et al. 2011, UTC-GSU 2011a) defined seven tasks for elaborating an evacuation plan in the preparation phase (see Figure II-1): 1) definition of forecast parameters and disaster scenarios; 2) characterization of the vulnerability of the territory and the population related to the hazard; 3) identification of action levers and other strategic data such as transport network capacities, the number and nature of the evacuees; 4) definition of evacuation strategy, which must specify the major choices and options in crisis management (e.g. the choice of transportation modes, vertical and/or horizontal evacuation, resource availability, etc.); 5) definition of evacuation scenarios and verification of the feasibility through specification of the implementation procedures and constraints related to the various hazard scenarios and the available levers of actions; 6) optimization of the scenarios and strategies by probing their sensitivity to the levers of action; 7) choose an evacuation plan and operate it in real-time. The first six tasks have been developed, which address the issues of elaborating the plans to prepare for the crisis. The seventh task refers to assessing the crisis situation and choosing and adapting the best plan for implementing in crisis management, which is just the topic of the study by this thesis.

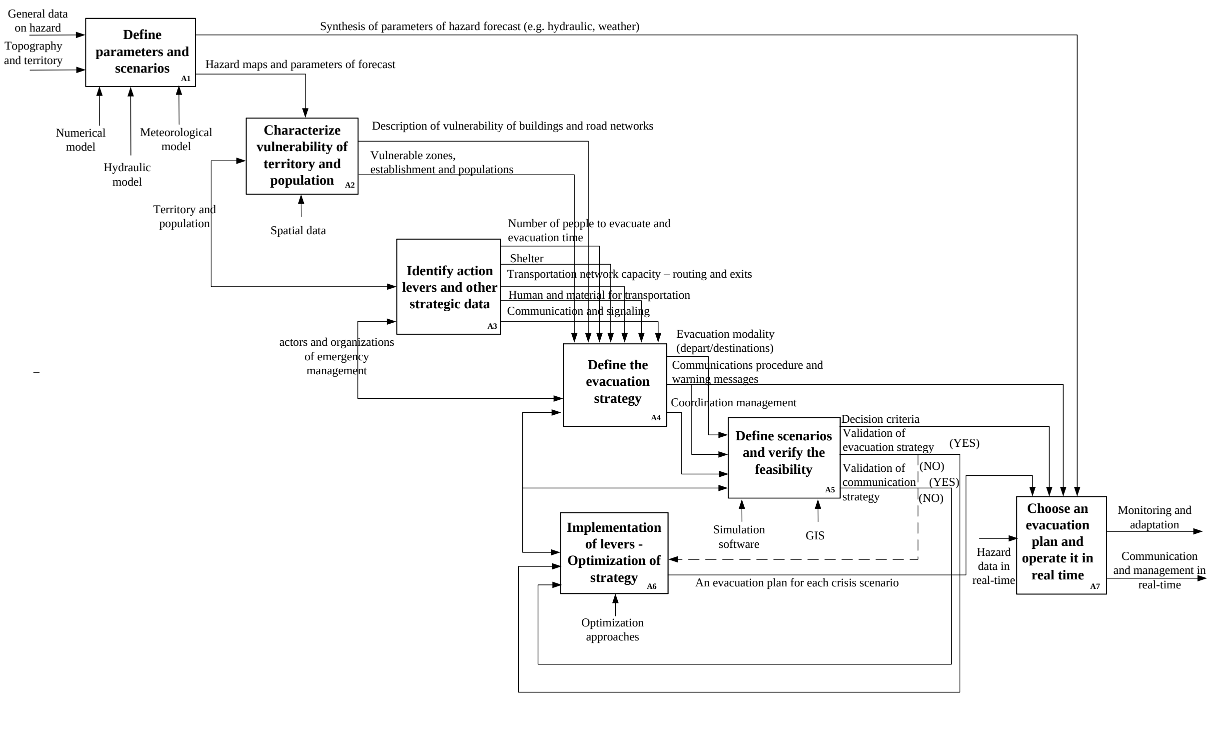


Figure II-1 SADT diagram for the function “prepare an evacuation plan” (Morel et al. 2011)

Generally speaking, our work focuses on the methods for evaluating the pre-crisis situation to transit from the forecast and other real-time data to the evacuation decision and then to management of one of the plan option that has been partially defined in advance thanks to the planning process.

2.2. Evacuation models and support tools for planning

In the literature and government references, the evacuation process is often conceptualized and computer modeled to form a variety of tools that support efficient evacuation planning. With the development of computer simulation and GIS, evacuation modeling techniques have significantly improved. Today, simulation programs or/and GISs can be used to model and simulate weather, flooding, traffic flow, evacuation movements and behaviors, and strategy optimization (evacuation strategies and traffic control strategies) (Wolshon et al. 2005a, de Silva et al. 2000, Chiu & Liu 2008).

According to the purpose of the models, evacuation modeling can be broadly classified into two types: disaster-specific models and evacuation support models. The disaster-specific models (hazard-oriented approach) analyze physical characteristics and impacts of disasters (e.g. the intensity of hazard, the severity of disaster etc.) in order to define the evacuation characteristics (evacuation areas, evacuation roads, shelter locations etc.). The evacuation support models (crisis-oriented approach) focus on either the analyses of evacuation communication or the estimation of the evacuation time in order to optimize traffic strategies and evacuation routes.

2.2.1. **Disaster-specific models as support for evacuation preparation**

Since evacuations must adapt to a specific incident or type of incident, they are dependent on the disaster context (Wolshon et al. 2005a). For example, in the context of a flood disaster, activities involving evacuations are dependent on the nature and impacts of the flood on the territory, the roads, the networks …. (HR Wallingford 2006).

Therefore, disaster-specific models focus on a specific type of disaster (e.g. floods, storms, hurricane etc.) and are used as a tool to predict the impact level of the disaster in space and time, as well as the potential areas to be evacuated. For example, the SLOSH model (Sea, Land and Overland Surges from Hurricanes) developed by the National Weather Service (NWS) in the USA estimates storm surge heights (Atkins 2011). In the preparation stage, SLOSH can generate surge-related flooding maps for different categories of storms, which are then used to support evacuation planning. In the earlier stage of a crisis, the SLOSH model is used to support hurricane evacuation decision making in real-time in coastal basins of the USA.

In the context of flood risk management, Table II-1 gives general categories of flood models and tools to support evacuation planning. The CRUE research report (HR Wallingford

2010) reviewed current available tools and technologies for the flood evacuation planning and management.

Category of models and tools	Example of evacuation planning support
Flood hazard mapping (Lumbroso & Vinet 2012): e.g. Environment Agency Flood Map, England and Wales LIZARD – flooding, the Netherlands	Flood hazard maps for determining potential evacuation areas (WL Delft Hydraulics 2007)
Risk to life: e.g. Life Safety Model, UK/Canada (Johnston 2012)	Evaluation of evacuation strategies (Jonkman et al. 2008)
Accessibility of roads (Morel et al. 2010b)	Evacuation route planning (UTC-GSU 2011a)
Vulnerability of critical infrastructure and buildings	Identification of evacuation facilities (UTC-GSU 2011a)

Table II-1 Flood disaster support tools for evacuation planning

In France, the software “OSIRIS-Inondation” is used to help Communes and security managers to prepare and manage flood safety plans (Plan Communal de Sauvegarde Inondation) (Morel et al. 2009). The software was developed by the Loire Département, in partnership with the Centre of Maritime and River Technical studies (CETMEF). It provides details of inundation depths on maps and the action required for a particular level of hazard which can be used for supporting the evacuation planning and preparation. It also acts as an emergency management tool by interpreting flood forecasts to flood scenarios.

2.2.2. **Evacuation support models**

The evacuation planning partly depends on a specific disaster, but the way to tackle the evacuation process as a crisis management activity is relatively common to different kinds of hazards (HR Wallingford 2006). Therefore, evacuation processes are modeled in different ways for developing and testing evacuation plans that can correspond to various situations and hazards. Research interests in evacuation models have been mainly performed in three fields: people behavior, engineering-related and disaster/emergency management (Wolshon et al. 2005a). Hence, the existing evacuation models can be categorized into three groups: evacuation behavior models, traffic-related models and time-line/critical paths management diagrams (HR Wallingford 2006).

2.2.2.1. ***Evacuation behavior models***

Evacuation as a behavioral topic in social science research emphasizes on what people do individually and together to respond to evacuation forecasted disaster and an evacuation alert, before, during, and after the evacuation phase itself.

At a local community level, the social processes produce different patterns of behavior in response to the main phase of the process and alert, such as warning, evacuation itself (withdrawal movement), sheltering, and return to home (Quarantell et al. 1980). Traditionally, major categories of behavioral researches include:

- Modeling warning dissemination process: once evacuation decision is made, it must be disseminated from decision makers to evacuees. The research on warning dissemination focuses on two broad aspects: warning messages and warning response. To effectively predict behaviors, how individual process warning messages is modeled taking into account the physical environment, the nature of danger, the psychology and sociology of population, technology, social relations, and culture (Aguirre 1994). These models reflect the nature of the information dissemination process. The outputs of these models are depicted as a warning response curve which shows the percentage of warned evacuees evolving with time (Shaw et al. 2011). This warning response curve is useful for estimating evacuation time, because people's response to evacuation warning influences the time when the individual evacuation begins. Evacuation time is actually a critical factor in the evacuation decision making, which will be discussed in section 3.

- Modeling evacuation behaviors (only referring to the evacuees' movement from affected areas to a safe destination): according to whether or not to evacuate by transportation, evacuation behavior can be sorted into pedestrians and vehicles. Based on the assumption of individual behaviors, a flood evacuation model simulates the number of families in the process of evacuation and calculates the time required for all evacuees to reach safe areas (Simonovic & Ahmad 2005). Since transportation plays a very important role in mass evacuation, traffic-related evacuation modeling attracts more interest in this literature review. These traffic-related models are discussed in section 2.2.2.2 from the perspective of the engineering rather than social sciences.

- Modeling sheltering behavior: Shaw et al. (2011) reviewed the literature on different aspects and analytical models of sheltering including demand estimation, shelter selection, allocation and management. As the location of shelters varies in the city, the spatial distribution will have an impact on evacuation times. Shelters are considered as the final destination of an evacuation, so that the choice of sheltering would impact the transportation aspects such as the means of transportation, vehicles per household, time of evacuee departures and role of information in evacuation routes choice (Dow & Cutter 2002). This highlights interaction and overlapping between different kinds of evacuation-related behaviors and researches.

On an individual level, evacuation behavior models conceptualize human behavior in response to an emergency situation. These models take into account multiple aspects of human factors that contribute to the evacuation time assessment based on empirical data in a mathematical way (e.g. such as age, awareness of the hazard, knowledge of the area at risk) (Baker 1991, Lazo et al. 2010, Elder et al. 2007). Traditionally, the research emphasizes on the warning response, but a growing literature focuses on the individual evacuation decision-making (Dash & Gladwin 2007). Simonovic & Ahmad (2005) modeled the decision making at the family level using a dynamic system approach based on empirical data acquired through surveys. Kusenbach et al. (2010) examined the vulnerability to a hurricane and the evacuation readiness among coastal mobile home residents for individual evacuation decision making. Dash & Gladwin (2007) provides more information on the individual and household evacuation decision and behavior responses.

These models also enable to put forward and propose improvements in the dissemination of evacuation warnings or changes in the location or number of shelters. It appears that more complex models of evacuation have been developed with multifaceted behaviors (Dash & Gladwin 2007).

2.2.2.2. ***Traffic-related models***

In the literature, traffic-related evacuation models look at the physical movement of people and vehicles from the hazard-prone zone (the origin) to the safe places (the destination). During an evacuation, it is widely acknowledged that a large number of vehicles have to be moved across a road network in a relatively short period of time, which becomes particularly significant in an urban area and with a high risk of creating big congestions. Learning from lessons of Hurricane Georges (1998) and Floyd (1999), massive evacuations may result in multistate traffic problems during events, for example, traffic delays at intersections (Cova & Johnson 2003), which can influence the evacuation safety (Wolshon et al. 2005a).

The question of the evacuees who travel by vehicles towards safe destinations is discussed in this section. Globally, evacuation traffic-based modeling simplifies the road network representation in a specific evacuation area as a network model made of segments (road sections) and nodes (the intersections of road sections). Evacuation movement is simplified as a flow with origin-destination in the network. The various and numerous approaches of traffic modeling and simulation can be classified as follows:

- Flow-based models: these models are mainly based on traffic flow using optimization approaches and all individual vehicles modeled as a homogeneous group which forms a traffic flow (Kwon & Pitt 2005, Chiu et al. 2007, Cova & Church 1997, Cova & Johnson 2003, Zhou et al. 2010). Optimization models seek to compute an optimal solution for a certain objective. Therefore, the evacuation traffic planning problem becomes the question of how to obtain the minimization cost (e.g. the shortest time or paths for evacuation route planning) between predefined origin-destination routes.
- Agent-based models: agent-based modeling decomposes a complex system into a number of constituent units called agents. In an agent-based evacuation model, individual vehicles are represented as agents with an autonomous behavior. They consider the autonomous decisions for selecting egress routes and each vehicle interacts with other vehicles on the road and the driving environment (Chen & Zhan 2008, Stepanov & Smith 2009, Chen et al. 2006, Pidd et al. 1996).
- Scenario-based simulation models: these models are used to evaluate given traffic networks under a certain or under different scenarios including management strategies (Cova & Johnson 2002) in order to identify bottlenecks and to estimate evacuation time (Lindell & Prater 2007a). Southworth (1991) reviewed and proposed a framework for regional evacuation modeling, which includes five steps: traffic generation, traffic departure times, destination selection, traffic route selection and implementation of traffic management controls. He summarized the necessary input data like the estimation about population, the number of vehicles or the determination of the traffic loading curve. In order to obtain more realistic simulations, the scenario-based simulation models have to integrate social processes (e.g. warning, behavior, etc.) likeEMBLEM2 (Lindell 2008).

Different extensive literature reviews of evacuation mathematics modeling methods were addressed by Hamacher & Tjandra (2002), Bretschneider's (2013) and Santos & Aguirre (2004).

In summary, all traffic-related models need a set of basic assumptions and data related to hazard scenarios, population-at-risk, behavioral and socioeconomic characteristics, the road network and traffic control strategies. They are used to assess road network capacities and identify critical links in the evacuation network. The outputs of these models are estimated evacuation time, bottlenecks identification and road closures. Based on these outputs, traffic operational strategies can be implemented and optimized as the core of the evacuation implementation strategy. Therefore, these models can help the authorities to better understand the issues of managing the traffic within the existing road infrastructure and to test the relative influence of some parameters as levers of action. The results of these models can also provide additional information and decision criteria about the capacity, difficulties and safety of an evacuation scenario, in order to help the authorities better understand evacuation situations.

The underlying principles related with each of these approaches influence the associated model capabilities (Wolshon et al. 2005b, Wilmot & Mei 2004). Hardy & Wunderlich (2007) reviewed more than thirty transportation modeling tools applied to evacuation planning in terms of geographic scope (macro, meso, and micro) and analytical complexity (see Figure II-2). Macro models deal with individual vehicles as a homogeneous group and a global flow on the network. Micro models represent individual vehicles behavior on individual lanes and each roadway segment. Meso models fall between macro and micro modeling approaches, which can represent larger geographic areas than micro models and allow for more precise results than macro model (Hardy & Wunderlich 2007). Meso models generally represent individual roadway links and vehicles on a network but not individual lanes on each roadway segment (Hardy & Wunderlich 2007).

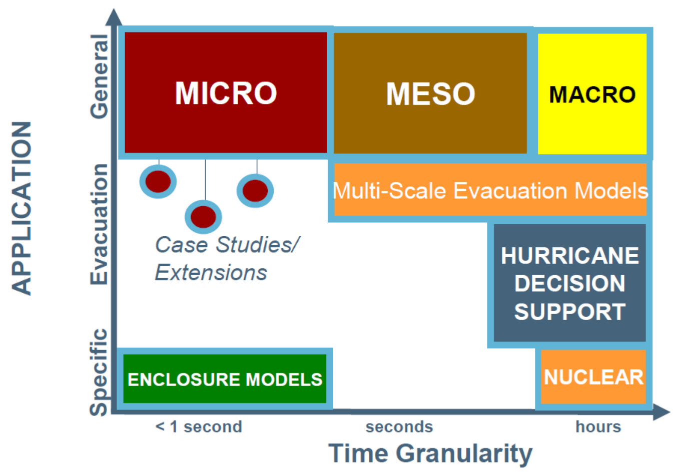


Figure II-2 Evacuation model specialization (adapted from Hardy & Wunderlich 2007)

Table II-2 shows some of the traffic-related models to support evacuation planning and simulation. More detailed information can be found in the studies by Hardy & Wunderlich (2007), Jafari et al. (2003), and HR Wallingford (2006).

Model name	Scale	Description
Integrated Dynamic traffic assignment model (INDY)	Meso	A flood evacuation model based on a dynamic assignment traffic model
Life Safety Model (LSM)	Micro	A flood evacuation model including traffic model and a loss of life model
Evacuation Calculator (EC)	Macro	A simplified flood evacuation model based on a static assignment traffic model
MASSVAC	Macro	A macro-level model using traffic flow relationships which can test operational strategies
HURREVA	Macro	A hurricane evacuation tool assisting decision makers before and during an evacuation, which can estimate conditions and analyze alternative strategies
EMBLEM2	Macro	A simple, rapid method for calculating evacuation time for real-time applications

Table II-2 Some traffic-related models (adapted from Mak 2008, Wolshon et al. 2005a, Lindell 2008)

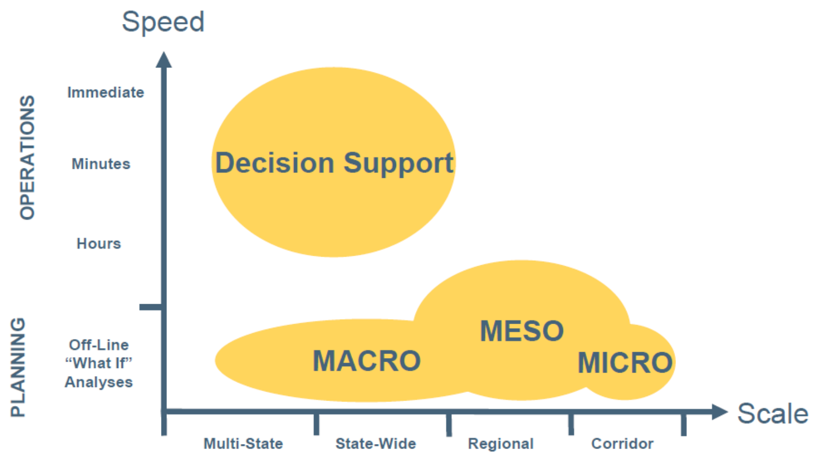


Figure II-3 Evacuation transportation model scale and speed continuum
(adapted from Hardy & Wunderlich 2007)

The precision and capability of decision support models and tools can be discussed in terms of trade-offs between the scale level and the computational speed (planning and operations) (see Figure II-3). Micro models represent more details, but they require both a massive amount of input data and computing power. It is also difficult to calibrate a micro model at the regional level because of the amount of data (Hardy & Wunderlich 2007). On the contrary, Macro models are able to incorporate real-time analysis aspects for a large geographic area. This highlights that macro models are becoming more prevalent as real-time decision support tools because of their capability of computing data and scenarios and providing information in real-time. However, macro models are difficult to use for designing very specific traffic control plans.

2.2.2.3. *Evacuation timeline/critical path models*

Given an emergency management topic (e.g. hurricanes, floods etc.), evacuation is also a (real-time) planning activity. The planning problem is generally conceptualized as a set of sequential and/or merged phases, and is often represented with time-line/critical path management diagrams/models (Lumbroso et al. 2008, Hissel 2011, Barendregt et al. 2005, Stepanov & Smith 2009). For example, Opper et al. (2010) propose that the start of the timeline can be defined as the first sign of flood, and the end of the evacuation time can be defined with the closure by the flooding of the last useable evacuation route. Some key elements of timeline can be such as warning, traffic movement etc. A timeline diagram/critical path tool is the simplest form, which shows the critical steps/stages of the emergency response to an evacuation. The resulting timeline can then be used to help the actors of the crisis management to organize their activities (e.g. What has to be done? When it has to be started? How long it might take during a specific flood scenario?)

Actually, behavior models, traffic models (discussed in the former sections), or timeline models are widely used as support tools in evacuation planning (Litman 2006, Goldblatt 2004). In recent decades, evacuation planning also benefits from the development of GIS (Geographical Information System) tools and techniques to produce numbers of maps like evacuation zones, evacuation routes, and to facilitate up-date data.

2.2.3. **GIS-based support for evacuation**

The literature shows that GISs play a major role in the development of support tools for emergency management (Cova 1999, Shaw et al. 2011). GISs are currently used for many purposes such as hazard/risk assessment and mapping, evacuation zone mapping, routing planning (e.g. evacuation route choice), shelters planning (e.g. shelter choice), etc. Leonard et al. (2009) and Shaw et al. (2011) discuss about spatial data used in evacuation planning to identify and to evaluate evacuation zones. Zepeda & Sol (2007) study how to elaborate the hazard zone from geographic information for the volcano evacuation planning. GISs are also used to model and visualize the vulnerability (geography, population, traffic bottleneck etc.) (Tang & Wannemacher 2005, Chakraborty et al. 2005).

In the past decades, a special effort for combining GIS and simulation models has been explored to support evacuation planning (Chiu & Liu 2008, Franzese & Liu 2008, Liu & Tuttle 2008). Actually, those two kinds of tools are complementary to cover the main needs of DSS (Decision Support System) for evacuation. The integration of the simulation data into GIS database introduces the time dimension and permits to analyze scenarios and data evolution in both space and time. The applications of GIS for evacuation planning enable to display the results of evacuation characteristics on maps, which is easier for decision makers to understand.

Some prototypes of spatial decision support systems were developed which combine a GIS (ARC/INFO) with an object-oriented micro/dynamic simulator system (Pidd et al. 1996, de Silva & Eglese 2000). Cova & Church (1997) evaluated evacuation difficulties (e.g. congestions) in a road network within a GIS context using a systematical method based on critical cluster model and heuristic algorithm. It appears that the integration of the three technologies of GIS, simulation models and 3D visualization for traffic impact analysis (Wang 2005) brings new perspectives for evacuation planning and decision-making.

2.3. From evacuation planning to decision making

In summary, evacuation planning helps authorities:

- Identify different phase of evacuation and relating works: what tasks and activities need to be carried out and what should be the priorities under different circumstances.
- Provide essential data, maps and models to describe the situation and to support the decision, such as hazard specifications, possible evacuation time, shelter choice, geographical information etc.

It should be noted that the estimated evacuation time is a major result of evacuation models and a key criterion to assess the feasibility of the evacuation process and to determine the final evacuation decision (evacuation or no evacuation).

In a word, evacuation planning is a decision basis, which includes plenty of disaster and evacuation data and decision information. However, decision makers face challenges to deal with the detailed data and information to get an overall evaluation of a crisis situation.

3. Evacuation decision making

In case of a crisis, evacuation is not always a relevant decision to protect the lives of residents. The situation is often complex and its assessment needs to take into account a lot of factors and uncertainties. Hence, decision to active a mass evacuation plan through assessing the crisis situation becomes a problem which challenges decision makers.

The literature deals with several points: decision criteria, decision process and uncertainty, decision modeling (Mileti et al. 1985, Lindell & Prater 2007a, Kailiponi 2010, Regnier 2008).

The issues related to evacuation decision making vary, and evacuation decision is often discussed as part of a more global disaster/crisis decision making system. Lumbroso et al. (2008) reviewed evacuation operations as part of the flood risk management practice in Europe. In France, the "Plan Communal de Sauvegarde" (PCS) guideline (2005) mentions some issues related to evacuation but not as a stand-alone and specific part.

The evacuation planning guideline by the Emergency Management in Australia (2005) points out the issues related to evacuation decision including the definition of authorities' roles and responsibilities, decision criteria, decision making times and evacuation warning dissemination. According to the evacuation return of experience in 1995 in the Netherlands, issues such as authorities and responsibilities, proceeding information, warning and evacuation process are questioned (Bezuyen et al. 1998). In our study, we concentrate on the evacuation decision making in the early crisis stage based on evaluating the actual situation.

3.1. Decision criteria

The evacuation decision criteria proposed by authors partly depend on the type of hazard events and the geographic location. In the case of the Hurricane Hugo in South Carolina, officials took an evacuation decision based on two main criteria: the local storm strength level and the time necessary to evacuate for that storm category (Baker 1990). More advanced procedures developed for the city of New York include key storm information, the status level of evacuation zones and shelters, real-time public response and critical interregional facilities status (see Figure II-4, Atkins 2011).

From the experiences of chemical incidents, three factors determining the level of protection (evacuation vs. shelter-in-place) were discussed: characteristics of the hazard related to chemical, characteristics of the building structures of the surroundings and the critical time related to evacuation (Sorensen et al. 2004).

In the case of the 1995 flood in Nijmegen region in the Netherlands, the decision of a massive evacuation of 230 000 people in the province was taken by decision makers referring to experts' experience facing high water levels of the river (Bezuyen et al. 1998). Three evacuation reasons were put forward: a life-threatening situation, no guarantee of dike safety and the good management of the evacuation at the beginning.

In flood evacuation studies, Lumbroso et al. (2008) indicates that the required information for evacuation decision includes: likelihood of the occurrence of a flooding event, possible size and extent of the flood event, elements at risk, possible number of casualties, the time required for the evacuation, the current and future state of the road network and the time left before the flood occurs.

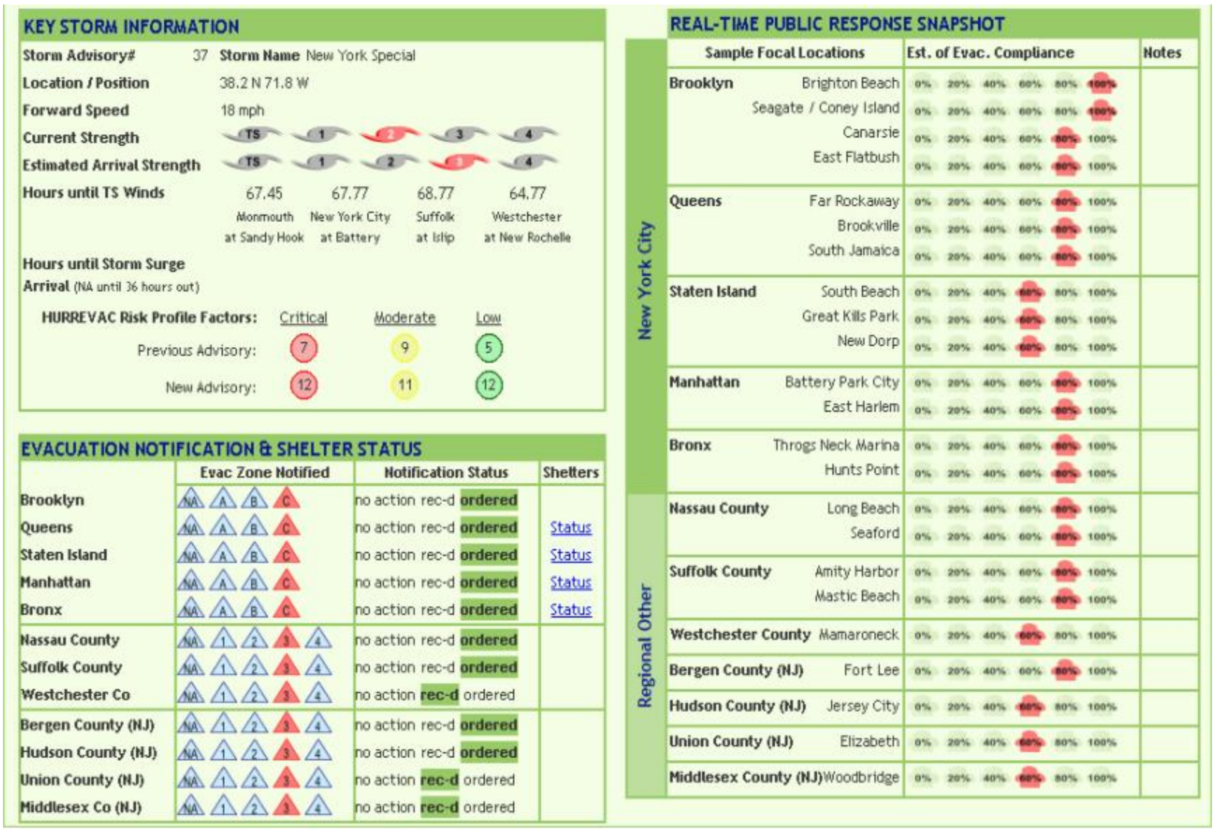


Figure II-4 Evacuation bulletin (Atkins 2011)

Apart from the emphasis on technical and physical criteria about the situation (e.g. hazardous events and evacuation safety), Quarantell et al. (1980) addressed the social, political, economical and cultural factors from the perspective of social science.

However, the most typical factors considered by existing evacuation decision methods and models are developed in the next sections.

3.1.1. **Hazard forecast and alert.**

First of all, an early disaster warning system (e.g. flood, hurricane) plays a key role for deciding an evacuation. Obviously, the basis for a warning system is an effective forecasting system, which permits the early identification and quantification of an imminent disastrous event to which a population is exposed.

Numerous studies have been done to estimate the flood impact and damages according to the flood forecasted water levels of the river and the risk of dike breaching (Kailiponi 2010, Frieser 2004). In the USA, to estimate the local impact of a hurricane and decide an evacuation, local decision makers benefit from the consistency and validity of the hurricane forecasts provided by the National Hurricane Center (NHC). The hurricane forecast includes values about track and intensity, probabilistic wind-speed, which are helpful for the hurricane evacuation decisions in coastal cities (Baker 1990, Atkins 2011).

Secondly, the arrival time of the forecasted hazard is also used to determine evacuation decision. For example, Barendregt et al. (2005) tried to determine critical times related to the evacuation decision-making. They estimate that 6 hours are needed for the total decision time using experts experience approach. In New York City, the hurricane evacuation decision time is provided by taking the forecasted storm arrival time and subtracting the estimated evacuation time (Atkins 2011).

Furthermore, the recent research on evacuation decision time takes into account the probability of the hazard, which measures the forecast precision related to the occurrence of the events through historic analyses (Regnier 2008, Frieser 2004). The specific issued of uncertainty during the evacuation decision is discussed in section 3.1.5.

Therefore, forecast data provide the essential information to detect a particular event or situation constituting a threat and justifying an evacuation decision. For example, evacuation decision starts with some signs like rainfall or rising river levels which trigger a flood crisis. Forecast data also provide critical times for determining the decision points by taking into account the hazard arrival time and the forecast precision over time.

3.1.2. **Hazard/risk assessment**

Once a forecast of emergency is detected, it then becomes necessary to estimate what can be the potential impact like the loss of lives in a locality or a region. The procedure of hazard/risk assessment can provide a risk profile that includes both actual data and subjective threat assessment, thus allowing decision makers to be better informed of relative risks and to track trends from the forecast and warning advisory.

Generally, hazard/risk analyses help characterize evacuation needs (e.g. evacuation boundary, population to evacuate etc.). Thus, the hazard/risk maps are often used to support evacuation zones mapping. For example, flood evacuation zones are determined based on flood water depth to elaborate evacuation zone maps. On this spatial basis, some interesting features of potential evacuation zones such as evacuation sectors, shelters, departure spots, evacuation routes etc. are then added on the maps (WL Delft Hydraulics 2007, Shaw et al. 2011). The hurricane evacuation zones maps are identified by storm category (Atkins 2011). Actually, the evacuation zone maps often consider only parameters about the hazard event (e.g. flood water depth, storm categories).

On the contrary, Jonkman et al. (2008) proposed a model for risk to life also taking into account the evacuation consequences. This model estimates the rate of life loss before and after an evacuation in order to assess the evacuation effectiveness.

The risk profile and representation is often simplified in a set of 3 or 4 categories, like for the hurricane risk profile criterion-forecast peak wind which is classified into three color-coded degree (Red, Yellow, Green) (Atkins 2011). This kind of representation is also very useful for local communities and decision makers (Tsamalashvili 2010), but it does not include enough information for the evacuation decision.

As we concentrate on flood evacuation decision making, some support tools have been discussed in the planning part in section 2.2.1. As aforementioned, some studies on the hazard/risk assessment linking evacuation planning and decisions have been explored. However, more systematic methods need to be developed for combining the different information needed for evaluating the areas to be evacuated.

3.1.3. **Evacuation time**

Time and potential risks are both key factors of the evacuation decision and achievement (Hamacher & Tjandra 2002). Thus, besides the nature and level of the hazard, a useful and important data is the estimated evacuation time for the people living in the affected area (Bretschneider 2013). With the value of the estimated evacuation time and the prediction of when a disaster will strike a certain area, decision makers have key information to determine when the evacuation must begin for a hopeful achievement (Baker 1990).

In a broad sense, evacuation time can be defined as the time needed to complete an evacuation process (Hamacher & Tjandra 2002) and it includes several components: decision time, initial warning time, individual’s evacuation preparation time and movement time (Barendregt et al. 2005, Stepanov & Smith 2009, Opper et al. 2010).

In a more restrictive sense, evacuation time refers to the transfer duration (the time it takes evacuating people and vehicles from the affected areas to the safe places). Throughout this thesis, we will call the “movement or transfer time” “evacuation time”. The evaluation of the evacuation time for risk-prone communities requires complex analysis of necessary information and the development of sophisticated models. Significant progress of the evacuation modeling has been made over the last decades (different evacuation models have been discussed in section 2.2).

The estimation of the evacuation time requires accurate assumptions about the behavior of the risk-prone population, but social scientists’ research on population’s behavior has been poorly integrated in the development of evacuation models by transport engineers (Lindell & Prater 2007b). Lindell (2008) proposed the model and simulator EMBLEM2 integrating behavior assumptions based on empirical data to estimate evacuation time.

In the evacuation decision process, evacuation time is often compared with the forecasted disaster arrival time to determine the decision points (Baker 1990, Regnier 2008).

In conclusion, we can say that the evacuation time is an often used decision criterion, which well represents and synthesize the evacuation implementation characteristics.

3.1.4. **Evacuation costs**

A few studies focus on evacuation costs and mainly from the economic perspective in the past decades. Evacuation costs have not been systematically assessed or quantified even in a specific disaster context (e.g. flood, hurricane).

Johnson (2009) proposed a flood evacuation cost function including parameters like the probability of the number of people to evacuate, the direct and indirect costs that households, businesses, agriculture and the public sector incur as a result. Whitehead (2003) estimated household evacuation costs for coastal counties of North Carolina, ranging from about $1 to $50 million which depends on the storm intensity and the emergency management policy. In Frieser’s (2004) probabilistic model for evacuation decision, the evacuation cost was calculated taking into account five aspects: initial evacuation costs, economic damage due to business interruption, indirect damage, economic valuation of loss of life and loss of moveable goods. Regnier (2008) discussed the costs of warning credibility, which indicates the public trust in government in the case of the crisis.

These studies initially explore the evacuation costs for evacuation decision making. However, there is very few data available in the current disaster management context (Lindell

& Prater 2007a). The most comprehensive research to date has concluded that evacuation costs are very difficult to estimate, not well reported and difficult to quantify (Lumbroso et al. 2008).

In the evacuation decision process, evacuation economic costs are generally compared with damages caused by the disasters to obtain decision points in a cost-benefit approach (e.g. if economic costs are superior to damages – no evacuation; if economic costs are inferior to damages - evacuation) (Frieser 2004). However, two difficulties are put forward: 1) the economic valuation of loss of life in the trade-off process (Meyer et al. 2007); 2) decision points depend on the comparative value (e.g. the comparative result between economic costs and damages) but not the values to evaluate the actual situation.

3.1.5. **Decision uncertainties**

Evacuation decision must be made on the basis of imperfect and uncertain information, especially on disaster forecast, risk assessment, and population behavior. Thus, the decision to evacuate is subject to a set of significant uncertainties, in particular at the local level (Sorensen & Mileti 1987). Mileti et al. (1985) reviewed four broad uncertainties (interpretation of the impending event, communications, perceived impact of decision and exogenous influences) in the evacuation decision process over 40 historical accounts and documented findings at all levels of management. In the context of this research, the uncertainties are discussed within three main categories of data: forecast, hazard/risk assessment and evacuation-related behavior.

An evacuation decision emerges because of the detection of a possible disaster through a forecast setting a threat to the population. However, accounting for the forecast uncertainty and incorporating it into the decision process is the difficult part of decision making (Baker 1991). Several researches have been led to quantify the uncertainty in forecasts and help the decision maker identify the appropriate decision time.

Frieser (2004) quantified the uncertainty in the water level prediction for the evacuation decision, using a probabilistic decision model to determine an optimal decision (evacuation, no evacuation) for each point in time. Regnier (2008) explored the decision making point according to the different probabilities of the predicted track of an Atlantic hurricane using a Markov model. It concluded that reducing decision making time from 72 to 48 hours before a hurricane event for major urban centers could save an average of hundreds of millions of dollars in evacuation costs annually. Kailiponi (2010) identifies the uncertainty in predicted levels of rising water when evacuation actions should be taken by emergency managers in a storm surge scenario, using a multi-attribute utility theory (MAUT). In France, Goutx et al. (2011) explicitly analyzed the forecast uncertainty in predicted rising water levels and in dike breaching in the Loire valley and simply reviewed the risk of evacuation decision based on this uncertainty. These studies illustrate how different levels in forecast uncertainty affect the optimal evacuation decision over time.

Once the global magnitude and characteristics of the threat triggers a crisis, a more accurate analysis must be made to evaluate the local impact of the disaster in all risk-prone areas. The natural hazard assessments are always subject to uncertainties due to missing knowledge and the complexity of the physical processes as well as their natural variability (Kunz et al. 2011). Therefore, the importance of the uncertainty interpretation while forecasting the local level of danger and in the perspective of an evacuation is underlined in most researches (Mileti 1985, Sorensen & Mileti 1987). As aforementioned in section 3.1.2, the levels of threat as well as the thresholds for triggering an evacuation alert are often partly assessed or defined in a subjective way largely depending on expert experiences.

In evacuation decision making, population behavior which plays a major role in the success of the operation also presents significant uncertainty. Lindell & Prater (2007a) defined the uncertainty about evacuee behavior with a list of 22 parameters. They incorporated these evacuation behavioral uncertainties as well as the hurricane forecast uncertainty into the decision process by using a decision analysis approach in order to elaborate a decision tree.

Some of the constraints (e.g. time) that have been identified in this research could be addressed through planning. Therefore, crisis and evacuation planning can play some role in reducing uncertainties (Sorensen & Mileti 1987). The existing studies have primarily sought to identify the forecast uncertainty over time that first contributes to evacuation decision making. The subjective factors of uncertainty are clearly less discussed and more difficult to model. Therefore, it requires a method integrating subjective uncertainty in the evacuation decision process.

3.2. Decision criteria assessment methods

As discussed in section 3.1, criteria for evacuation decision making can be classified in four main categories:

- Hazard forecast: a global forecast of the intensity level of the incoming disaster (are we going to be hit by a hazard?)
- Hazard impact assessments: evaluation of the hazard intensity and impact locally on the territory and people and evacuation scenarios (how bad is it going to get?)
- Evacuation characteristics: evacuation capacity (time, resources, costs …), safety and consequences (can everybody get out in time?)
- Uncertainties: they concern all aspects and phases of the evacuation process (hazard, decision, implementation …).

These criteria have been analyzed with different details in evacuation planning methods (UTC-GSU 2011a). However, decision makers have limited knowledge of the overall situation and the evacuation plan when a crisis occurs (Quarantell et al. 1980). So authorities face challenges to incorporate the numerous and various information from these criteria in the real-time evacuation decision making process. Therefore, criteria assessment methods/models should be used to support decision making of evacuation in the pre-alert or alert phase of a crisis (Lumbroso et al. 2008). Different qualitative and quantitative methods can be found in the literature.

3.2.1. **Qualitative methods**

Several types of qualitative methods have been experimented to evaluate crisis situations through making an inventory of decision criteria for the crisis management, such as checklists, decision matrices, decision trees or decision tables (Sorensen et al. 2004).

Checklists list attributes of decision criteria and allow evaluating these attributes one by one. For example, Sorensen et al. (2004) formulated an evacuation/sheltering decision checklist for chemical accidents. It includes three columns with various decision attributes (first column) and the attribute values that favor either on-the-spot shelters (second column) or horizontal evacuation (third column). For example, the attribute "time of day" corresponds to the value "night" which favors shelters, or "day" which favors evacuation. The decision for each attribute is clear-cut in a checklist, but it lacks an integrated evaluation result for the final decision. This kind of approach seems limited to take into account the complexity of the actual situation.

Decision matrices frame the decision outcomes with 2 or 3 key attributes. For example, the evacuation guideline plan of Taiwan classifies five levels of urgency to evacuate corresponding to the combination of three decision attributes (river water, precipitation, sluices for flood) (Kang et al. 2005). The decision matrices simplify the decision attributes analysis by proposing a set of limited decision values from the combination of 2 or 3 criteria.

Decision trees are also used to structure the decision problem with a series of yes/no questions which leads decision makers to go down the branches of the tree towards a final decision outcome (Lindell & Prater 2007a, Frieser 2004, Sorensen et al. 2004, Cova et al. 2009). The evacuation decision trees generally simplify the decision possible outcomes: evacuation, no evacuation, or delay decision (Lindell & Prater 2007a, Frieser 2004, Sorensen et al. 2004). Sorensen et al. (2004) concluded that even if an evacuation deals with complex decision criteria, our current theoretical understanding of the decision does not allow complex decision trees. In addition, even with more complex trees, it remains the problem of lacking empirical foundations to apply the decision logic (Lindell & Prater 2007a, Sorensen et al. 2004).

Decision tables list sets of criteria by questions in groups which lead to a decision outcome (Atkins 2011). For example, the hurricane evacuation decision support system of New York lists two main categories of decision criteria on a risk profile for the evacuation decision (Atkins 2011). Each criterion of a risk profile is identified by three levels (Red, Yellow, or Green) according criteria attributes values based on experts' experience (see Figure II-5). These profiles summarize the catalogue of decision criteria and provide a graphical depiction of the hazard level, the evacuation status and their changes within each criteria area. The tool allows decision makers to track trends in emerging risk as a storm approaches. However, there is no rule or algorithm to analyze and process a combination of these data and make a global assessment of the situation.

In examining the qualitative methods for evacuation decision, except decision matrices, it appears that these methods are relatively easy to use and a decision for each criterion is clear-cut, but on the contrary the combination of all information on decision criteria is not made to result in a final decision that can be justified.

Hurricane Risk Profile (State) for New York		
1. Greatest rainfall forecasted for NY/Northern NJ county in next 72 hours? Ex.: Data not available for advisory > 24 hours old	Red = Yellow = Green =	Greater than 6 inches 3 to 6 inches Less than 3 inches (or NA)
2. What is the highest astronomical tide predicted within the 24-hour period prior to closest approach? Ex.: Lower than average	Red = Yellow = Green =	Higher than average (spring tide) Near average Lower than average (neap tide)
3. Timing of storm's closest approach with diurnal tide cycle at gage closest to forecast track? Ex.: SANDY HOOK: 0 hrs to high tide of 4.17 ft, +6 hrs to low tide of .15 ft	Red = Yellow = Green =	Near high tide Near mid tide Near low tide
4. Has the radius of maximum hurricane force winds expanded from previous advisories? Ex.: No expansion or decrease	Red = Yellow = Green =	Expanding over previous two advisories Expanding since the last advisory No expansion or decrease
Hurricane Risk Profile (Local) for NYC Metro County NY		
1. Amount of rainfall forecasted for this county in the next 72 hours? Ex.: Data not available for advisory > 24 hours old	Red = Yellow = Green =	Greater than 6 inches 3 to 6 inches Less than 3 inches (or NA)
2. Are tides higher than normal within the 24-hour period prior to closest approach? Ex.: Lower than average	Red = Yellow = Green =	Higher than average (spring tide) Near average Lower than average (neap tide)
3. Timing of storm's closest approach with diurnal tide cycle at gage closest to county? Ex.: SANDY HOOK: 0 hrs to high tide of 4.17 ft, +6 hrs to low tide of .15 ft	Red = Yellow = Green =	Near high tide Near mid tide Near low tide
4. Has the radius of maximum hurricane force winds expanded from previous advisories? Ex.: No expansion or decrease	Red = Yellow = Green =	Expanding over previous two advisories Expanding since the last advisory No expansion or decrease

Figure II-5 Example of decision tables of risk profile for the evacuation decision (Atkins 2011)

Furthermore, in order to structure the complex relationships between decision criteria, influence/flow diagrams are used to analytically model evacuation decision problem in details (Sorensen et al. 2004, Kailiponi 2010). These detailed conceptual models require computer simulations based on sets of assumptions because the problem is too complex or have too many dimensions to be analyzed with simple methods like matrix or decision trees. This kind of advanced model is discussed in the next section.

3.2.2. **Quantitative methods**

Several studies have been done to structure multiple evacuation scenarios and to optimize the decision using different simulation methods given the forecast uncertainty and preferences for multiple, complex and conflicting criteria (Regnier 2008, Kailiponi 2010, Frieser 2004). The optimal decision generally aims to minimize life loss and/or evacuation economic costs.

Frieser (2004) proposed a probabilistic evacuation decision model incorporating the cost of evacuation, the potential flood damage, and the probability of water levels. This model determines a rational decision (evacuation, no evacuation) for any point in time during the event and by comparing the monetary value of life loss and evacuation costs. It takes into account the stochastic uncertainty in predicted water levels of the river.

Regnier (2008) defined a framework for quantifying hurricane uncertainty in decision-relevant terms, as a function of decision making time corresponding to the forecast precision (24h, 48h, and 72h) and geographic location (four Atlantic coastal cities). The trade-off between risks to life and costly false alarms is analyzed under this quantitative frame. The uncertainty of the hurricane track taken into account in the decision making time can be used to improve plans. It can also allow rational assessment of the trade-off decision making time between early (precautionary preparation) and later (more accurate forecasts).

Lindell & Prater (2007a) separates the evacuation decision problem into the behavior of the hurricane relevant to an evacuation and the behavior of evacuees relevant to the hurricane. The uncertain behavior of these two systems is modeled in an evacuation decision management decision support system (EMDSS). The hurricane EMDSS describes and displays information about the minimum, most, and maximum probable evacuation time estimated in comparison with the earliest, most, and latest probable estimated time of arrival of hurricane conditions. In addition, the EMDSS calculates the cost of false positive (the economic cost of an evacuation) and false negative (lives lost in a late evacuation) decision errors.

Kailiponi (2010) discusses uncertainties about river water levels in the decision space (assessment of the optimal evacuation decision for different forecast precisions) using the Multi-Attribute Utility Theory (MAUT). An analytical framework incorporating the loss of life, economic disruption and organizational costs is proposed, through which multiple and different objectives are analyzed and compared to make an optimal evacuation decision (no action, advisory, mild evacuation order, or urgent evacuation order) based on a cost-benefit trade-off.

All these studies have primarily sought to optimize the evacuation decision using decision analysis approaches (e.g. decision tree, MAUT, probability etc.) and by quantifying the stochastic uncertainty of forecast in a critical time context (see Figure II-6).

These analytic and multicriteria methods propose an evacuation decision based on a set of rational input data that are supposed to be well known and quantified. However, at present, there is limited information available on life loss resulting from a failure to evacuate and no reliable data whatsoever on economic costs and lost credibility (Lindell & Prater 2007a).

Therefore, the input data for evacuation decision tends to be ambiguous, imprecise, incomplete and mainly qualitative.

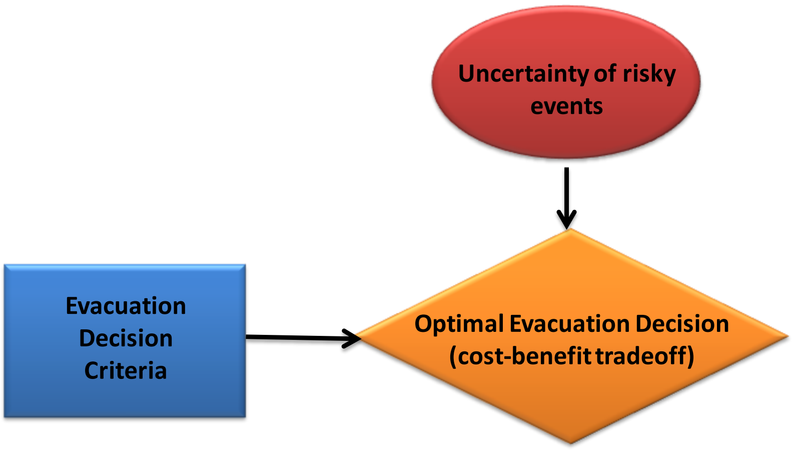


Figure II-6 Basic Evacuation Decision Context

Furthermore, these decision analysis methods are generally used in business or normal situations to evaluate different alternatives and to optimize decisions, but in an emergency situation decision makers should select the best action plan based both on past experiences and the actual situation (Sinha 2005). Therefore, in such contexts of emergency, one should first try to evaluate the actual situation and its possible evolution rather than compare scenarios on a theoretical cost-benefit approach.

4. Brief introduction to evacuation implementation and management

Once the decision to evacuate is taken and communicated to the population, the evacuation plan becomes an official list of actions to put in place, which requires the use of human and material resources and their coordination. The evacuation strategy must be monitored during the whole process. According to the evolution of the situation on the field, other stages of decision may be required in order to adapt the provisional plan to the actual context. Thanks to software communication and GIS techniques, evacuation decision support systems have been developed making easier to update the relevant data in real-time for the evacuation management. The literature review relative to the evacuation implementation and management is not explicitly discussed in this chapter.

5. Limits of the existing methods/models supporting the evacuation decision

Traditionally, an evacuation decision in the context of a natural disaster threat is based on both deterministic criteria (a water level) but also on subjective criteria referring to expert judgments (Bezuyen et al. 1998, Frieser 2004). Deterministic methods usually limit the number of decision criteria to one or two, like the water level forecast or the evacuation time estimation. They are clear-cut, but lack a rational and global decision process taking into account enough relevant factors. In reality, it is hard to decide an evacuation in an actual emergency situation, with a lot of uncertain parameters to estimate.

In the past decades, several qualitative and quantitative methods have been explored to propose a more rational decision process leading to an evacuation. Qualitative methods collect explicit decision criteria, but lack of a clear-cut evaluation of the global situation. Quantitative methods provide an optimal decision taking into account statistical uncertainty of a risky event and an economic evaluation of the evacuation. An optimal decision solution is expected to outcome from the trade-off between benefit and cost from the economic perspective. Although economic costs affect the policy decision, people safety remains the most important objective in a crisis situation (Kailiponi 2010), and decisions cannot be taken on an economical evaluation only.

Nowadays, few methods or tools are able to combine qualitative and quantitative information about decision criteria from different sources to give a global evaluation of a crisis situation (Lumbroso & Vinet 2012). Therefore, our purpose is to develop such a method in order to evaluate multiple criteria in an integrated way and incorporating experts' experience (subjective uncertainty) to help authorities make an evacuation decision.

6. Application of fuzzy logic method in crisis management

Fuzzy logic is a logic-mathematic approach that allows the representation of the way people reason approximately rather than exactly. The essence of fuzzy logic is that everything is a matter of degree (Zedeh 1994). It provides a simple way to reason with vague, ambiguous and imprecise input or knowledge, which seems adapted to the context of risk and crisis management in a first view.

The main applications of fuzzy logic are in the engineering field but, more recently, there are more and more applications in disaster management.

Fuzzy logic provides a useful way to assess risk levels (e.g. Lliadis 2005, Takacs 2010, Jiang et al. 2009) and vulnerability (e.g. Rashed & Weeks 2003, Aghataher et al.2008) in cases where the experts do not have enough reliable data to apply statistical or analytical approaches. Assessing urban risk/vulnerability for hazards such as earthquakes, floods etc. can be regarded as an ill-structured problem, for which there is not a unique, identifiable, objectively optimal solution (Rashed & Weeks 2003). It is observable that this assessment concerns a very complex system characterized by multi-parameters, multiple evaluation rules, and a lack of complete and precise data (Takacs 2010). It must be pointed out that there is a number of contrasting definitions of what risk/vulnerability means, as well as numerous conflicting perspectives on what should or should not be included within this assessment in a wide way (Rashed & Weeks 2003). However, fuzzy logic-based disaster assessment successfully already solved some complex and ill-structured problems based on available information sources and the expert knowledge (Takacs 2010, Rashed & Weeks 2003). The assessment results contribute to increase the risk management efficiency and can support the stakeholders in taking more informed and relevant decisions (Takacs 2010).

Fuzzy logic has also been successfully applied in disaster forecast modeling and operational management in real-time (e.g., Alvisi et al. 2006, Nayak et al. 2005a, Dubrovin et al. 2002, Liong et al. 2000). Fuzzy logic approach performs well when the physical phenomena considered are synthesized by both a limited number of variables and IF-THEN logic statements (Alvisi et al. 2006). Fuzzy logic coupled with other methods (e.g. neural networks) suggests a better applicability for forecast modeling especially (Corani & Guariso 2005, Nayak et al. 2005b, Chau et al. 2005). The model results indicate that the fuzzy logic approach avoids abrupt transitions between the different predictions (Corani & Guariso 2005).

The linguistic (qualitative) and conditional (IF-THEN rules) assessment capabilities of fuzzy logic are extremely useful first to aggregate the inputs and secondly to generate the elements of the multi-objective decision matrix (Akter & Simonovic 2005).

The applications of fuzzy logic for the issues of evacuation have only been conducted in the case of individual decision (Tiglioglu 2001, Hori & Shiiba 2004). The relationship of every components in the fuzzy logic system is expressed with fuzzy inference rules. This fuzzy model permits to simulate scenarios in which people follow or neglect the information provided by authorities.

However, few works have been led on the application of fuzzy logic to help authorities make a mass evacuation decision. Examining the literature and government documents, it was found that the evacuation decision to be taken in complex contexts, characterized by the presence of multiple aspects, is generally affected by uncertainty. This uncertainty essentially comes from the insufficient and/or imprecise nature of input data as well as the subjective preferences of the decision maker. Expert knowledge also plays a very important role in the evacuation decision process. , Expert systems using ‘IF-THEN’ rules have been developed to support sheltering and evacuation decision making in a nuclear emergency situation (Papamichail & French 1999).

Since the need for mass evacuation is rare (like the occurrence of major disasters), there are few examples of practice and return of experience from which to learn. However, the statistical-based and numerical methods need long-term experiments to be well calibrated. The deterministic methods and optimization approaches can give acceptable results for some finite dimensional problems, but without the management of uncertainties. Since decision making should take into account human subjectivity, fuzzy logic dealing with subjective uncertainty proves to work better than employing only (objective) probabilistic or heuristic approaches.

Upon examining the applications of fuzzy logic in disaster management, the use of the fuzzy set theory allows us to incorporate unquantifiable, incomplete, and non obtainable information, and partially ignored facts into the decision model (see our proposal in Chapter III).

Therefore, fuzzy logic techniques seem to be particularly adapted to evacuation decision, where data is scarce, the cause-effect knowledge is imprecise and observations and criteria can be expressed in linguistic qualitative terms.

7. Summary and provisional conclusions

An extensive research literature exists on evacuation planning, especially on transportation modeling. Evacuation planning is based on the assumption that if the forecasted disaster and situation is deemed to be severe, staying or sheltering in place is no longer an option.

A large body of research also exists about how individuals and families interpret and respond to an emergency alert based on empirical knowledge. After reviewing the research on three broad areas that often overlap: warning, risk perception and evacuation, Dash & Gladwin (2007) remark that one should look much more closely at the content and flow of information from forecasters to decision makers, the latter including officials who make evacuation calls.

Existing studies on methods, models and tools for evacuation planning (e.g. warning, traffic, shelters etc.) provide the basis for decision making in terms of data and process. However, currently, evacuation decision making methods have not been well documented. The literature on evacuation decision during the early crisis stage indicates that few studies have been done which integrate multiple decision criteria into a continuous evaluation of situations.

Upon examining the scientific literature and government guidelines, it was found that emergency managers were concerned about when and where they should make an evacuation decision. There are three important aspects of the evacuation decision which emerge according to Baker (1990):

- At which level the hazard and the risk need and justify an evacuation (disaster risk assessment)?
- Is it possible to implement a safe evacuation (evacuation risk assessment)?
- How to take account of the uncertainties and the links between uncertainties?

To respond to these concerns, we present in the next chapter a proposal of a fuzzy-logic model which results should contribute to a better understanding of the evacuation situations and decision, including the subjective uncertainty, through evaluating the necessity to evacuate locally.

Chapter III. Methodology for flood evacuation decision-making

1. Introduction

According to a survey of flood managers in England, Wales, France and the Netherlands, a combination of experts' judgment and multicriteria information from the ground is necessary for efficient emergency management (Lumbroso & Vinet 2012), but they are rarelly integrated in decision support systems. Fuzzy logic has been proved to be an applicable technique for merging multiple criteria with consideration of the experience of many experts.

Therefore, in this study, fuzzy logic is proposed to evaluate the necessity to evacuate through combining qualitative and quantitative values of decision criteria. The term "necessity to evacuate" (NTE) is defined as a number ranging between 0 and 1, which indicates the level of potential need for evacuation in local areas. The higher it is, the more necessary an evacuation requires with the goal of protecting the exposed population. It gives a synthetic information based on the hazard forecast, the potential danger for people, the ability of preventing them from contacting floodwaters, and also evacuation capacity and safety in case of a flood emergency. With the help of a Geographic Information System (GIS), the NTE can finally be displayed on maps which can be used as decision support for the evacuation management.

This chapter begins with a brief review of the evacuation decision process and the main criteria that determine the decision (section 2). A clear understanding of the multifaceted nature of the evacuation decision will facilitate the implementation of a fuzzy logic system for evacuation decision making. Then, section 3 outlines the general concept of the fuzzy logic theory. Next, section 4 focuses on the procedure of the implementation of a fuzzy logic system for the evacuation decision based on the NTE, which can be visualized on maps. Finally, conclusions of this chapter are given to summarize the key points of evacuation decision fuzzy model in section 5.

2. Evacuation decision problem and process

2.1. Context, objectives and hypothesis

The method presented in this chapter can be applied in different contexts of urban mass evacuation and different types of hazard. Nevertheless, it assumes a set of basic hypothesis and prerequisites which have to be clarified.

It mainly concerns an exceptional event (natural hazards) that authorities can forecast several hours before it impacts prone areas, so that a preventive evacuation of the population at risk can be organized. Evacuation means that the majority of people – if not all – in areas at risk have to leave these areas and reach secured zones or shelters. In some cases, the shelters can be inside the prone area (vertical evacuation) (Sorensen et al. 2004). In the context of an alert for a major disaster, the organization of crisis management can't be improvised, especially in case of mass evacuation for which specific plans have to be prepared in advance, well before any crises. These plans can be used as first level support for decision, but are not sufficient to take into account real-time and updated data.

The majority of existing methods and tools for evacuation plans preparation and management have been designed for river floods (especially in Netherlands: (Mak 2008)) and hurricanes (especially in the USA: (Lindell & Prater 2007a)) but not exclusively. The typical case we are dealing with is a major coastal submersion of a city on the Atlantic coast of Western Europe, caused by a combination of high tide, strong wind and waves (maritime storm).

2.2. Questions, uncertainty and decision

Then, in real time, when the forecast triggers an alert of submersion, there are three main questions that authorities have to answer before taking a decision of evacuation (Figure III-1):

- What will be the real level of danger for people's life in prone areas and does it justify an evacuation of those areas?
- Can an evacuation be achieved safely (mainly considering time availability in this study)?
- Is the local government able (in terms of resources and time) to evacuate part or all of the population at risk in the time before the event strikes?

First of all, the need for an evacuation decision is caused by a potential catastrophic threat like a severe flood. In general, the information (hydrographs, maximum forecasted discharge/water level) about a flood threat is compared to pre-defined thresholds corresponding to statistical flood frequency/magnitude (e.g. 100-year-flood or 500-year-flood). A flood warning is triggered when a critical threshold of water level, indicating a possibility of flooding, is exceeded from flood forecasting and warning systems (Weeink 2010). A forecast and warning system is usually based on a number of color-coded warning levels (e.g., red, orange, yellow etc.), which indicate the forecasted level of risk (e.g., major, moderate, minor etc.).

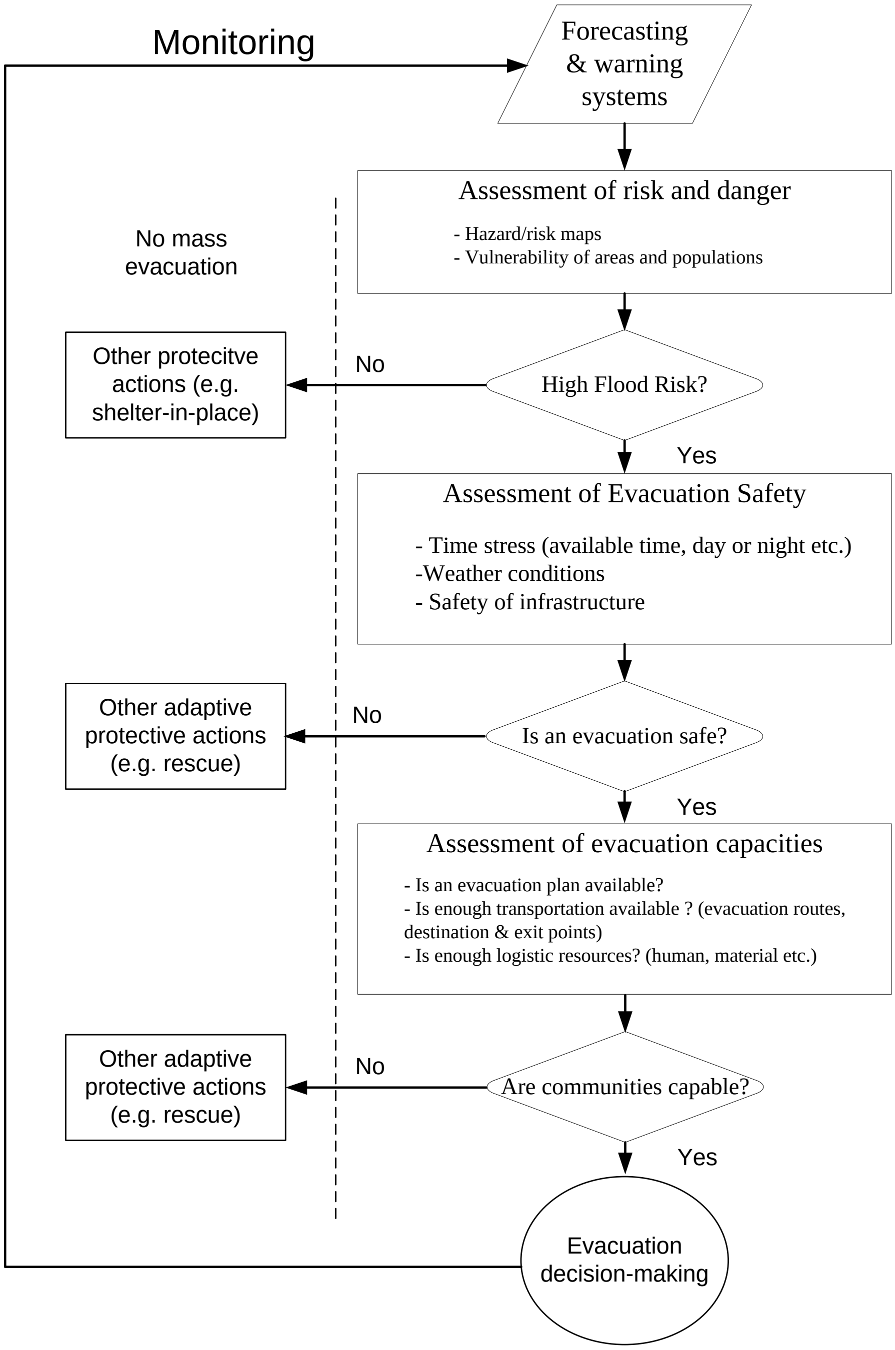


Figure III-1 Evacuation decision-making process and critical relevant factors

It requires the analysis of flood risk and its potential impacts to answer the question about whether the level of risk is high enough, so that an evacuation can be justified from the security and the governance point of view. Evacuation may reduce only the damage to life and moveable goods (Frieser 2004). Therefore, understanding the flood risk and danger to life is a major issue in the evacuation decision judgment. The loss of life is broadly caused by the combination of the area vulnerability (inside/outside building, nature of housing etc.), flood characteristics (depth, velocity, etc.) and population characteristics (age, health, etc.) (Ramsbottom et al. 2003, Tapsell & Priest 2009)

To answer the question about evacuation safety mainly involves weather conditions, time stress and safety of infrastructure. Weather conditions (rain, fog, snow, wind etc.) affect traffic operations and safety (Park et al. 2010). Time is the most important factor during the evacuation. Because evacuation during the flooding can be worse than shelters-in-place and waiting for proper rescues, it is important to achieve it successfully before the flood happens (Asselman & Jonkman 2003, Waarts & Vrouwenvelder 2004, Barendregt et al. 2005). Time stress also includes daytime or night, which influences the public response to the evacuation warning (Goutx et al. 2011). Indeed, the road network plays an important role in a large-scale evacuation. Infrastructure damages like bridges or roadways, which are possibly used for evacuation, should be informed timely.

To answer the question about evacuation capacity is helpful to understand the ability of the local government to deal with emergencies, including items like evacuation plans, available transportation and resources (e.g. humans, equipments, facilities and funds). The emergency capabilities of the local government affect the efficiency of the evacuation, which is thus very important in the evacuation decision making (Litman 2006).

One of the main problem of the evacuation decision is that it is not possible to simply answer “yes” or “no” to these questions which depend on a lot of criteria, part of which can be correctly anticipated (in advance thanks to preparation plans or real time data), but part of which remains uncertain and fluctuating during the event and the decision process:

- The local level of danger for people depends on the forecast and simulation models which cumulates uncertainty due to the evolution of the phenomena and inaccuracy due to data acquisition and numerical modeling. The forecast and alert system generally gives a global level of danger (red, orange, yellow …), but crisis management and intervention need more accurate information based on local water levels and risk mapping.

- The human and material resources can partly be identified and organized in preparation phase (Morel et al. 2011). Nevertheless the actual availability of these resources remains uncertain depending on the time of the event and to the reaction of people to the situation.
- The implementation of the evacuation conditions on the ground is also subject to unpredictable events like networks failure (Morel & Hissel 2010b), accidents and fuel shortage (Litman 2006).

The final evacuation decision is subject to a range of interpretations of information about the hazardous event, the available time to evacuate and evacuation feasibility. The interpretation process by decision makers itself can raise uncertainties and have an influence on the final decision (Mileti et al. 1985). For example, in the recent flood caused by storm Xynthia in France, the local civil protection services failed to understand that a severe flood was likely to occur from the Météo-France forecast, so that the evacuation decision order was delayed (Kolen et al. 2010). Thus, such uncertainty due to subjective judgment results from the way that emergency states and thresholds are defined. In order to make a more sound interpretation in emergency management, most experienced experts consider that experience is the best tool for such decisions.

Hence, for dealing with the multiple decision criteria and the combination of expert experiences, fuzzy logic is proposed to model the evacuation decision process, which will be detailed in section 4.

2.3. Interpreting evacuation plans in a real-time context of alert

As discussed above, so many aspects should be taken into account in the evacuation decision process. Therefore, it is important for our multi-criteria decision method to well select the relevant decision criteria which will correctly represent the decision circumstances in a crisis context, in order to answer the three questions mentioned in section 2.2.

Firstly, since evacuation planning methods and their output (the evacuation plans) are supposed to include all the data needed for crisis management, they represent the best basis to determine the set of decision criteria. Indeed, evacuation plans include the possible scenarios and evacuation strategies, traffic control management, coordination of material and human resources etc. The planning method developed in the framework of the FP7 THESEUS project (UTC-GSU 2011a) can be used as a tool that helps the mayor to prepare and manage an evacuation in response to a crisis. Moreover, in the context of a flood crisis, it can also help to make the link between the forecast, evacuation zones maps, evacuation routing, traffic management and finally to choose the most suitable plan and adapt it to the real situation.

Our study is expected to be adapted for flood evacuation decision in the context of the Gironde estuary and the city of Bordeaux. Therefore, our approach consisted in extracting the decision criteria from the previous work led in the framework of the FP7 THESEUS project. The two following documents were utilized to make emerge the explicit decision criteria which can be found in the Appendix A.

- A methodology guide of the evacuation planning which describes a seven-step modeling process (UTC-GSU 2011a);
- A catalog of classified data needed to implement the plans which are grouped into six categories: forecast and hazard, buildings, networks, population, organization and actors, and finally real-time data (UTC-GSU 2011b).

The process which led to determine the final indicators for the decision support method with a group of experts took place in three main phases. Firstly, all the data that intervene in the seven steps of the planning and management process were given a priority order in the logic of the evacuation decision, with the possible values {3: very important for the decision, 2: important, 1: less important, 0: not important} (see Appendix A). Then, from this first sort, a list of twenty-one decision criteria regrouped in five categories was extracted (see Appendix B). This list of indicators actually covers the most important items that should intervene in the decision and represents a first interesting result of our research that can be utilize in further work. Nevertheless, the number of criteria was still too numerous in the perspective of experimenting a multi-criteria method based on fuzzy logic. It was then necessary to apply a new phase of selection and synthesis among these parameters.

Finally, the twenty-one initial criteria have been simplified and synthesized in a limited subset of the most important indicators which are detailed in section 4.2. On the one hand, according to the studies on flood risk assessment, flood risk maps include two essential aspects: flood hazard and area vulnerability. On the other hand, according to the studies on the assessment of evacuation scenarios, the most simulated parameters include estimated evacuation time, percentage of people to evacuate etc.

Therefore, the four final selected indicators considered for the decision support process are the global forecast, the local level of danger, the area vulnerability and the evacuation capacity and security. These four criteria are used to calculate the necessity to evacuate which can be visualized on maps and represents the final explicit and synthetic indicator used for decision, which is developed and discussed in section 4.

3. Overview of fuzzy logic

In the past decades, fuzzy logic has been widely used in different fields such as industrial process control, meteorological forecast, flood risk analysis, decision-support systems (Bojadziev & Bojadziev 1995, Ross 2009, Murtha 1995, Makropoulos et al. 2003, Alvisi et al. 2006). This section describes the theoretical basis of fuzzy logic, before presenting our own proposal and application (see section 4).

3.1. General description of the fuzzy logic approach

In some circumstances, precisely defined decision knowledge and rules can be unsatisfactory as they result from a rigid decision-making process that does not fit to a human decision-making process. For example, a physician may deem it appropriate to prescribe a medication to a patient if he is old and suffering from a high fever. What does then “old” mean? What is a “high fever”? Given the decision rules that a person of 65 years old or older is “old”, and that a measured body temperature of at least 38.8ºC is high, does that then mean that someone aged 64 and 10 months whose body temperature is 38.8ºC would not be a candidate for the medication, while someone 2 months older would be? What about someone 72 years of age, who has a body temperature of 37.7 ºC? In cases such as this, thinking in less restrictive terms may be more appropriate. The fuzzy set theory provides a way to address this kind of decision-making problems. One might think that people aged 60 are starting to be old, while people aged 80 are definitely old. A temperature of 37.2ºC is a little bit elevated, and a temperature of 37.7ºC is definitely high by any standard. Decision rules of this example should be: “if the patient is old and suffering from a high fever” instead of referring to precise numerical values like 65 years old or older and 38.8ºC.

Thus, fuzzy logic is a way to conceptualize and to implement rules of experience with qualitative indicators instead of precisely describing the crisp/clear-cutting edge of quantitative decision criteria.

In fuzzy logic, the rules of experience represent the relative importance of precision (Zedeh 1994). For example (see Figure III-2), in some circumstances, an imprecise expression (e.g. “look out”) is more explicit and efficient than precise technical values for a man in danger to make a correct decision. Fuzzy logic trades off between significance and precision using fuzzy sets, something that humans have been managing for a very long time in every day practice.

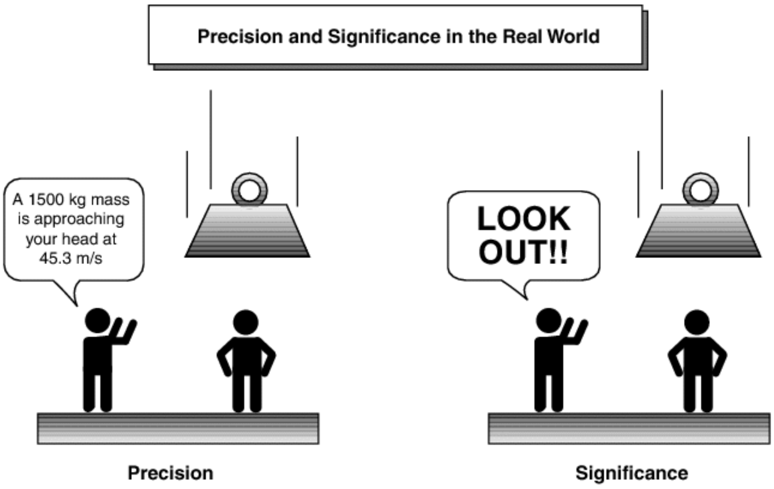


Figure III-2 An example of fuzzy logic trading off between precision and significance (adapted from help document of Matlab)

In this sense, fuzzy logic is both old and new because, although the modern and methodical science of fuzzy logic is still young, the principles of fuzzy logic rely on a very old skill of human reasoning to synthesize and simplify complex decision problems.

3.2. Uncertainty in fuzzy logic

Uncertainty touches most aspects of life, especially when we make decisions that have consequences that we cannot predict (Figure III-3).

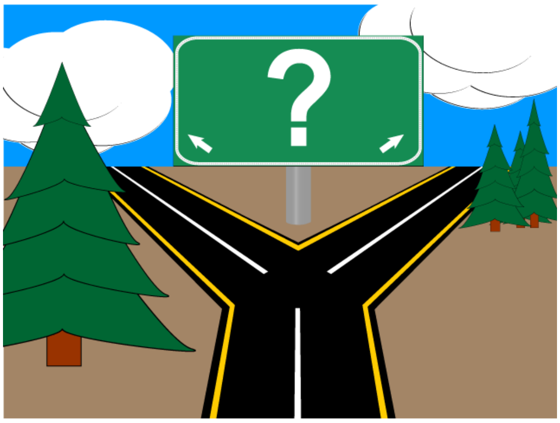


Figure III-3 Uncertainty occurs in the decision-making process

Uncertainty is a term used in subtly different ways in numerous research fields (Tannert at al. 2007, Klir & Folger 1988). It is then necessary to distinguish two kinds of uncertainties: stochastic uncertainty and subjective uncertainty.

Stochastic uncertainty deals with the occurrence of a certain event, which can be quite precisely described, such as a 10 years return period flood. This uncertainty is quantified by the degree of probability (one chance out of ten each year in average). For example, if one does not know whether it will rain tomorrow, then he/she is in a state of uncertainty. If one applies probabilities to the possible outcomes using weather forecasts or even just a calibrated probability assessment, he/she can quantify the uncertainty, for example as 90% chance of sunshine.

Subjective uncertainty deals with the definition of uncertain states or outcomes (Schwarze 1996). This type of uncertainty emerges from the linguistic imprecision. Humans use imprecise terms or expressions to describe and evaluate concepts and to derive conclusions such as “tall man”, “hot days” or “stable currencies”, for which no exact definitions exist. The concept of hot days is a subjective category. For example, the temperature of 29ºC may indicate a hot day for a person living in a northern place, while the temperature of 35ºC may indicate a hot day for a person living in a southern place. Subjective uncertainty describes vagueness or ambiguity in concepts’ properties values (Mendel 2001, Regan et al. 2002).

The difference here is that subjective uncertainty is about human definitions and concepts, not an objective fact of nature. However, statements using subjective categories play a major role in human decision-making processes such as the previous example: a physician may deem it appropriate to prescribe a medication to a patient suffering from a certain condition if the patient is old and suffering from a high fever.

The theory of fuzzy logic provides appropriate descriptions for this subjective uncertainty by using fuzzy sets, which is discussed in the following sections.

3.3. Foundations of Fuzzy Logic

3.3.1. **Fuzzy Sets**

Fuzzy logic starts with the concept of fuzzy set. To understand what a fuzzy set is, first consider the definition of a classical set.

A classical set is a container that completely includes or completely excludes any given element. Generally speaking, an element X of a universe set must either be in set A or in set not-A. The two categories A and not-A contain the entire universe. Everything falls into either one group or the other. There is no element that is both in the set A and the set not-A.

Going back to the "old people" example, according WHO (World Health Organization), most developed world countries have accepted the age of 65 years as a definition of 'elderly' or older person. It is logic that the age of 65 is defined as the precise boundary to distinguish the old and the not-old. Thus, old and not-old can be represented by two sets (see Figure III-4). If someone is 65-year-old, he/she is old; while if someone is 64-year-old, he/she is not-old. Obviously, the "old-people" set unquestionably includes people of 65 years old and older (e.g. 65-year-old, 68-year-old and 75-year-old). It also unquestionably excludes people under 65 years old (e.g. 64-year-old, 60-year-old and 58-year-old). Therefore, in a classic set, an element belonging to a set is described by "yes" or "no" and the boundary of the set is crisp.

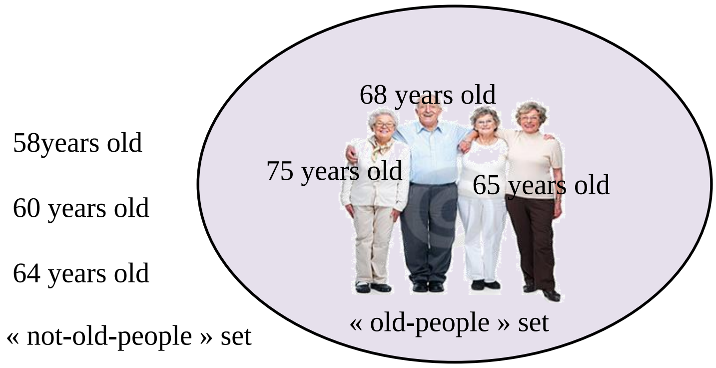


Figure III-4 An example of the classical set boundary

In reality, the boundary between middle aged and old aged people cannot be defined exactly because it does not have the same meaning in all societies. People at age 55, 60, 65 or 75 were possibly considered as old people (Roebuck 1979, Gorman 1999, Thane 1978). In classic set, only one boundary is defined to distinguish the belonging of an element.

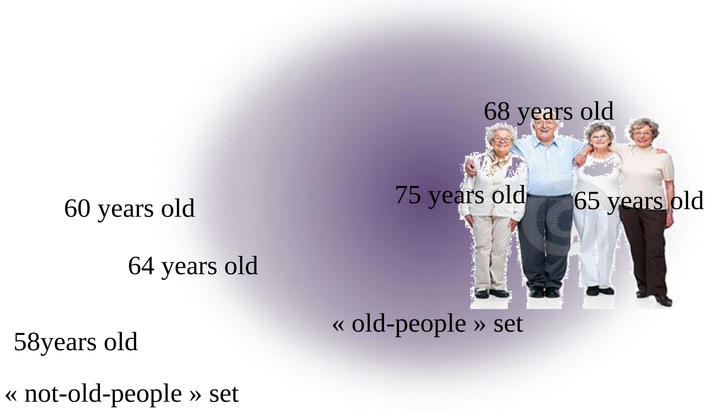


Figure III-5 An example of the fuzzy set boundary

On the contrary, a fuzzy set can describe all possible ages (55, 60 or 65 etc.) within the "old-people" set. Generally speaking, an element X of a universe set belongs to set A at a certain degree defined in the interval [0 1] or/and with qualitative nuances (little, moderate, strong …). If categories A and not-A contain the entire universe, it is possible that an element belongs to both at a certain degree. In the same example (see Figure III-5), there is not a clear boundary to distinguish the old and the not-old. In an “old-people” fuzzy set, age 55, 60, 65 and 75 can be respectively described as beginning old, a little bit old, moderately old and extremely old. Here, “beginning”, “a little bit”, “moderately” and “extremely” describe the degree of oldness, that is to say, a person at age 64 can be old and not-old, just the degree of membership to “old” set and to “not-old” set is different. Therefore, a fuzzy set describes a matter of degree instead of being YES or NO. A fuzzy set actually extends the boundary of the classical set and makes a gradual transition between sets.

In practice, the truth of any statement becomes a matter of degree. Now, let’s look at how to get the degree of the truth of one statement. Reasoning fuzzy logic is just a matter of generalizing the familiar yes-no logic. If you give to the logical value “true” the numerical value of 1 (100%) and to “false” the numerical value of 0, fuzzy logic also permits in-between values like 0.2 and 0.7453. For instance:

Q: Is a 75-year-old person old?

A: 1 (yes, or true)

Q: Is a 60-year-old person old?

A: 0 (no, or false)

Q: Is a 64-year-old person old?

A: 0.8 (for the most part yes, but not completely)

Q: Is a 65-year-old person old?

A: 0.95 (yes, but not quite as much as a 75-year-old person old).

From this example, one notices that a fuzzy set includes a numerical variable (e.g. 64-year-old age), a descriptive word like “old” and the degree of truth of “old” affected by the numerical value. In fuzzy logic, except for a numerical variable, the qualitative term is defined as a linguistic variable, that is, a variable whose values are words rather than numbers. For example, “old” is a linguistic variable. In effect, much of fuzzy logic may be viewed as a methodology for computing with words (or qualitative values) rather than numbers (quantitative values). Although words are inherently less precise than numbers, their use is closer to human intuition and are more adapted to represent experience and heuristic know-how.

3.3.2. **Membership functions**

Technically, a fuzzy set is quantitatively defined by a membership function. A membership function is a continuous curve that defines the degree of any numerical variable belonging to a linguistic variable. The degree of membership is between 0 and 1.

To return to the previous example, a fuzzy set is an extension of a classic set. Figure III-6 shows the membership function of a classical set "old", which gives the value 0 for the degree under 65 and the value 1 for the degree over 65.

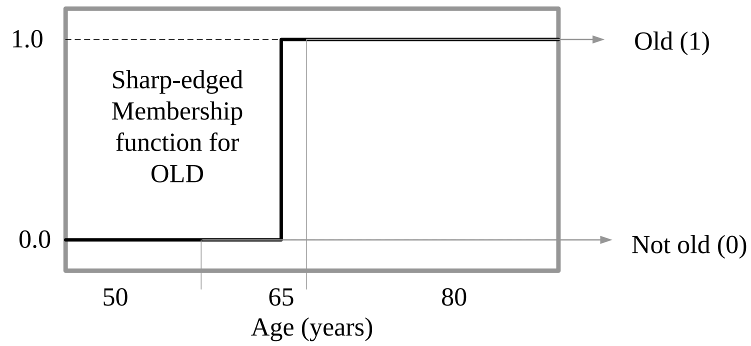


Figure III-6 An example of a membership function for a classic set

Figure III-7 shows the membership function of the fuzzy set "old". It can be seen that fuzzy logic defines the transition from not-old (0) to old (1) with intermediate values. This is just the technique of fuzzy logic for dealing with subjective judgment.

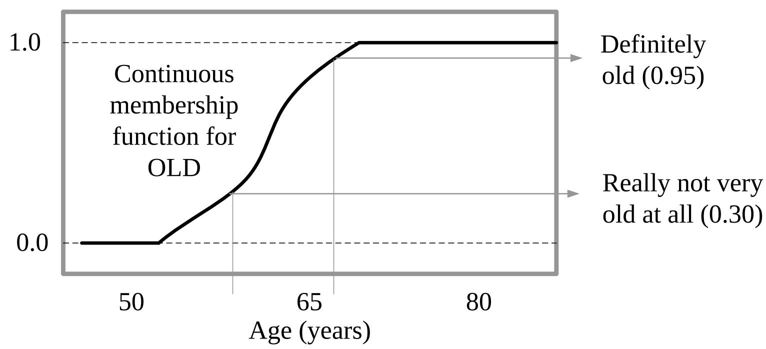


Figure III-7 An example of a membership function for a fuzzy set

Scientific publications have suggested many different types of membership functions for fuzzy logic (Dombi 1990, Cirstea et al. 2002). However, basic membership functions are generally linear or spline shape for practical implementations. Four different basic types of membership functions exist: Z-type, λ-type, π-type, and S-type (see Figure III-8).

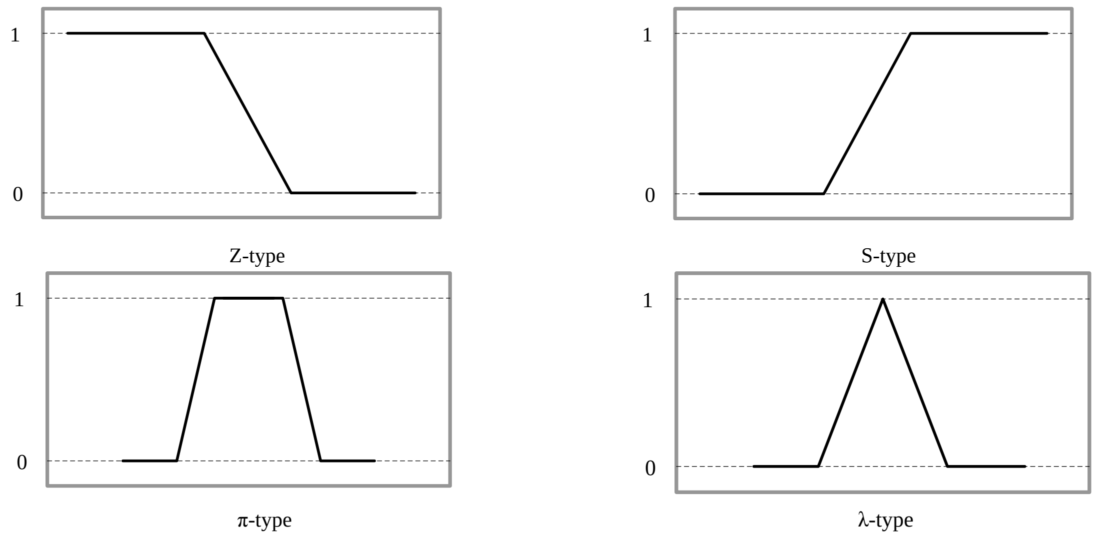


Figure III-8 Four basic membership functions shapes

These basic membership functions are simple functions but are accurate enough to model most parameters in decision systems. They always remain easy to interpret and their implementation is computationally very efficient. According to psycho-linguistic research on the human classification of continuous variables, spline basic membership functions provide more accurate models of human linguistic concepts for complex data analysis and decision support applications (Sivanandam et al. 2006).

In the field of evacuation planning and modeling, the λ-type and π-type membership functions have been used to design fuzzy logic systems. For example, Tiglioglu (2001) used a π-type function to design a fuzzy logic system which modeled human behavior during a hurricane evacuation.

3.3.3. **Fuzzy rules**

In the context of a multicriteria analysis for decision, one has to define how the different parameters will be "combined" to draw conclusions or propose solutions, depending on the type of problem. The fuzzy logic approach proposes to define heuristic or expert rules (of the type "IF conditions-THEN conclusions") to express the relationships between fuzzy parameters (the IF part of the rules) and the outputs or conclusions one can infer from these combinations (the THEN part). These rules are expressed with the fuzzy sets, that is with the qualitative values of criteria, which enables to define these rules with experts and common sense once the correspondence between numerical data and qualitative criteria has been clearly established.

To come back to the first example, let us describe the relationship between the symptom of a patient $x_1, his\ age\ x_2$, and the decision to prescribe a medication y. The qualitative input variables symptom and age can be defined by the following two sets $X_i : X_1\ and\ X_2$:

$$X_1 = \{high\ fever,\ normal\},$$
$$X_2 = \{old, \quad not\ old\}.$$

and similarly the output decision to prescribe a medication as

$$Y = \{medication,\ no - medication\}.$$

In classic logic, X_i and Y are classic sets and it is known that a crisp formulation of a relation $X_i \rightarrow Y$ between the crisp sets would look like this in tabular form:

Temperature / Age	1	0
1	1	0
0	0	0

The zeros and ones describe the "True" (0) or "False" (1) to this relation. This relation is now expressed by the rules. In this case, one can express inference rules between the input criteria and the decision like:

1. IF the symptom is high fever and age is old THEN prescribe a medication;
2. IF the symptom is normal and age is old THEN the decision is no-medication.

In fuzzy logic, X_i and Y are represented by membership grade, and the relation $X_i \rightarrow Y$ is represented in the same way as degrees of the set membership (which range in [0, 1]). Applying the fuzzy relation to this example, one possibility would look like this in tabular form:

Temperature / Age	0.9	0.5	0
1	0.95	0.8	0.5
0.8	0.7	0.65	0.4
0.5	0.6	0.5	0.2

This table represents a fuzzy relation and models the connectives in a fuzzy rule base. In a fuzzy relation, the inputs parameters and the output are both described as fuzzy sets. Thus, a fuzzy relation or rule describes a logical relation between fuzzy sets.

Before writing the rule base of the fuzzy model, fuzzy sets and membership functions must be clearly defined to agree on the meaning of qualitative variables, so that inference rules can be extracted from expert knowledge and return of experience with no ambiguity. Nevertheless, it is quite easy to modify these rules after testing them on different cases.

In the domain of evacuation planning and modeling, a model of individual decision process during a flood evacuation was conducted using an expert system with fuzzy inference rules at Kyoto University, Japan (Hori & Shiiba 2004).

3.3.4. **Fuzzy operations**

In a classical expert systems, inference rules are triggered and managed with not much difficulty since the value of an assertion is TRUE or FALSE. The way to trigger rules and to infer the conclusions is much more complex with fuzzy variables, and needs to use specific fuzzy operations, both on fuzzy sets and fuzzy relations.

Mathematically, fuzzy logic contains a wide variety of operations that can be performed on fuzzy relations and fuzzy sets (Cirstea et al. 2002, Betti et al. 2005). Professor Lotfi A. Zadeh (Zadeh 1965) formulated a fuzzy set theory in terms of the standard operations shown in Table D-1. Before illustrating with examples, one first need to define a fuzzy set as a function $\mu(x): U \to [0,1]$

where x is an element of a numerical variable; $\mu(x)$ is the degree of membership of x in a fuzzy set; and U is a fuzzy set.

Fuzzy operators	Functions	Description
Fuzzy OR	$\mu(x) = \max(\mu_i)$	To maximize degree values of membership of all sets
Fuzzy AND	$\mu(x) = \min(\mu_i)$	To minimize degree values of membership of all sets
Fuzzy NOT	$\bar{\mu}(x) = 1 - (\mu_i)$	Additive complement of degree values of all sets
Fuzzy product	$\mu(x) = \text{product}(\mu_i)$	To multiply each of the degree value of each set
Fuzzy sum	$\mu(x) = \sum \mu_i - \text{product}(\mu_i)$	The algebraic sum of degrees values of membership of all sets is minus their algebraic product values

Table III-1 Standard fuzzy set operators

By applying these fuzzy operations, Figure III-9 graphically illustrates the examples of fuzzy operations between two fuzzy sets: « high-fever » set and «old » set, given that the degrees of membership are respectively $\mu_1(x_1) = a,\ \mu_2(x_2) = b\ (0 \leq a \leq 1, 0 \leq b \leq 1, and\ a > b\ in\ the\ examples)$. The rectangles in grey correspond to the results through different types of fuzzy operators which have their translation in terms of algebraic operations.

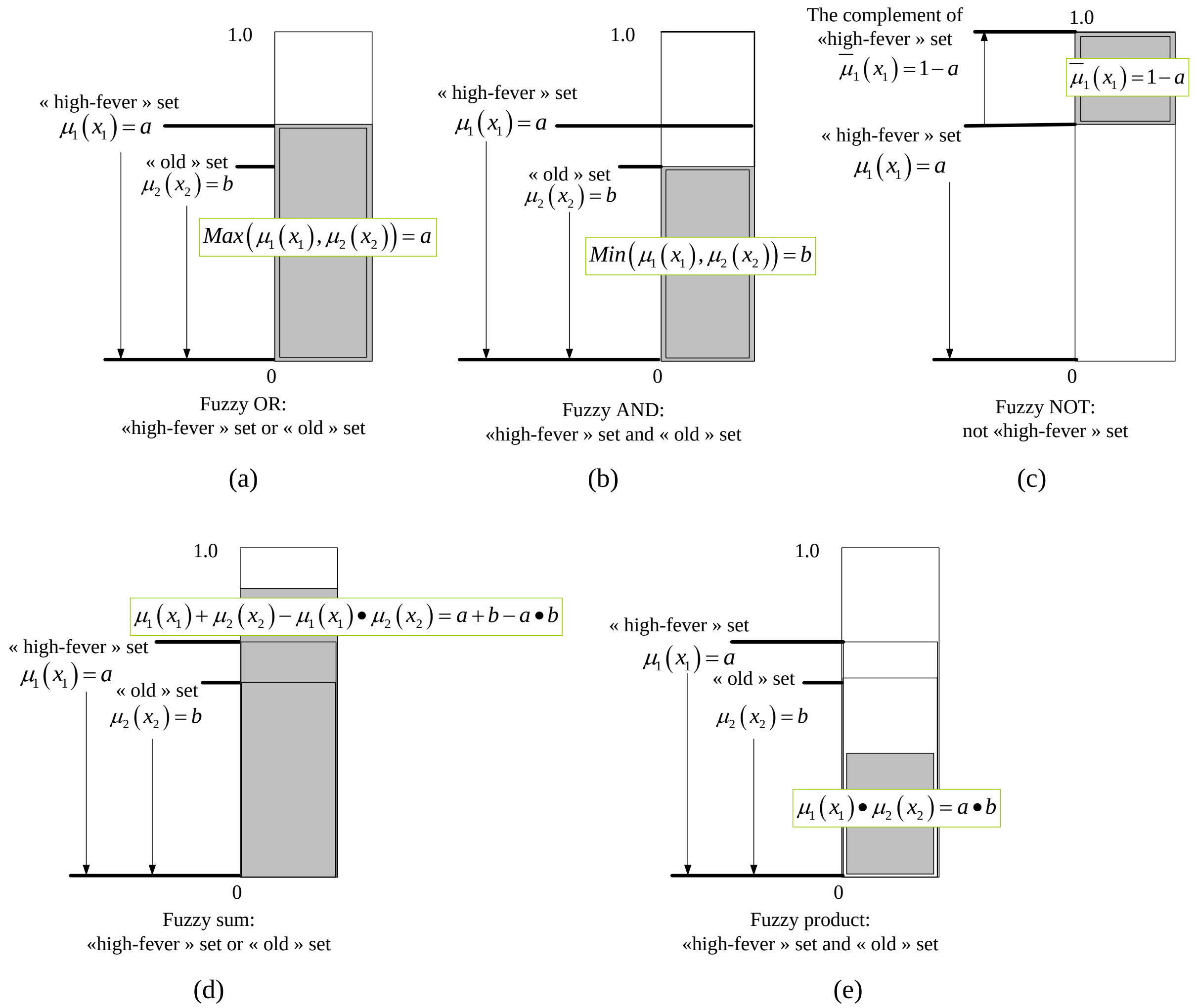


Figure III-9 Illustration of standard fuzzy operations with the algebraic formula

3.3.5. **Fuzzy reasoning**

Fuzzy basic operations have to be applied on inference rules. Let us examine once again the following example:

IF the symptom is high fever and age is old THEN prescribe a medication;

In fuzzy logic, “high fever”, “old” and “prescribe a medication” are actually defined as fuzzy sets associated with membership functions, so that this rule can be interpreted as follows:

IF the body temperature associated to high-fever is true to some degree and the age associated is old to some degree THEN the decision to prescribe a medication is true to some degree;

Thus, it is needed to operate the fuzzy inputs and fuzzy relations to produce an output that also represents the decision in a fuzzy way. This operation is called fuzzy reasoning or fuzzy inference, and it is not so simple and intuitive than in classical logic. The inference based on the rule depends on the implication: $IF\ x\ is\ A\ , THEN\ y\ is\ B\ (A \rightarrow B)$. Then, fuzzy rules can be interpreted by specific implication operators that have been widely studied by many authors. Table III-2 shows some most often used fuzzy implication operators (Fullér 1999, Rutkowska 2002). The propositional variables x and y are replaced by their degree of membership $\mu_A(x)$ and $\mu_B(y)$, and the implication can be replaced by the composition of fuzzy operators to form different fuzzy implication operators.

Fuzzy implication operators	Functions
Zadeh implication	$\mu_{A\to B}(x,y) = \max(\min(\mu_A(x), \mu_B(y)), 1-\mu_A(x))$
Mamdani minimum implication	$\mu_{A\to B}(x,y) = \min(\mu_A(x), \mu_B(y))$
Lukasiewicz implication	$\mu_{A\to B}(x,y) = \min(1, 1-\mu_A(x), \mu_B(y))$
Gödel implication:	$\mu_{A\to B}(x,y) = \begin{cases} 1 & if\ \mu_A(x) \le \mu_B(y) \\ \mu_B(y) & otherwise) \end{cases}$
Dienes-Rescher implication	$\mu_{A\to B}(x,y) = \max(1-\mu_A(x), \mu_B(y))$
Product implication	$\mu_{A\to B}(x,y) = \mu_A(x) \cdot \mu_B(y)$

Table III-2 Standard fuzzy implication operators

Only one of the most often used fuzzy implication operator, Mamdani minimum implication, which proposes to take the common minimum degree of membership of x and y (see Figure III-10). Mamdani (1977) proposed a fuzzy implication rule in 1977, as a simplification of Zadeh implication.

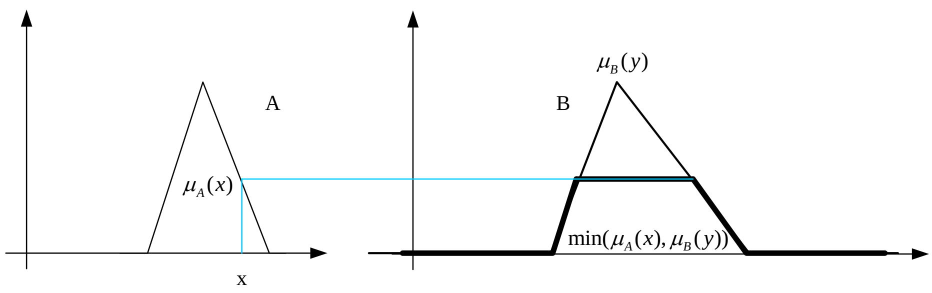


Figure III-10 Illustration of Mamdani minimum fuzzy implication operations

3.4. Fuzzy systems

3.4.1. **General overview of fuzzy systems**

Section 3.3 describes the concepts of fuzzy sets and fuzzy logic, which are the foundations that have been used in fuzzy systems. Most of them are rule-based fuzzy systems, in which relationships between variables are represented by fuzzy IF-THEN rules. These kinds of systems have been successfully applied, firstly in the engineering field of fuzzy controller such as an automatic train controller, a helicopter controller and so on. However, rule-based fuzzy systems can be employed to solve other problems closer to our own application domain: flood forecasting, flood risk management, individual evacuation behavior modeling (see e.g. Alvisi et al. 2006, Tiglioglu 2001, Chaves et al. 2005).

A rule-based fuzzy system refers to a system which incorporates both fuzzy logic and a rule based approach. Figure III-11 shows the general structure of such a fuzzy system, which is in fact a knowledge-based or expert system reasoning with fuzzy variables (inputs and outputs) instead of classical variables.

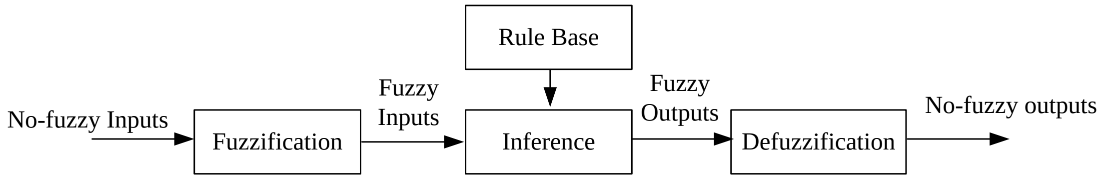


Figure III-11 General structure of a ruled-based fuzzy logic system

The central part of the system includes the fuzzy rule-base and the inference engine. The fuzzy rule base includes the knowledge and know-how of experts about a specific domain problem (for example “evacuation of risk prone areas in case of a severe flood” - Kolen et al. 2010), represented as a collection of fuzzy IF-THEN rules. The inference engine interprets the rule base by using membership functions of inputs and outputs fuzzy operators (see section 3.3.4), implication operators (see section 3.3.5) and defuzzification methods (see section 3.4.4). The rule-based inference system realizes a mapping from input fuzzy sets to output fuzzy sets. A fuzzification and a defuzzification process are used in order to offer the possibility to manage a system with no-fuzzy inputs and no-fuzzy outputs. Fuzzification (see section 3.4.2) consists in obtaining fuzzy inputs/outputs from no-fuzzy inputs/outputs using membership functions. Defuzzification (see section 3.4.4) consists in obtaining no-fuzzy outputs from fuzzy outputs, also using membership functions. The rule base makes the (fuzzy) logical link between fuzzy inputs and fuzzy outputs, by interpreting the rules using fuzzy operators and implication operators.

3.4.2. **Fuzzification**

Before a fuzzy system is built, all the quantitative and qualitative variables (inputs and outputs) should be selected and associated with two or more membership functions (MFs). A qualitative category associated to a numerical value can be defined as, for example the sets: “low”, “medium”, and “high”. The membership functions will give the correspondence between the initial numerical values and the qualitative values in a fuzzy way. The shape of the membership functions can be diverse but the λ-type and π-type are usually used (see

Figure III-12). It needs at least three (for λ-type) or four (for π-type) points to define the MF of one variable.

Example 1: if x is a variable that can take the values low, medium, and high and the degree of membership is represented as π-type and λ-type of MFs, respectively (see Figure III-12),

- The MF **low** will be defined by three points: $(x_1,\ x_2,\ x_3)$. However, in order to have a real π-type, it needs a fourth point at the left of x_1 (any negative one, e.g. x_0). Thus, the MF can be defined as $y^{low}(x; x_{0,}\ x_1,\ x_2,\ x_3) = max\left(min\left(\frac{x-x_0}{x_1-x_0}, 1, \frac{x_3-x}{x_3-x_2}\right), 0\right)$.
- Similarly, the MF **high** will be defined by four points: $(x_3,\ x_4,\ x_5,\ x_6)$ (x_6 any positive $> x_5$, being x_5 the higher possible value for x). Thus, the MF can be defined as $y^{high}(x; x_{3,}\ x_4,\ x_5,\ x_6) = max\left(min\left(\frac{x-x_3}{x_4-x_3}, 1, \frac{x_6-x}{x_6-x_5}\right), 0\right)$.
- Finally, the λ-type MF **medium** will be defined by three points: $(x_2,\ x_3,\ x_4)$. Thus, the λ-type MF can be defined as $y^{medium}(x; x_2, x_{3,}\ x_4) = max\left(min\left(\frac{x-x_2}{x_4-x_3}, \frac{x_4-x}{x_4-x_3}\right), 0\right)$.

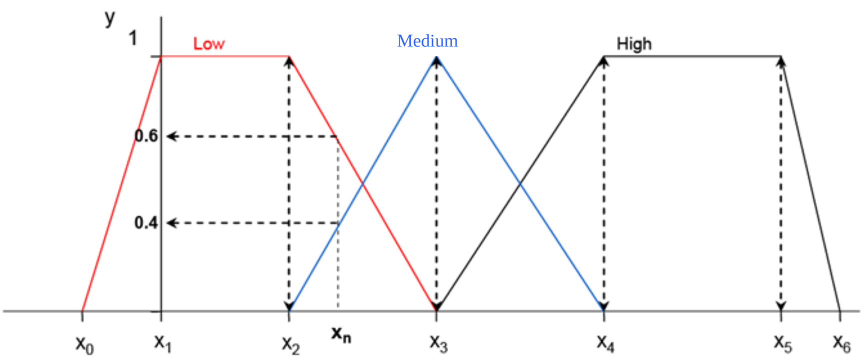


Figure III-12 Example of the three MFs for a given input

All numerical values of the initial quantitative variable x can be fuzzified to get the degree values y of membership through the MFs. This y value has to be between 0 and 1. Assume three MFs: low, medium and high and a given numerical value of x_n, then the degree values y of membership of each MF for x_n can be, for example, 0.6 for the MF low and 0.4 for the MF medium (see Figure III-12). Likewise, all the numerical values of any quantitative variable can be fuzzified and will belong to at least one MF with a certain degree of membership.

As seen above, fuzzification is the process of changing numerical values of each quantitative variable into a qualitative variable with membership functions (MFs).

Fuzzification is not a strict procedure and is partly done with intuition, experience and analysis of the set of rules which infer conclusions from a combination of inputs. However, it must be calibrated, tested and validated with realistic and accurate inputs and outputs (Pant & Holbert 2004).

3.4.3. **Rule base (decision matrix) definition**

Once the input and output variables and the MFs are defined, the rule-base including IF <conditions> THEN <conclusions> rules must be designed to transform the input variables into an output variable. The potential rules are defined depending on the number of qualitative inputs and output and also their possible values. The easiest case is a rule-base concerning only one input and one output. Of course, more variables imply more rules, but more rules can also make the inference more reliable for the same number of variables. Although realistic rules are generally derived from expert knowledge, it is not always necessary to translate the whole knowledge into rules. On the contrary, in some cases, some of the rules can sometimes be redundant. The decision matrix can be one method to help design the rule-base and the combination of inputs (e.g. Table III-3). For example:

$IF\ \boldsymbol{x_1} is\ \boldsymbol{low}\ \ THEN\ \boldsymbol{y}\ is\ \boldsymbol{low}\ ;$

$IF\ \boldsymbol{x_1} is\ \boldsymbol{medium}\ and\ \boldsymbol{x_2}\ is\ \boldsymbol{medium}\ \ THEN\ \boldsymbol{y}\ is\ \boldsymbol{medium}\ ;$

$IF\ \boldsymbol{x_1} is\ \boldsymbol{high}\ and\ \boldsymbol{x_2}\ is\ \boldsymbol{high}\ THEN\ \boldsymbol{y}\ is\ \boldsymbol{high}\ .$

		Input X_2				
		Very low	Low	Medium	High	Very high
Input X_1	Low	Low	Low	Low	Low	Low
	Medium	Low	Low	Medium	High	High
	High	Low	Low	Medium	High	High

Table III-3 Example of a decision matrix to design the rule-base

The rule-base is interpreted with the degree of membership of the output MFs through fuzzy reasoning, which has been discussed in section 3.3.5.

3.4.4. **Defuzzification methods**

The output of each rule, interpreted as a fuzzy value, is always a MF. Therefore, the MFs of outputs need to be converted into a non-fuzzy value of the output. The process of converting the fuzzy output is called defuzzification. Before an output is defuzzified, all the fuzzy outputs of a system are aggregated with the fuzzy maximum operator (see Figure III-13).

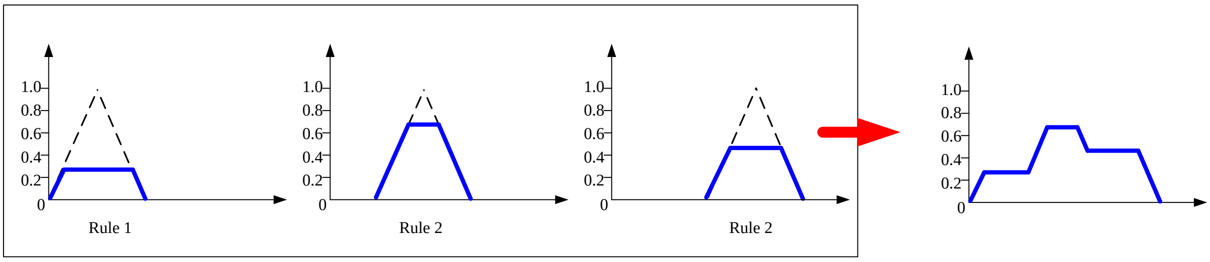


Figure III-13 Example of aggregated fuzzy outputs with fuzzy maximum operator

There are different methods and graphical examples for defuzzification (listed in Table III-4) to calculate the final value of the output from the aggregation curve.

These defuzzification methods provide flexibility and let the experts incorporate greater sensibility based on knowledge of how the results seem rational. The choice of the defuzzification method depends on the context of the decision problem (Tiglioglu 2001).

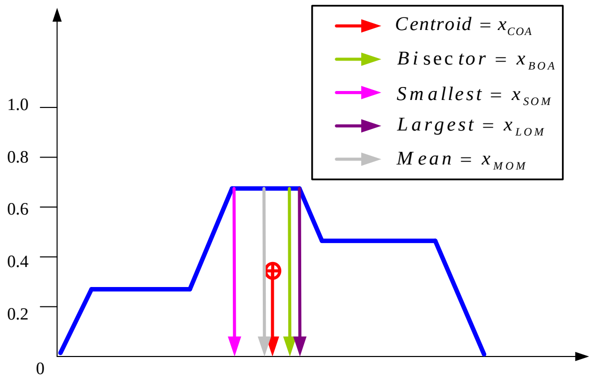
Defuzzification methods	Description	Graphical Example of the results of the defuzzification
Center of Area (COA)	COA defuzzification returns the center of areas under the curve	
Bisector of area (BOA)	BOA is the vertical line that will divide the region into two sub-regions of equal area.	
Mean value of maximum (MOM)	MOM is the average value of the fuzzy set with the highest resulting degree	
Largest value of maximum (LOM)	LOM is the largest value of the fuzzy set with the highest resulting degree	
Smallest value of maximum (SOM)	SOM is the smallest value of the fuzzy set with the highest resulting degree	

Table III-4 Defuzzification methods and their graphical results

4. Fuzzy logic application to flood evacuation decision-making

The final decision for a mass evacuation faces two difficulties, as aforementioned: i) numerous and heterogeneous criteria must be taken into account, often with imprecise and incomplete information; ii) a majority of these criteria values have an uncertain decision boundary.

An example for difficulty i) can be the choice of an evacuation route in case of congestion. Available information about the level of congestion along a main artery could either be numerical, such as the exact length of queues in meters, delays in minutes, etc., or be qualitative, such as traffic conditions globally or locally described as “light”, “heavy”, “bumper to bumper”, etc. In the absence of exact data on the length of queues, delay etc., one can imagine that a decision can nevertheless be made with an informal or qualitative information like “light”, “heavy” or others. Here, qualitative information, which partly represents a subjective knowledge using linguistic descriptions, must be handled in decision making. However, it is hard to process such information using classical mathematical logic and techniques. On the contrary, fuzzy logic is argued to be an extremely suitable concept for dealing with both subjective and objective knowledge.

Qualitative information cannot and should not be ignored in decision-making. Going back to the previous example, the information that “the traffic density is of 35 vehicles/lane/mile” or that “the car is going at 25 km/h” cannot always be directly and quickly processed by decision makers. Since most of them are not specialists in “Traffic Flow Theory”, they would not make calculations in order to take a decision about using a certain route. On the contrary, the information could be better understood and interpreted when the traffic condition to a certain route is said to be “light”, “heavy” or “bumper to bumper”. In certain situations, qualitative information tends to be more easily accepted than numerical information in decision-making. Another example, the intensity or level of a flood event, described as “minor”, “moderate” or “major”, gives a global estimation of the potential situation and damage. When the water level of the river reaches 6.5 m (minor) or 6.75 m (moderate), a flood is likely to happen with a certain level of corresponding danger. Does an additional height of water levels of 0.25 meters make a big difference for non-specialists? Obviously, the qualitative information on the flood from minor to major, since it has been defined from existing and validated thresholds, makes more sense for managers to decide what actions has to be taken. Such vagueness in human perceptions can be easily modeled using fuzzy logic.

For difficulty ii), values of criteria might involve some uncertainty of decision boundary, which may affect the decision-making. The forecasted water level of a river is taken as an example of the assessment of the flood, given that when the river water level reaches 5 meters in a particular location, a major flood may happen, and 5 meters is defined as the threshold to evacuate. Taking account an uncertainty, the forecasted water level is supposed to take a value in the interval [4.85, 5.05]. Thus, a slight additional or minus centimeters can significantly change the response to the evacuation decision between “yes” or “no”. With fuzzy logic, the interval of the water level value between 4.85 to 5.05m can be represented by a degree of membership, so that this difficulty can be avoided with the introduction of membership functions to give a gradual transition from one category to another category.

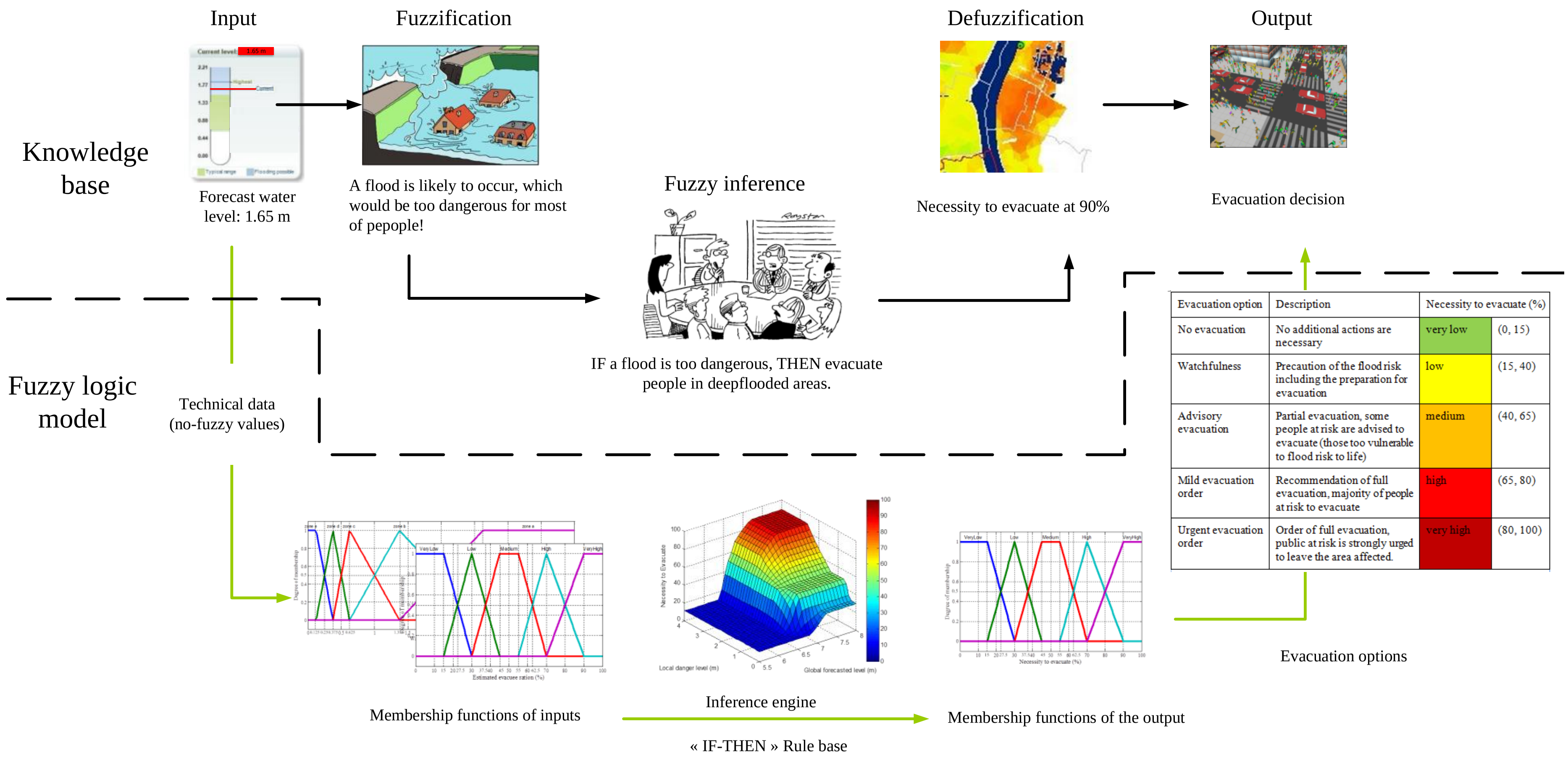
Fuzzy logic forms a vague yet robust system (Horgan 1995), which can generate precise solutions from an uncertain environment. Therefore, we propose to apply and experiment a multicriteria analysis to a mass evacuation decision with a fuzzy logic approach. Concerning the final decision of evacuation for a specific area, five options are actually conceivable: "no evacuation", "watchfulness", "advisory", "mild order" or "urgent order".

Therefore, in this section, fuzzy logic is applied to evaluate the necessity to evacuate (NTE) through combining qualitative and quantitative information of decision criteria. The NTE is expected to aid authorities to decide whether or not to evacuate an area in case of an emergency situation due to a severe flood.

4.1. Overview of the fuzzy system for flood evacuation decision

In the fuzzy system for flood evacuation decision, decision criteria are chosen as the inputs, and the necessity to evacuate (NTE) is defined as the single output. Decision criteria potentially include all relevant factors which should be considered in the evacuation decision making, especially those identified in the evacuation planning method (see Appendix A.). The necessity to evacuate indicates a level of evacuation need or possibility as a synthetic indicator for decision makers, which ranges in the interval [0, 1]. This fuzzy system aims at quantifying relations between decision criteria and NTE based on the local knowledge and experience. These relations are also expected to help decision makers to better understand how criteria and data from the field influence assessing the situation and the final evacuation decision.

Figure III-14 shows a global and intuitive overview of the fuzzy logic system for the evacuation decision.



Evacuation option	Description	Necessity to evacuate (%)	
No evacuation	No additional actions are necessary	very low	(0, 15)
Watchfulness	Precaution of the flood risk including the preparation for evacuation	low	(15, 40)
Advisory evacuation	Partial evacuation, some people at risk are advised to evacuate (those too vulnerable to flood risk to life)	medium	(40, 65)
Mild evacuation order	Recommendation of full evacuation, majority of people at risk to evacuate	high	(65, 80)
Urgent evacuation order	Order of full evacuation, public at risk is strongly urged to leave the area affected.	very high	(80, 100)

Figure III-14 Graphical scheme of the fuzzy logic system for the evacuation decision

Concerning the modeling of this system, there are six main steps to design and implement it, shown in Figure III-15.

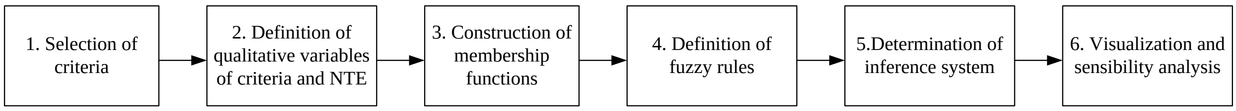


Figure III-15 Steps for building the fuzzy system for evacuation decision

First of all, the decision problem starts with determining the inputs (decision criteria) through different approaches and sources (e.g. brainstorming, actors consulting, public survey, evacuation plan analysis, literature review etc.). The selection of criteria must also take into account the availability of the relevant existing data (e.g. flood forecast, flood maps, population vulnerability, estimated evacuation time etc.). Before evaluating the suitability of potential criteria, officials and their organizations must first analyze the local situation and define their strategy. Our proposal clearly don't aim at validating a complete and exhaustive panel of decision criteria but to assess the feasibility of a new approach and method with a limited but representative set of varied criteria (see section 2.3).

Secondly, the quantitative and qualitative variables for each criterion and the NTE have to be clarified. All the quantitative variables ranges of values are then categorized to define the qualitative variables and their set of possible values. These categories are defined using the expert knowledge, statistical data, published thematic maps for flood hazards and evacuation plans analysis.

The following steps represent the core of the fuzzy logic system design. Thirdly, membership functions (MFs) of each criterion are built representing the correspondence between quantitative and qualitative variables and values. Similarly, MFs of the necessity to evacuate (NTE) are also defined. Fourthly, the rule base, describing fuzzy relations between decision criteria and NTE, is defined based on expert knowledge and experience. The knowledge rule base contains a series of 'if-then' rules which translate the conditions on combination of criteria's values into a conclusion on the NTE value. Then, the rule-base is interpreted using fuzzy reasoning process to set up quantitative relations between decision criteria and the NTE. To facilitate the analysis of criteria sensitivity on the output, 3D surfaces can help visualize the relative influence of two inputs on the output. According to the final value of NTE, corresponding suggestions in natural language can be given for helping the evacuation final decision.

Furthermore, this fuzzy system process is applied in the spatial dimension with the help of a Geographic Information System (GIS). The spatial distribution of the NTE (which both depends on global and local parameters) final value can be visualized on maps to get more elaborated decisions taking into account global and local information, such as prioritizing evacuation areas. Details about each step of this fuzzy system are explained in the following sections.

4.2. Step 1: selection of criteria

After analyzing the process of the flood evacuation decision (see section 2), it appears that such decision depends on the outcome of assessing flood risk situation and evacuation capacity and safety. The former reflects potential direct damages to human communities, while the later reflects potential negative aspects that could prevent a successful evacuation. Thus, according to the study of both existing researches and evacuation plans (see section 2.3), decision criteria should include flood hazard, potential danger/damage to life, evacuation traffic capacity, available time to evacuate, and so on. In practice, it is important to verify the criteria with experts, decision makers and stakeholders, including planners, managers and even the public involved in the evacuation.

In this study, a limited set of relevant criteria were chosen and defined in order to experiment the new fuzzy and heuristic method with a representative but not too complex example. Therefore, four decision criteria have been selected and synthesized as main indicators for the evacuation decision fuzzy system: 1) global flood forecast level, 2) local level of danger, 3) area vulnerability and 4) capacity and safety of the evacuation. The criterion of global flood forecast level, which determines an emergency in advance, is used to assess the flood risk globally, at the scale of a large city for example. The criterion of local danger level, which determines dangerous situations, is used to assess the flood severity and its potential impact locally (mainly based on the local water level). The criterion of area vulnerability, which determines the nature of areas preventing people from contacting floodwaters, is used to assess the ability to provide possible protection to people (e.g. shelter-in-place, vertical evacuation etc.). The criteria of capacity and safety of the evacuation, which determines constraints or potential negative aspects for achieving an evacuation, is used to assess the difficulty and risk caused by the evacuation itself.

4.2.1. **Global flood forecast level**

The global flood forecast level can be considered as the first indicator representative of the potential flood threat and impact on flood-prone areas, with and anticipation from a few hours to a few days which can allow organizing crisis management. This forecast can include a variety of dimensions such as frequency/magnitude, probability, arrival time, scope of impact, etc (du Plessis 2002, Quarantell et al. 1980). Nevertheless, the most important information is generally a maximum of water level reached by the river of the sea during the incoming event, and this data is sufficient to give an overview of the incoming flood risk and for local officials to understand what will happen and prepare emergency measures to protect their community.

Therefore, any public mass evacuation decision starts with determining the global flood forecast level, especially when a catastrophic event is likely to occur.

There are various variables which can be used to estimate the global flood forecast level, such as hydrological variables, meteorological variables, maritime variables etc. (Cloke & Pappenberger 2009, Bocquet et al. 2009). Hydrological variables include discharge, water levels in a certain catchment. Meteorological variables include the precipitation, wind, pressure etc. Maritime variables, which mainly concern coastal cities prone to sea submersion, include sea levels, tide, surges etc.

So far, existing forecast models combine hydro-meteorological variables and basin characteristics to forecast the discharge and/or water levels and its uncertainty (du Plessis 2002, Cloke & Pappenberger 2009). In coastal areas, models also include maritime variables. For example, in the Gironde estuary, a region prone both to maritime and river floods, French authorities have developed a forecast model of water levels (see Figure III-16) combining the discharge of two rivers, high tide, pressure and wind, sea levels etc. (see also Chapter IV the implementation of our system with this example).

Forecasted water levels of the river or the sea can also be compared with similar values of historical events and floods, which can sometimes help estimate the magnitude of the incoming flood by comparing with historical observations and a similar flood experience. This forecasted water level is also often associated with an uncertainty (an interval of values) (Weeink 2010), which can be helpful for decision making.

In this study, we assume that the forecast and warning system exists and is reliable. Hence, only the forecasted water level is considered as the quantitative variable representative of the global incoming flood maximum level from which the impact and the need for evacuation can be estimated. Details about the definition of the quantitative and qualitative variables of this criterion are described in section 4.3.1.

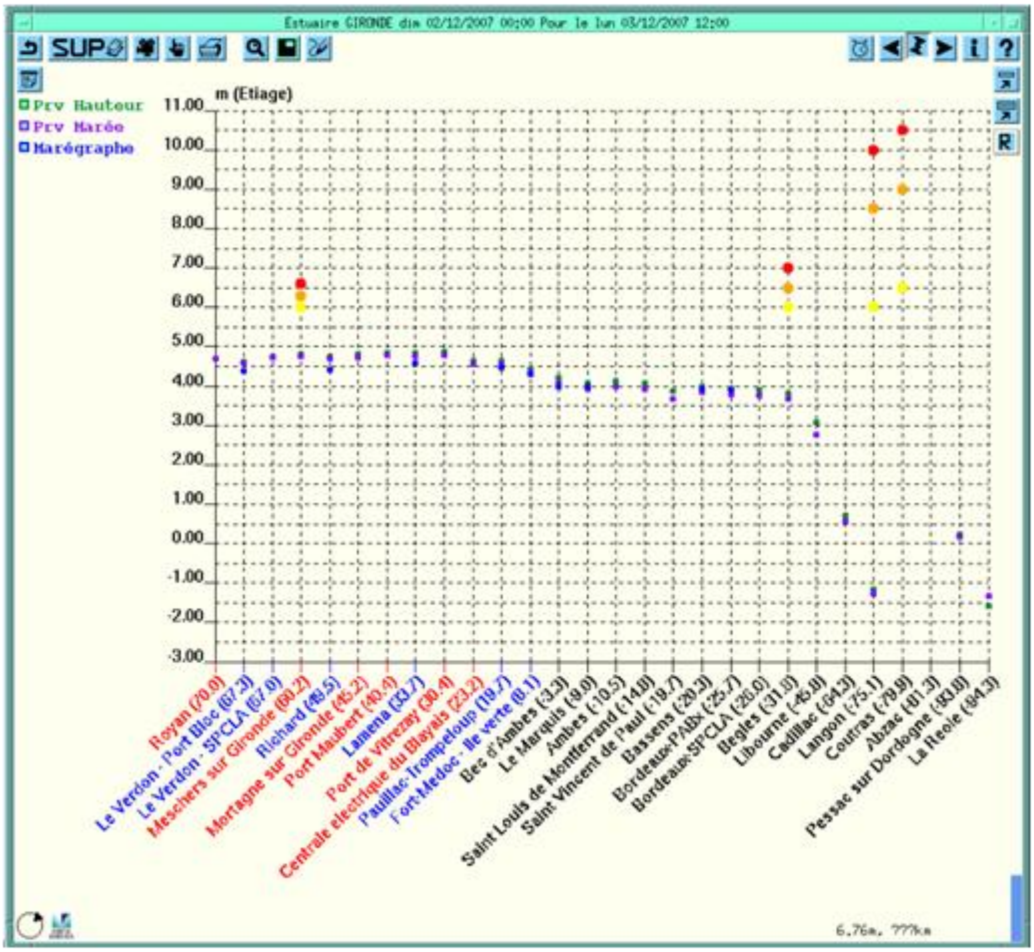


Figure III-16 Example of forecasted water levels in the Gironde estuary (Sarralde, 2010)

4.2.2. **Local danger level**

The global forecast gives an idea of the whole flood but is not sufficient to estimate the risk for people locally, in each flood prone areas and even at the scale of a house. Local danger level represents the physical characteristics of the flood very locally and its potential impact on facilities at stakes and especially the security of people. It is important for local officials and decision makers to precisely understand how serious the flood will be within their community and in each district, each street. This detailed and spatial knowledge of the event will guide the implementation of protection actions and possibly the decision to evacuate certain areas in priority. Therefore, any public mass evacuation decision should determine the local danger level and visualize it on a map.

The variables of the local danger level affecting the evacuation decision mainly concern the flood hazard characteristics, the duration of the flood event, the potential destructive impact on human health and safety, the floodplain context, etc. (Priest et al. 2007). The characteristics of the flood hazard include flood depths, velocity, debris, water rising rate, etc. (Ramsbottom et al. 2003, Dekay & McClelland 1993). The impact on human health and safety includes the density of population exposed and the presence the vulnerable people (e.g. elderly, children, disables etc.). The floodplain context includes the topographical, geological, hydraulic conditions, catchment characteristics, and structural defenses, etc., which can affect the nature of the flood event (Priest et al. 2007).

Flood depth and velocity are the most important parameters to describe the flood potential impact on people's security. Many of the studies have used either one of them or the product of depth and velocity as a function to describe flood danger level locally (Ramsbottom et al. 2003, Karvonen et al. 2000). The existing flood risk studies and tools can provide the useful data for the local danger criterion. Especially, flood hydraulic models (including statistical methods, rainfall run-off models and digital elevation model) are often used to create flood hazard maps related to certain frequencies of flood with GIS tools (Gilles & Moore 2010).

In this study, we only consider the flood hazard itself as the main factor of the local danger level. Thus, the water depth in local sections is chosen as the quantitative variable of the local danger level. Then, the hazard map can be used to estimate the places needing an evacuation decision at the local scale. Details about the definition of the quantitative and qualitative variables for this criterion are described in section 4.3.2.

4.2.3. **Area Vulnerability**

We define the area vulnerability as the non capacity of this area to prevent people to be in direct contact with the flood waters during the event. It is important for local officials to understand what protection actions are possible inside flood prone areas and within their community, which influences the choice of protection actions (shelter-in-place *vs.* horizontal evacuation etc.). Therefore, the possibility of protection inside the areas at risk appears as a key factor to take into account before an evacuation decision.

The variables of the area vulnerability include the nature of land use such as residence, open field, specific spots (e.g. hotels, hospitals, schools etc.), the height of buildings, etc. The nature of land use can provide different ability to resist to different levels of flood. For example, areas with campsites, mobile homes or large open recreational spaces, which will provide little ability of shelter, tend to be more vulnerable, making the population directly in contact with floodwaters, while urban residential areas or other locations with buildings, which in theory provide a higher level capability of shelters, tend to be less vulnerable (Priest et al. 2007).

In this study, the types of land use are assumed to be the variable representative of the area vulnerability, and its quantitative and qualitative values are defined in section 4.3.3.

4.2.4. **Capacity and safety of evacuations**

The capacity and safety of the evacuation can be defined as the set of constraints (e.g. road capacity, exit points, etc.) and potential negative aspects (e.g. bad weather conditions, accidents, traffic congestions etc.), which can delay or prevent achieving the evacuation successfully. This indicator is used to assess the difficulty and risk caused by the evacuation itself, which influence the efficiency and effectiveness of an evacuation. Therefore, taking into account this specific evacuation hazard in advance can influence the evacuation decision itself that must anticipate a maximum of possible circumstances.

Such a criterion is synthesized from multiple important variables of evacuations such as the number of people to evacuate, available time to evacuate, available transportation, estimated evacuation time, roads capacity, exit points of the flood prone areas etc. (Morel et al. 2011).

Time is the most important variable during the evacuation, since it is generally aimed at achieving the evacuation of an area before it begins to be impacted by the flood. If it is not the case, a mass evacuation during the flooding can be worse for the population than going to shelters-in-place and waiting for proper rescues (Asselman & Jonkman 2003, Waarts & Vrouwenvelder 2004, Barendregt et al. 2005). Hence, different kinds of evacuation time models were proposed. For example, in the simple evacuation time model (Barendregt et al. 2005) shown in Figure III-17, available evacuation time $(t_5 - t_1)$ and required evacuation time $(t_4 - t_1)$ have been proposed to decide whether or not to evacuate. If available evacuation time is greater than required evacuation time $((t_5 - t_1) > (t_4 - t_1)$ evacuation decision is yes and *vice versa*. This evacuation time model is, to some extent, helpful to understand evacuation safety under time stress.

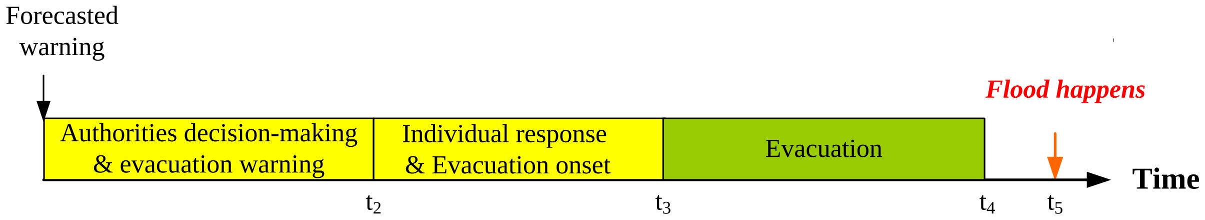


Figure III-17 Example of simplified evacuation time model

As transportation networks (roads, railways, subways, waterways and airways) play a critical role in the emergency chain, they are used to leave the threatened area and go to a shelter in safe areas. However, the limited evacuation routes and dense population in urban areas make the evacuation difficult to achieve in a limited time. The serious traffic problems during an evacuation create potential increasing risks of injury or death. Thus, accurate evaluation of the demand and offer of transportation need for the evacuation is necessary to assess the ability of the government in place to actually implement the evacuation plan in a given situation. It is also useful to assess the risks that the evacuation process itself can induce.

In the past decades, evacuation models including traffic simulation (see Chapter II) have been developed to help estimate evacuation time, routes intersection load, evacuation distances, congestion levels etc. (Raymond 2005, Cova & Church 1997).

Raymond (2005) modeled evacuation vulnerability (see Figure III-18) to assess the level of difficulty during an evacuation from a hurricane. This model combines social, transportation, and geophysical aspects of natural hazard in order to assess evacuation vulnerability from a broader perspective rather than solely from a transportation perspective. Obviously, the analysis of evacuation vulnerability is helpful to improve evacuation management and decisions.

In this study, the various parameters representing the capacity and safety to evacuate that we discussed above are supposed to be synthesized in a single indicator representing the estimated evacuee ratio. Estimated evacuee ratio is defined as the percentage of people achieving evacuation before the incoming floods (see section 4.3.4 for the values).

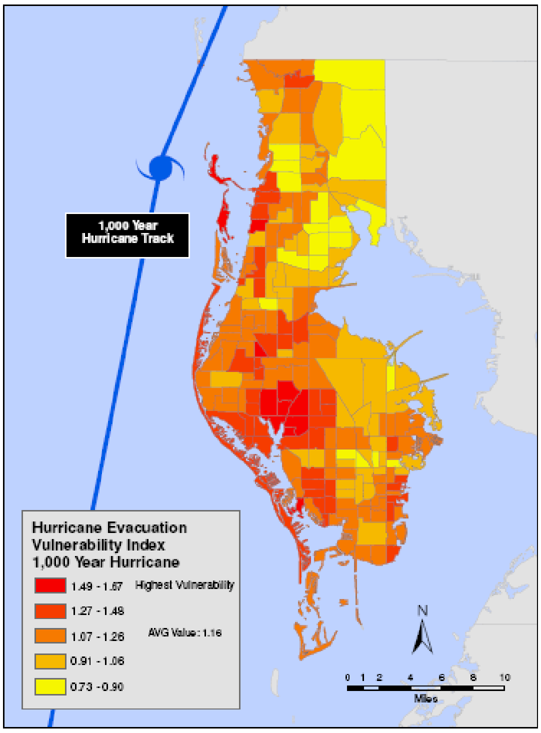


Figure III-18 Example of Evacuation Vulnerability map within Pinellas County (USA)

4.3. Step 2: definition of qualitative variables of decision criteria and NTE

Initially, the different decision criteria for evacuation have either quantitative or qualitative values. Before building the fuzzy system for evacuation decision, it is necessary to associate each criterion with qualitative variables, according to the values of its quantitative variable when necessary. The qualitative variables of each criterion are defined with explicit terms like “red”, “zone a”, “high” etc., which each time represent a range of quantitative values, for example, $''red'' = [7.0, \propto)$ (more than 7 meters for a water level for example)

Definitions of the qualitative variables are mainly extracted from existing research, studies and experience in the relevant fields such as flood forecast and warning, flood risk management, evacuation planning and modeling etc. However, concerning the variables of the output criteria (NTE) which is quite new, there is not sufficient information in existing documents, so the qualitative variables are defined based on assumptions. For example, we assume that the fourth decision criterion (the capacity and safety of the evacuation, represented by the estimated evacuee ratio) has five qualitative variables defined in the set (very low, low, moderate, high and very high) corresponding to five numerical ranges ([0, 27.5], [27.5, 37.5], [37.5, 67.5], [67.5, 80], [80, 100]).

The critical values of the interval boundaries may be argued. However, the fuzzy logic method can deal with the uncertainty of the definition and the set of values can evolve by calibrating the model with test cases. Moreover, the assumptions mainly aim at demonstrating the proposed method, not to definitely valid the criteria and their values. In the future, the variables and definitions of decision criteria and NTE will need further work, especially by being confronted with more real cases and more accurate data.

4.3.1. **Qualitative variable for the global flood forecast level**

Definition of the qualitative variable for the global forecast should correspond to the actual levels of risk which are currently used for alert systems, decision support and crisis communication in case or meteorological or flood alert, for example, in France[1].

The French alert system defines four categories of flood risk and alert in color-coded, which can be distinguished and visualized in the national “Flood vigilance map”. Four terms like “red”, “orange”, “yellow” and “green” are chosen to represent the four categories of the incoming flood risk (at the scale level of a river section, which actually remains a global indicator):

- Red: risk of major flooding, which cause direct threat to the general safety of persons and property.
- Orange: risk of generating a significant level of inundation, which may have a significant impact on community life and on the safety of property and persons.
- Yellow: risk of flooding or rapid rise of water, which does not involve significant harm, but requires special vigilance in the case of seasonal and/or outdoor activities.
- Green: no risk of flood warning.

The boundaries (or thresholds) of the water level that trigger a corresponding alert depend on a particular basin, and each basin can use its own tools to forecast the water levels. Particularly, when the basin is also on the coast, the water levels forecast models should include the maritime variables. For example, in Bordeaux, when the water level of Garonne is over 6.5m (or the water level is over 5.8m and there is a high tide/ a very strong wind etc.), the flood alert will be at “yellow” (PCS 2008).

Therefore, in this study, the terms: “red”, “orange”, “yellow” and “green” define the set of values for the qualitative variable of the global flood forecast level. And these four qualitative values correspond to four ranges of local numerical values of official water levels in Bordeaux (see Table IV-1).

[1] www.vigicrues.fr

Global flood forecast level	Description	Critical values (m)
Red	Risk of major flooding	> 7.0
Orange	Risk of generating a significant level of inundation	$[6.7, 7.0]$
Yellow	Risk of flooding or rapid rise of water	$[6.5, 6.7]$
Green	No risk	< 6.5

Table III-5 Example of values for the global flood forecast level in Bordeaux, according to Vigicrues

4.3.2. **Qualitative variable of local danger level**

For flood hazard, many studies (e.g. Priest et al. 2007, Jonkman 2007) have developed methods to estimate the damages of a disaster with respect to the physical parameters of the flood (flood depth, velocity etc.). There is not yet a unique standard to distinguish areas at-risk according to the impacts of different situation of floods and parameters.

A number of studies have explored how flood depth and velocity affect the ability of human stability and safety in a water stream. Figure III-19 identifies thresholds where different individuals are in danger in the water. In practice, many studies only considerate the flood depth in the flood hazard maps to estimate the risk.

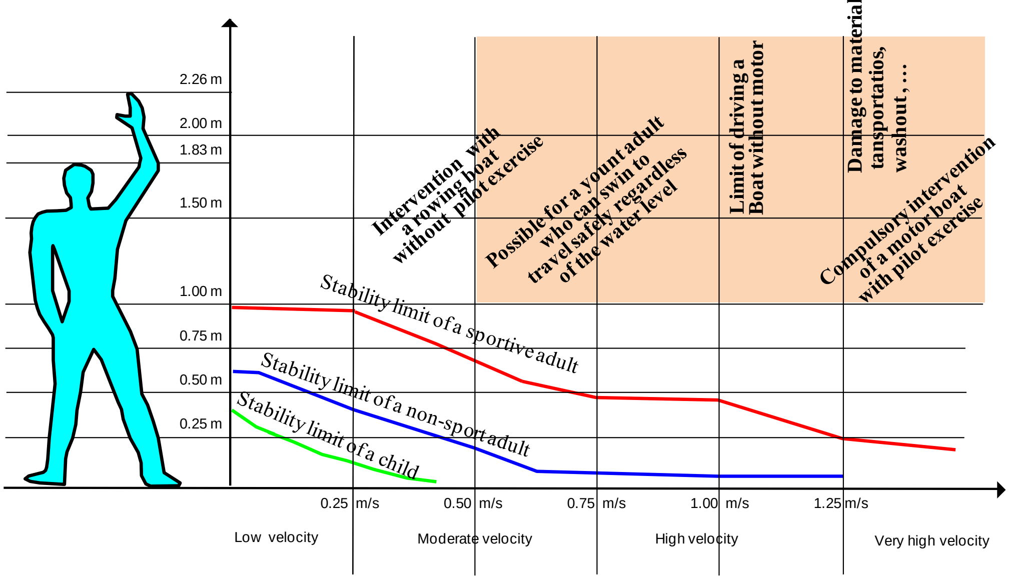


Figure III-19 Stability limits in water according to Direction départementale de l'équipement (DDE) du Vaucluse/DDE94 (Source : P.R.R.I.-Val-de-Marne, 2007, p23)

The methodology for the implementation of mass evacuation plans have been studied in the THESEUS EU FP7 project. In this methodology (Hissel 2011), one such categorization of the risk-prone areas has been proposed as follows:

- Zone a: breach zone (with $hv \geq 7m^2/s$);

- Zone b: maximal water height $h \geq 1m$;
- Zone c: maximal water height ($0.5m \leq h < 1m$);
- Zone d: maximal water height ($0.25m \leq h < 0.5m$);
- Zone e: maximal water height ($h < 0.25m$).

Zone b, c, d, e are respectively defined only by the flood water depth (h). Zone a refers to the dike failure prone areas and the parameter is defined by the flood water depth (h) multiplied by the flow velocity (v).

According to the studies mentioned above, the terms: zone a, zone b, zone c, zone d, zone e are chosen to represent the values of the qualitative variables of the criteria “local danger level”. In section 4.3.2, the flood depth has been chosen as the single quantitative variable, because it is often the only data known in practice and it facilitates the consistency of the fuzzy simplified model. Therefore, the zone a, b, c, d, e are finally categorized only by the flood depth. They correspond to five ranges of values for flood depths that are shown in Table III-6 (Priest et al. 2007, Delft Hydraulics 2007).

Local danger level	Description	Critical values (m)
Zone a	Deep flood water might result in destabilization of people or collapses of buildings. In this case, the danger is for all	> 2.0
Zone b	The ground floor of the houses will be flooded. In this case, the danger is for all	$[1.0, 2.0]$
Zone c	The ground floor of houses with shallow flood water, and electricity will have failed. In this case, the danger is for most of people	$[0.5, 1.0]$
Zone d	Non-floating rescue vehicles will not be able to travel. In this case, the danger is for some (e.g. child, elderly, disabled, etc.)	$[0.25, 0.5]$
Zone e	Most houses will stay dry and it is still possible to walk through the water, and little danger for people directly contact with flood waters	< 0.25

Table III-6 The values of the criterion for the local danger level

4.3.3. **Qualitative variable of areas vulnerability**

The FLOODsite project (EU-FP7), which studied the risk of flood to life, proposed the following definitions and classification for the levels of area vulnerability (high, medium and low), mainly depending on the ability of sheltering in place (Priest et al. 2007).

- High vulnerability, with few shelters in direct contact with flood waters: areas include mobile homes, campsites, bungalows and poorly constructed properties, open fields;

- Medium vulnerability, with some shelters: typical residential areas with mixed types of properties;
- Low vulnerability with many shelters in theory. However, in severe flooding the integrity of these shelters may be compromised by either structural damages or in some cases total collapse: areas characterized by multi-storey apartments and masonry concrete and brick properties.

There are no technical/physical values for the nature of areas. However, in order to build a continuous membership function (see section 4.4.1), we assume that each level of area vulnerability can be assigned a number, for example 1, 2 and 3 corresponding to, low, medium and high (Priest et al. 2007). This abstract correspondence is made to be homogeneous with other criteria of the method and to be able to define membership functions for the global fuzzy reasoning. Table 7 shows the correspondence between these values and their description.

Area vulnerability	Description	Critical values
High	Few shelters like mobile homes, campsites, open fields	3
Medium	Some shelters like typical residential areas, mixed types of properties.	2
Low	Areas with much shelter in theory including multi-storey apartments and masonry concrete and brick properties.	1

Table III-7 The values of the criterion of the area vulnerability

4.3.4. **Qualitative variable of capacity and safety of evacuations**

For the capacity and safety of evacuations, we chose the quantitative variable estimating the evacuee ratio, which represents the percentage of people that can be evacuated before the flooding reaches the concerned area (see section 4.2.4). The evacuation traffic models (e.g. Evacuation Calculator see Chapter II) can actually estimate the percentage of people able to evacuate in a given duration.

According to existing evacuation plans, studies and returns of experience, there are no clear identification of cases that could help categorize this parameter. There are nevertheless interesting returns of experience of the response to an evacuation alert that propose some figures and hints. During hurricane Georges in the U.S (1998), the percentage of the residents in the affected states who actually evacuated varied from 70% to 88%, when the evacuation order was given (Post, Buckley, Schuh & Jernigan, Inc. 1999). Jonkman (2007) assumed that about 95% of people evacuate after an evacuation order during a flood in Netherland, where there is a strong policy of prevention and awareness. Evacuation plans in the Val d'Orléans in France (Goutx et al. 2011) assumed that 70% of the residents would evacuate by themselves and that 30% of them will need rescuing services. As we see through these examples, the evacuee ratio very depends on the local context, the prevention policy, the culture of risk and evacuation.

Therefore, in this study, we simply propose to categorize this parameter through a variable with five qualitative values [very low, low, medium, high, very high] corresponding to interval of values of the percentage of people achieving evacuation (see Table III-8).

Capacity and safety of evacuations	Description	Critical values (%)
Very high	Nearly all people achieve evacuations.	> 80
High	Most of the people achieve evacuations	$[67.5, 80]$
Medium	About half of people achieve evacuations	$[37.5, 67.5]$
Low	Some people achieve evacuations	$[27.5, 37.5]$
Very low	A few of people or few achieve	$[0, 27.5]$

Table III-8 The values of the criterion of the capacity and safety of the evacuation

4.3.5. **Definition of qualitative variable of the NTE**

In existing sites, a cost-benefit approach of evacuation is often proposed to analyze and help the evacuation decision (Lindell & Prater 2007a, Kailiponi 2010, Frieser 2004). This approach is clearly not adapted to the main objective of saving lives.

Nevertheless, other methods are proposed, like the estimated evacuation possibility (varied from 0 to 100%) used to analyze the risk of evacuation decision (Goutx et al. 2011). In this approach, the percentage of the population to evacuate is estimated based on the discharge of the flood related to the frequency. Some critical values of the percentage of the population are proposed and analyzed in this study such as 10%, 20%, 50% etc.

In this study, the necessity to evacuate (NTE) is proposed to synthesize the decision criteria. The necessity to evacuate is defined as the level of potential need for evacuation in local areas, relatively to the priority objective of people's security. It can vary from 0 to 100%. It gives a synthetic indicator for decision makers, resulting from the fuzzy multicriteria analysis based on the four input criteria: global risk, local danger, area vulnerability and evacuation capacity and safety in case of a flood emergency. It is assumed that this indicator is defined by five qualitative values in the sets "very low", "low", "medium", "high", "very high" corresponding to the level of NTE expressed as a ratio or a percentage (see Table III-9).

NTE	Critical values (%)
Very high	> 80
High	$[67.5, 80]$
Medium	$[37.5, 67.5]$
Low	$[27.5, 37.5]$
Very low	$[0, 27.5]$

Table III-9 The values for the criterion of the necessity to evacuate (NTE)

4.4. Step 3: fuzzification for inputs and outputs

After all qualitative and quantitative variables of decision criteria and NTE have been defined (see section 4.2 and 4.3), the inputs (decision criteria) and the output (NTE) of the fuzzy system for evacuation decision can be "fuzzified" through the design of membership functions (MFs). As aforementioned in section 3.3.2, there are different shapes of membership functions. In this study, the triangular and trapezoidal functions are assigned because it is quite easy to interpret them (linear extrapolation) and sufficient to design, test and evaluate our fuzzy logic system. More details are discussed in the following sections.

4.4.1. **Membership functions for the inputs**

The defined input criteria and their variables (reminded and synthesized in Table III-10) are used to experiment the fuzzy logic method with a representative example. This example aims at illustrating the fuzzy model for the evacuation decision, but the values in this model are also those applied in Chapter IV for a more complete case study analysis.

Criteria	Qualitative variables	Qualitative variables
Global flood forecast level	Minor, moderate, major flood	Forecast water levels
Local danger level	Zone a, b, c, d, e	Local Flood depths
Vulnerability of areas	Low, medium, high	Types of land use
Capacity and safety of evacuations	Very low, low, medium, high, very high	Estimated evacuee ratio

Table III-10 Criteria and their variables for the flood evacuation decision

Firstly, for the criterion of the global flood forecasted level, as defined in section 4.3.1, qualitative values and the correspondence with the clear boundaries of the global flood forecast levels are described in Table III-11.

Global forecasted levels	Green	Yellow	Orange	Red
Forecast water level (m)	< 6.5	[6.5, 6.7]	[6.7, 7.0]	> 7.0

Table III-11 Qualitative values with the clear boundaries of the global forecast level

Hence, the fuzzy sets (corresponding to the 4 qualitative values) of the global flood forecasted level are defined with four membership functions (Figure III-20). These membership functions and the form of the curves are defined from typical values. Take the fuzzy set “yellow” for example; it is assumed that 6.5m and 6.7m respectively take 0.5 as degree of membership. Then, the triangular membership function of the “yellow” set is defined with three typical numerical values: the typical value 6.6 for “yellow” defines a full-membership point (the value of degree equals 1), the typical values 6.4 and 6.8 respectively define non-membership points (the value of degree equals 0). The MFs of the “green”, “orange” and “red” set can be defined similarly (see Figure III-20).

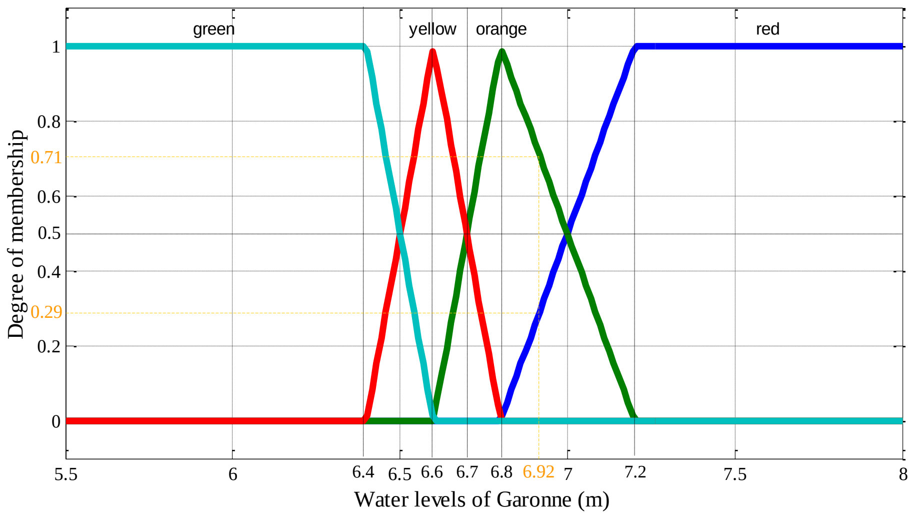


Figure III-20 Membership functions for the global flood forecast level

The choice of these typical values largely depends on the experience in a certain field. A reliable output of the fuzzy decision system thus depends on these choices that must be done judiciously in agreement with specialists. This is the critical process of calibrating the system with an expertise and reliable data. It is here that the experience of the system developer becomes very important

As shown in Figure III-20, each possible value of the water level will belong to at least one fuzzy set and possibly to more than one fuzzy set. The adjacent fuzzy sets/values (ex: yellow and orange) are designed to overlap, and this is one of the foundations and interest of fuzzy logic to manage the transition between two values. A rule of thumb suggests ensuring that the sets overlap by approximately 25% (Tan et al. 1995). For example, a value of water level of 6.92 m is seen to be a member of two sets: a 0.71 degree of membership in the "orange" set and a 0.29 degree of membership in the "red" set, and a 0 degree of membership in the two other sets. The continuity of the membership functions in the interval [0 1] avoids abrupt discontinuities that would be caused by the assignment of precise boundaries in binary logic. It seems to be a better way to manage the transition from a threshold to another in decision making and management under uncertainty.

Secondly, for the criterion of the local danger level, as defined in section 4.3.2, Table III-12 shows the qualitative values with the clear boundaries of the local water levels.

Local danger levels	Zone e	Zone d	Zone b	Zone c	Zone a
Local water level (m)	< 0.25	$[0.25, 0.5]$	$[0.5, 1.0]$	$[1.0, 2.0]$	≥ 2

Table III-12 Qualitative variables with the clear boundaries of the local danger level

Five MFs are defined as shown in Figure III-21.

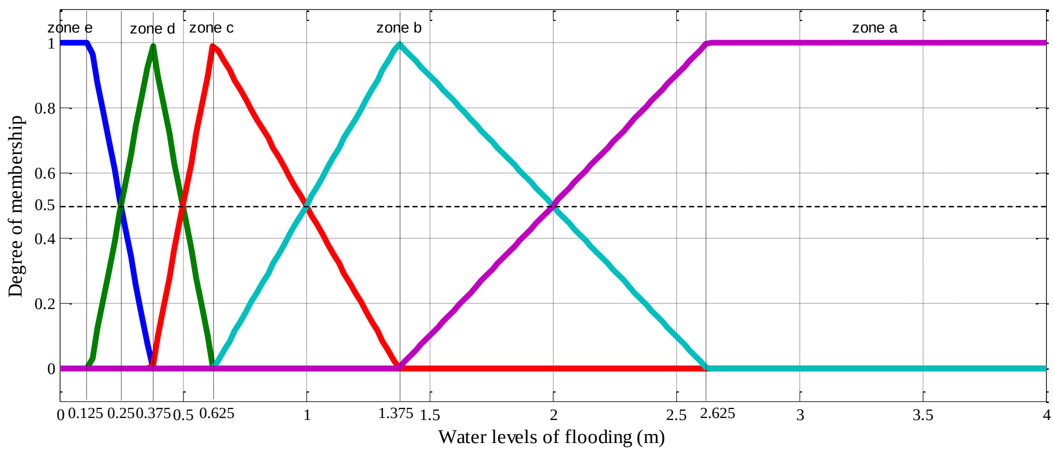


Figure III-21 Membership functions for the local danger level

Thirdly, concerning the criterion of the area vulnerability, as defined in section 4.3.3, Table III-13 shows the correspondence between qualitative values and numerical values, which in this case is just a convention.

vulnerability of areas	Low	Moderate	High
Numerical value	1	2	3

Table III-13 Qualitative variables with clear boundary of the area vulnerability

Three MFs of the area vulnerability are shown in Figure III-22. In some cases the membership functions describe nonphysical values of inputs, in order to be homogeneous with other criteria, but this has no negative effect on the global fuzzy algorithm.

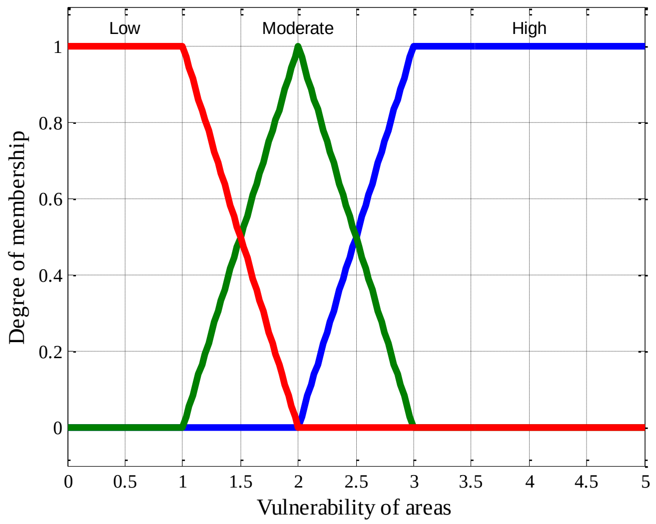


Figure III-22 Membership functions for vulnerability of areas

Fourthly, for the criterion of the capacity and safety of evacuations, as defined in section 4.2.4, Table III-14 shows the qualitative values and the correspondence with the boundaries of the evacuee ratio.

Capacity and safety	Very low	Low	Medium	High	Very high
Evacuee ratio	$[0, 27.5]$	$[0, 37.5]$	$[37.5, 67.5]$	$[67.5, 80]$	> 80

Table III-14 Qualitative values of the capacity of evacuation and the corresponding intervals of the evacuee ratio

The Five MFs of the evacuation safety and capacity criterion are illustrated in Figure III-23.

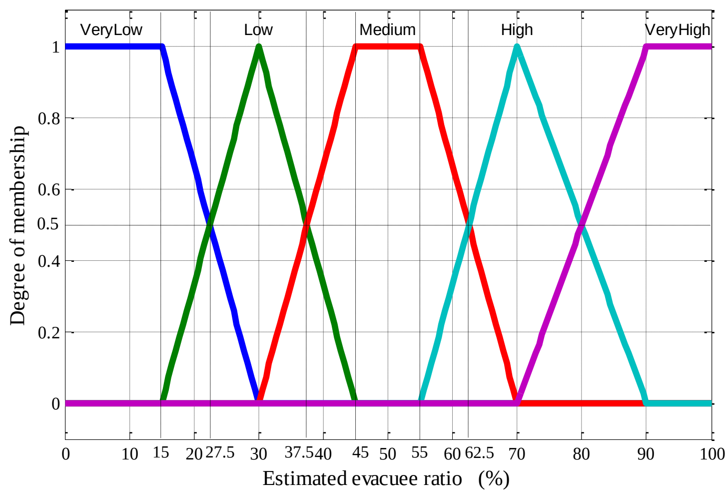


Figure III-23 Membership functions for evacuation safety and capacity

All input values of criteria are now transferred into fuzzy sets by the definition of membership functions. So it becomes easier to make a synthesis of such heterogeneous criteria to get the final output of necessity to evacuate, which tends to be closer to the final decision. Such synthesis is realized thanks to an "if-then" fuzzy rule base. This will be discussed in section 4.5.

4.4.2. **Membership functions for the output**

The necessity to evacuate (NTE) is defined as the output of this fuzzy system for the evacuation decision. Like input criteria, it also needs to be fuzzified in order to apply the rules.

For the NTE, as defined in section 4.3.5, Table III-15 shows the qualitative values with the corresponding boundaries of the ratio for the NTE.

Necessity to evacuate(NTE)	Very low	Low	Medium	High	Very high
% of NTE	$[0, 27.5]$	$[0, 37.5]$	$[37.5, 67.5]$	$[67.5, 80]$	> 80

Table III-15 Qualitative variables with clear boundary of the NTE

Five membership functions of the output are defined (Figure III-24), similarly to the inputs.

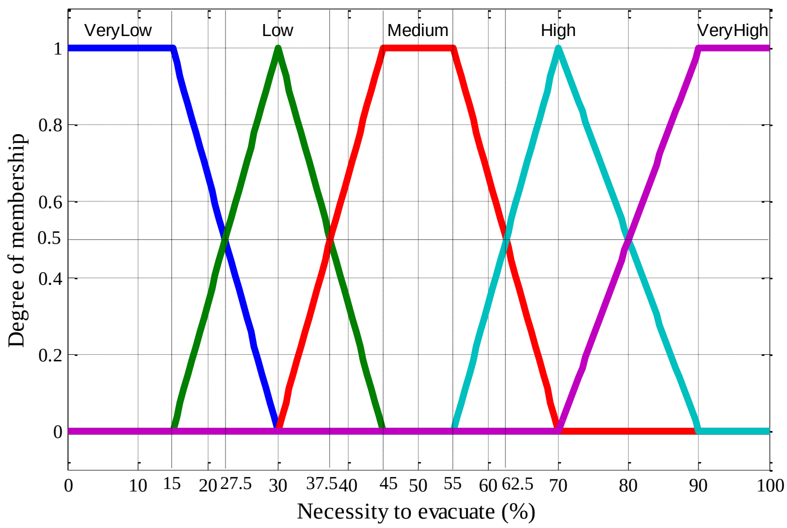


Figure III-24 Membership Functions for the necessity to evacuate (NTE)

The output membership functions aid in determining a final value of the necessity to evacuate with the defuzzification procedure, which will be discussed in section 4.6.5.

4.5. Step 4: the rule base design

An "if-then" rule consists of a condition (if-part) and a conclusion (then-part). The conditional statements include expressions on the values of qualitative variables and the fuzzy logical relations between these variables. An example of such a rule might be:

IF global forecast level is red AND local danger level is zone a AND area vulnerability is high AND capacity and safety to evacuate is very high, THEN necessity to evacuate is very high

The “if-then” rules express various kinds of potential situations that may happen and the conclusion that can be inferred according to an existing knowledge and experience. In this study, the knowledge to define the rules is based on the analysis of relative research papers, technical reports, government documents etc. (e.g. Priest et al. 2007, Tapsell & Priest 2009, Hurricane Evacuation Studies, PCS 2008, Evacuation operational guidelines of Taiwan 2010, Shaw et al. 2011). Once a first basic and general model is made, it can be calibrated and improved on each local case with the help of local experts and managers.

The knowledge available is actually limited, particularly at the beginning of a new case analysis, and only part of the all potential rules can be defined in the fuzzy system. However, the rule base can be completed with new rules with the contribution of new expertise or return of experience, thus improving the accuracy of the fuzzy model on the long term.

Theoretically, the total number of possible rules that can be defined in a fuzzy system is equal to all combinations of qualitative values of inputs. For example, in this fuzzy system, the total number of rules is $4 \times 5 \times 3 \times 5 = 300$. All potential combinations of qualitative values of criteria that can postulate to the evacuation rules in our model can be found in Appendix C.

It is easy to see how the number of rules rapidly expands with the number of inputs and related fuzzy sets. Thus, it is necessary to simplify the handling of the rules or/and to limit the number of inputs in a fuzzy system. One solution is to merge several initial criteria to form synthetic indicators as inputs of the fuzzy system. Another solution consists in developing a multi-layers fuzzy system (see Figure III-25). The details about multi-layers fuzzy systems are out of the scope of this thesis, but it could be put forward as a perspective of our proposal.

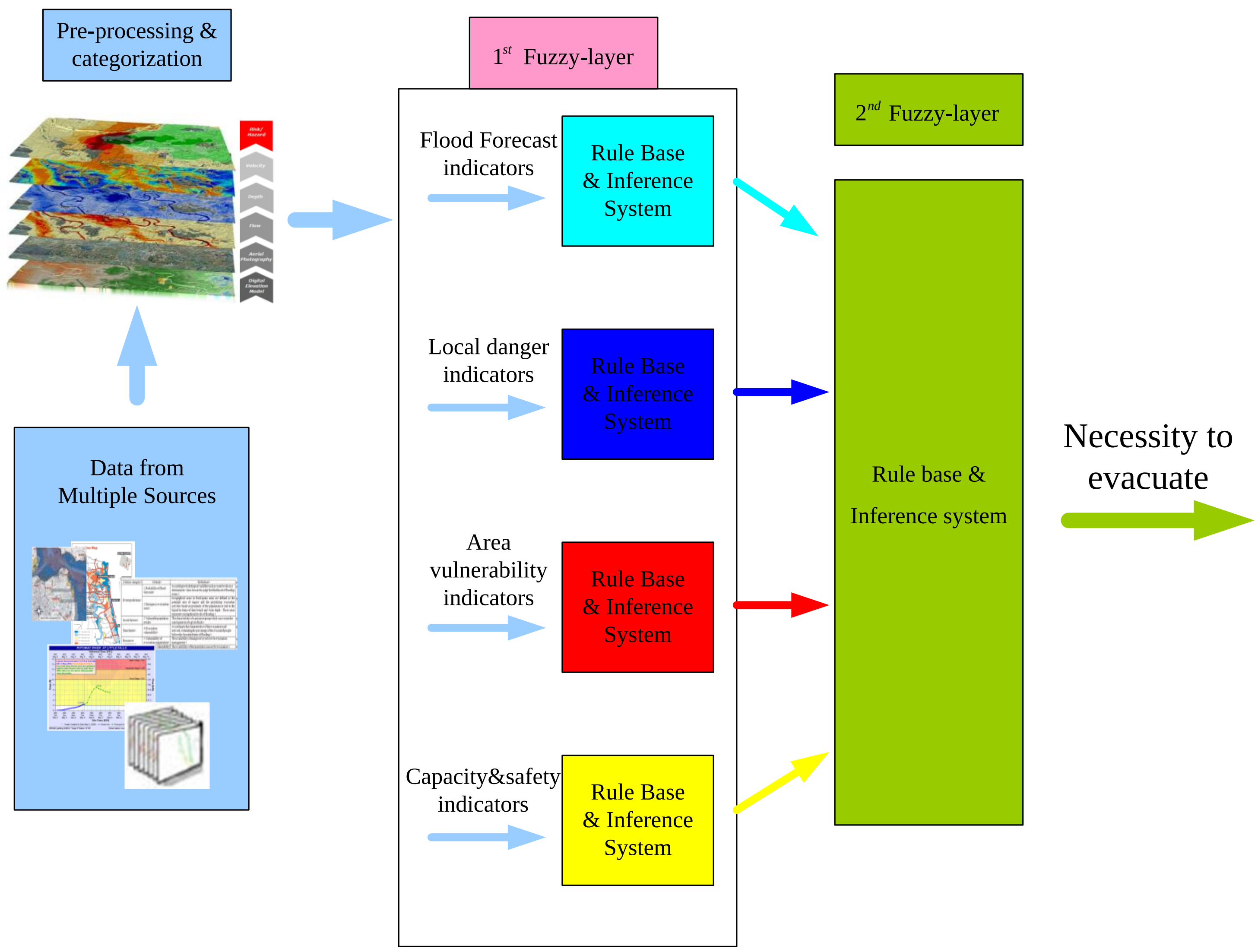


Figure III-25 Overview of the architecture of a multi-layers version of our fuzzy system

4.6. Step 5: the fuzzy inference system and the interpretation for decision

The rule base for the evacuation decision is interpreted from given input values of criteria to an output value of the NTE through the fuzzy inference system, which includes membership functions (see section 4.4), fuzzy operators (see section 3.3.4), implication operators (see section 3.3.5) and defuzzification methods (see section 3.4.4). The fuzzy inference process includes five steps (see Figure III-26):

1. Step 5.1: application of membership functions to get fuzzy inputs from real values of criteria;
2. Step 5.2: application of fuzzy operators to get one fuzzy input;
3. Step 5. 3: application of the implication operators to get fuzzy outputs;
4. Step 5.4: application of fuzzy operators to aggregate one fuzzy output;
5. Step 5.5: application of defuzzification methods to get one non-fuzzy value of output.

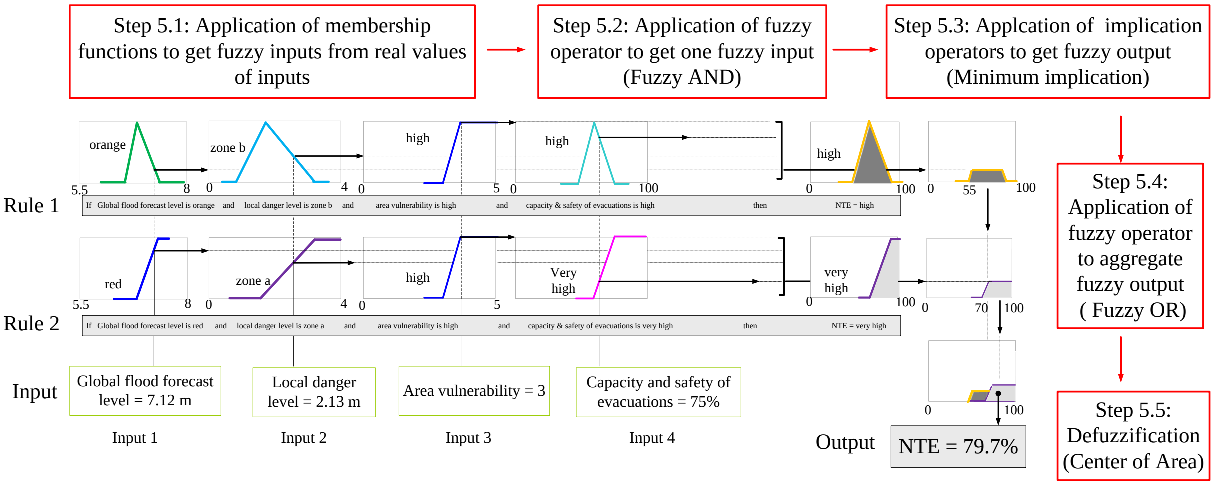


Figure III-26 Overview of the steps of the fuzzy inference system

Figure III-26 illustrates the data flow of decision criteria (from left to right), from four input numerical values to a single output value of the necessity to evacuation (NTE), processed by the rule base for the evacuation decision. The value of the final NTE varies from 0 to 100%.

To get a general idea about how the fuzzy system works, the inference process is explained through a simplified example (only two rules are interpreted), step by step, in the following sections.

Our example is made of two rules:

1. If global flood forecast level is orange and local danger level is zone b and area vulnerability is high and capacity & safety of evacuations is high then NTE is high;
2. If global flood forecast level is red and local danger level is zone a and area vulnerability is high and capacity & safety of evacuations is very high then NTE is very high.

and given the real values of the four input criteria as follows:

$$Global\ flood\ forecast\ level = 7.12m;$$
$$local\ danger\ level = 2.13m;$$
$$area\ vulnerability = 3;$$
$$capacity\ \&\ safety\ of\ evacuations = 75\%$$

4.6.1. **Step 5.1:application of membership functions to get fuzzy values from real values of criteria**

The first step consists in applying membership functions of inputs (see 4.4.1) to get fuzzy values from real values of criteria. For example, to fuzzify the real value (7.12) of the global flood forecast level associated with fuzzy variable "red" within Rule 1, the degree of membership of the "red" set is 0.8 based on the MFs of the global flood forecast level (see Figure III-27).

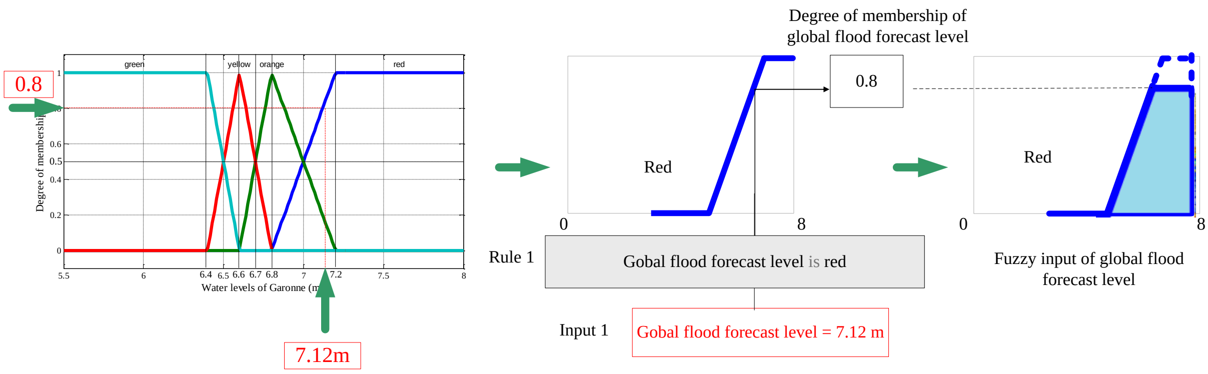


Figure III-27 Example of fuzzifying the initial value of the global forecast criteria

In this way, each real value of the four decision criteria is fuzzified over all the qualified membership functions required by the rules. Our example includes four inputs and two rules, so the results of the fuzzification are four fuzzy inputs within each rule (see Figure III-28).

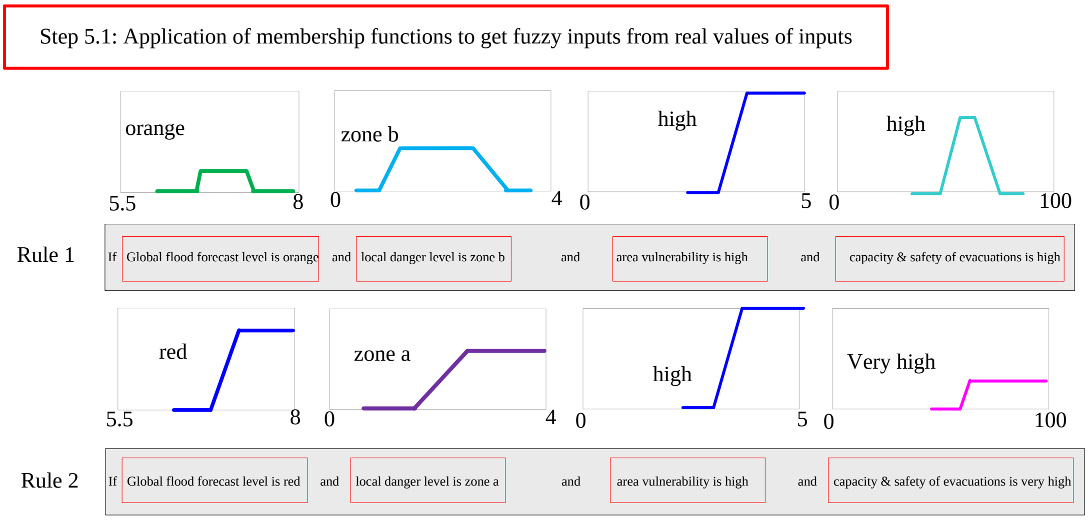


Figure III-28 Results of the fuzzification first step applied to 2 rules

4.6.2. **Step 5.2: application of fuzzy operators to get one fuzzy input**

The second step consists in combining all fuzzy inputs (for each rule) to get a single fuzzy input using fuzzy operators corresponding to the logical operators used in the conditional part of the rules (AND, OR …). For example, AND is used to link the four inputs within Rule 1 ("global flood forecast is orange AND local danger level is zone b AND area vulnerability is high AND capacity & safety of evacuations is high"). As defined in section 3.3.4, two standard fuzzy operators (fuzzy AND, fuzzy product) can be applied to the logical relation AND.

$$Fuzzy\ AND: \mu(x) = \min(\mu_i)\,;$$
$$Fuzzy\ product: \mu(x) = \text{product}\ (\mu_i).$$

The fuzzy AND operator is chosen in this example. The operation of minimizing the four fuzzy inputs within the "if-part" of Rule 1 (degrees of membership: 0.2, 0.4, 1.0 and 0.75) yields one fuzzy input (degree of membership is 0.2) for Rule 1 (see Figure III-29 Rule 1). The operation of minimizing the four fuzzy inputs within the "if-part" of Rule 2 (maximum degrees of membership: 0.8, 0.6, 1.0, and 0.25) yields one fuzzy input (degree of membership is 0.25) of Rule 2 (see Figure III-29 Rule 2).

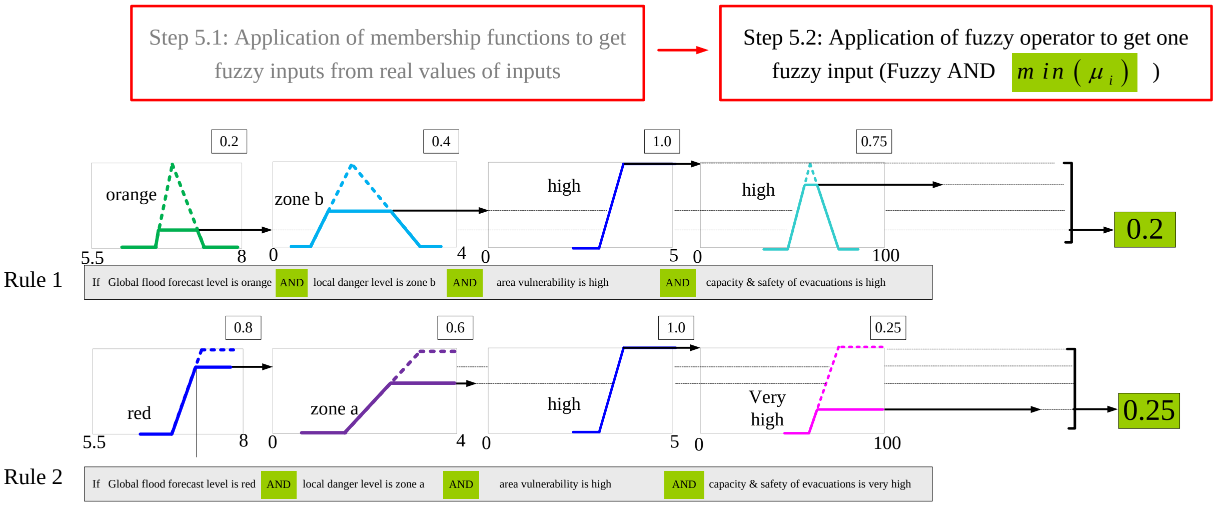


Figure III-29 Examples of combining fuzzy inputs to get a single input, using the fuzzy AND operator

4.6.3. **Step 5.3: application of the implication operators to get fuzzy output for each rule**

The third step aims at applying implication operators (see section 3.3.5) to get a fuzzy output within each rule. The minimum implication operator is chosen for our example (see Figure III-30).

$$Minimum\ implication: \mu_{A\to B}(x,y) = \min(\mu_A(x), \mu_B(y))$$

For example, the "then-part" of Rule 1 ("… then NET is high") indicates the fuzzy output: membership function of the "high" set (degrees of membership from 0 to 1). The degree of membership of the combined fuzzy input is 0.2 (see Figure III-29 Rule 1). The application of the minimum implication operator (min (0.2, 1)) reshapes (or "cuts") the MF of "high" set of the NTE at 0.2 (the degree of membership of the combined fuzzy input of Rule1 - see Figure III-30 Rule 1). Similarly, the MF of the "very high" set of the NTE within Rule 2 can be determined at 0.25 (the degree of membership of the combined fuzzy input of Rule 2) (see Figure III-30 rule 2).

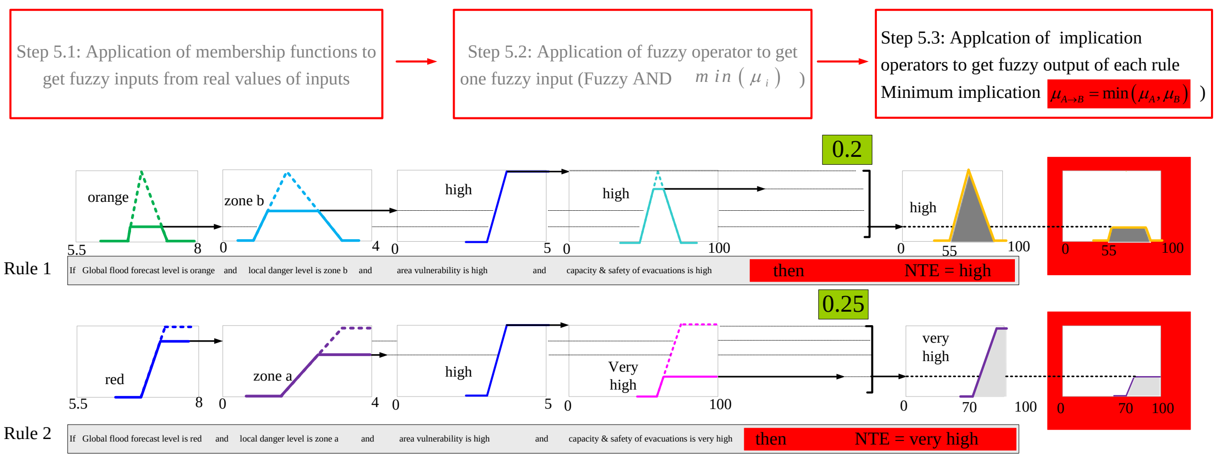


Figure III-30 Example of applying minimum implication operator to get fuzzy outputs

4.6.4. **Step 5.4: application of fuzzy operators to get one fuzzy output**

The fourth step of the inference process consists in applying fuzzy operators (see section 3.3.4) to aggregate all fuzzy outputs within the rule base. Two standard fuzzy operators (fuzzy OR, fuzzy sum) can be used to aggregate all the rules.

$$Fuzzy\ OR: \mu(x) = \max(\mu_i)\,;$$

$$Fuzzy\ sum: \mu(x) = \sum \mu_i - \mathrm{product}(\mu_i).$$

Fuzzy OR operator is chosen for the example. Rule 1 has a maximum degree of membership of 0.2, while the one of Rule 2 is 0.25. The fuzzy OR operator ($\max(0.2, 0.25)$) yields the maximum degree of membership of the final fuzzy output as 0.25. The two reshaped fuzzy outputs have been put together to show how the results of all rules are combined into a single fuzzy set of the NTE (see Figure III-31).

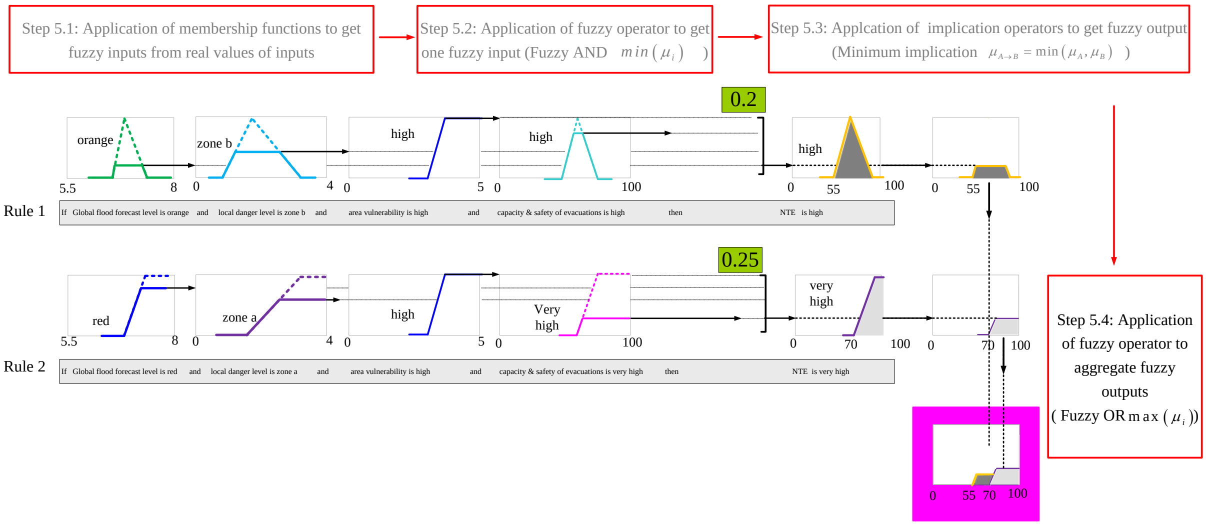


Figure III-31 Example of applying fuzzy OR operator to get one fuzzy output

4.6.5. **Step 5.5: application of a defuzzification method to get one final value of the NTE**

The fifth step consists in applying a defuzzification method (see section 3.4.4) to get the final value of the NTE. The center of area (COA) method is chosen for the example (see Figure III-32). The final value of the output (NTE) based on the two rules is 79.7%.

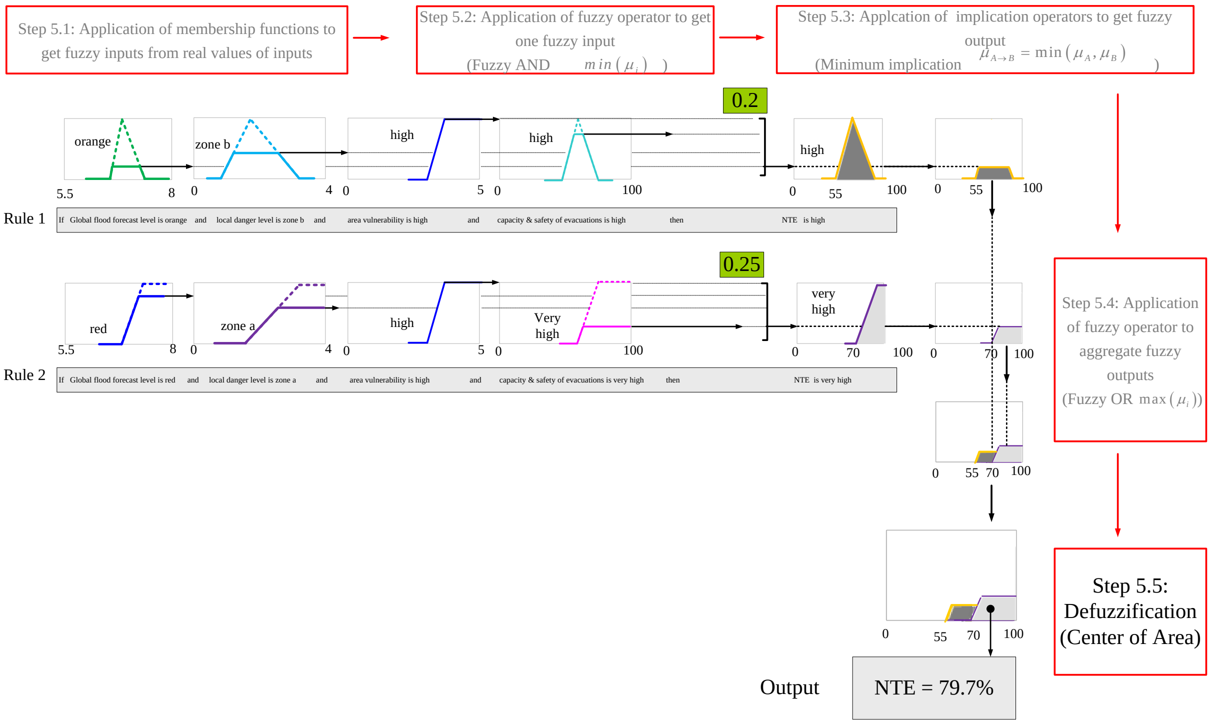


Figure III-32 Example of applying defuzzification methods to get the final value of the NTE

Once one gets this final numerical value of NTE through the fuzzy logic complete process, the way it can be exploited for decision making is developed in further sections, especially in section 4.9.

4.7. Step 6: implementation of the method with Matlab tools and sensibility analysis

4.7.1. **Overview of the tool and interface**

As explained above, a multicriteria fuzzy evacuation decision model has been set up using fuzzy logic (see from section 4.2 to section 4.6). This model was implemented with the Matlab Fuzzy Logic Toolbox™. All the examples presented in Chapter III and IV have been designed and tested with this tool but details of this implementation are technical and are not developed in this thesis report (see the user guide document for the Matlab Fuzzy Logic Toolbox™)

This tool also allows intuitive visualization of 3D fuzzy surfaces, which can represent the relations between two variable inputs (the others being fixed) and one output. This kind of representation can help understand how the system is going to behave for the entire range of values in the input space (see Figure III-34). As well, it can be used to check and calibrate the rules and the membership functions, and to see if appropriate modifications are needed to improve the output. If necessary, the rule base for the fuzzy sets is modified until the output curves fit the experts' point of view.

This Matlab Fuzzy Logic Toolbox™ includes the Fuzzy Inference System (FIS) Editor to help design the fuzzy model system. Figure III-33 shows the interface of the FIS Editor.

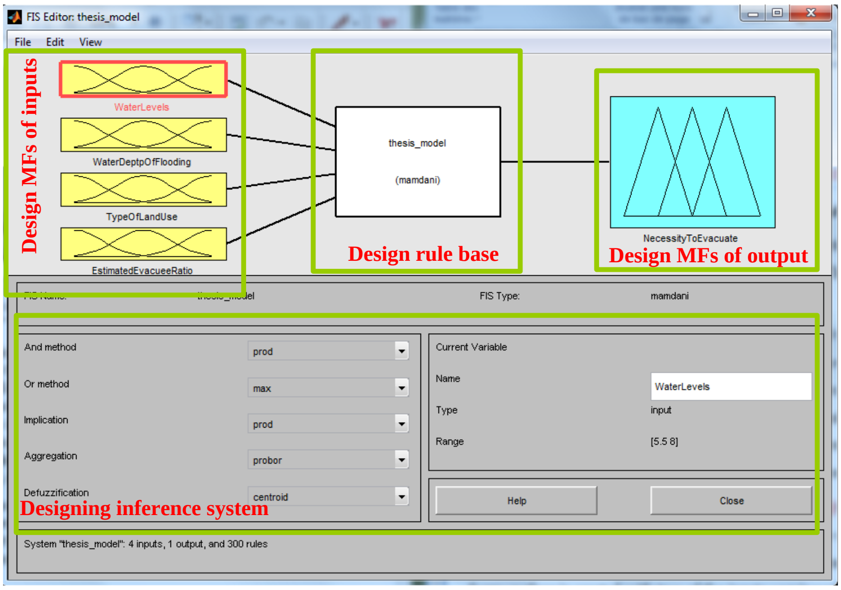


Figure III-33 Interface of the FIS Editor in the Matlab Fuzzy Logic Toolbox™

Figure III-34 shows the interface of the Surface Viewer which visualizes 3D surfaces from three parameters of the model.

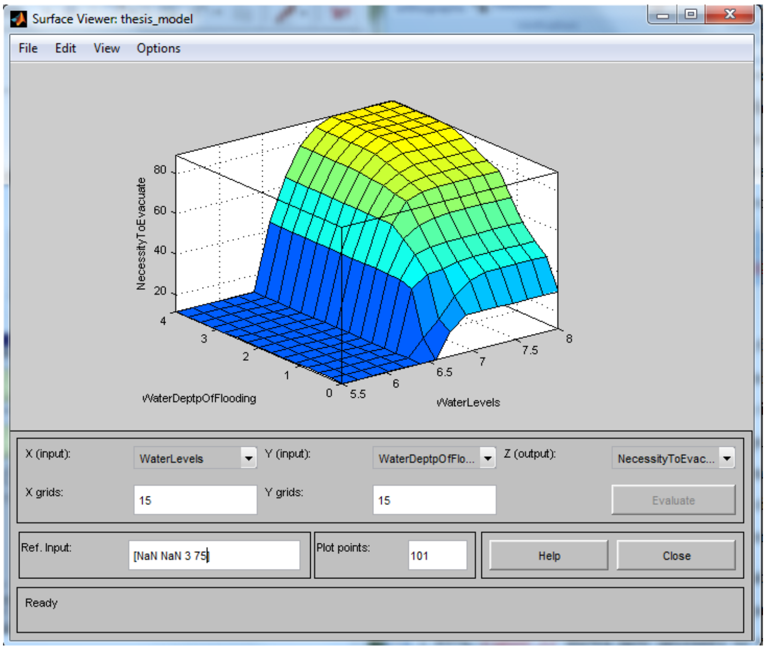


Figure III-34 Interface of the Surface Viewer

4.7.2. **Examples of scenarios and sensitivity analysis**

For the evacuation decision problem, the simplified fuzzy model we proposed above includes four inputs and one-output. In this case, a 3D fuzzy surface cannot show in one shot the entire numerical relations between all input criteria and the necessity to evacuate (one single output), which would need a five-dimensional space. In such a case, several 3D fuzzy surfaces are created with two of the inputs varying while the two other inputs remain constant, which are shown through different examples from Figure III-35 to Figure III-38. So, each surface corresponds to one scenario (hypothesis on the fixed value of two input parameters) and permits to make a sensibility analysis of the NTE output with the two others input variables.

In the first scenario, the local area vulnerability is fixed at low (the value =1) and the evacuation capacity and safety at very high (the value = 95%). Figure III-35 shows how the NTE behaves with the variation of the global forecasted level and the local danger level. This evolution is quite logic and evident for the common sense but the 3D curve enables to assess the detailed evolution of the output and possibly to detect threshold effects of the input variable or combination of inputs. For example, it is noticeable that NTE becomes very sensitive when the global forecasted level approaches 7m and local danger level simultaneously approaches 2m. In Bordeaux, global forecasted level reaching 7m indicates flood warning in “red”. And the low vulnerability area means that there are multi-storey apartments and buildings that can provide shelter-in-place for population in theory. Thus, the NTE significantly increases over than 50% with a local danger level above 1.25m. For this figure, the NTE tendency is actually limited in the range [10% - 90%], because with the defuzzification method (center of area) of aggregate fuzzy sets, the two ends of the range around 0 and 100% cannot be fully reached. However, this does not affect the NTE as decision support. The suggestions about evacuation action can well be done according to the available range [10%-90%] of necessity to evacuate. In the future, it is expected to find the solution to improve this range narrowing problem.

The second example scenario represents the situation where the global forecasted level reaches 6.9m (flood warning in orange) and the area vulnerability is low (the value=1). Figure III-36 shows how the NTE varies with the local danger level and the estimated evacuee ratio. In this scenario, it can be noticed that the NTE mainly depends on the local danger level. However, when the estimated evacuee ratio falls under 40%, regardless of the increase of the local danger level, the NTE is no more than 50%. This kind of remark should indicate that there also exist minimum thresholds for available resources to trigger an evacuation for example, which can also be from common sense, but it is the kind of information that some decision makers can forget in a panic situation.

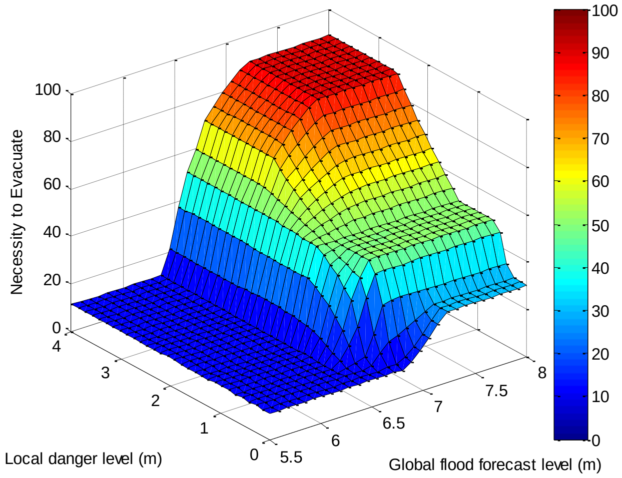


Figure III-35 Fuzzy surface of NTE varying with the global forecasted level and the local danger level

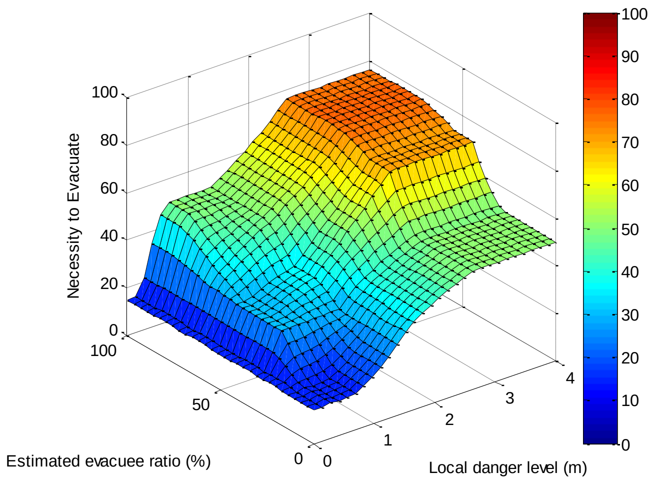


Figure III-36 Fuzzy surface of NTE varying with the local danger level and the evacuee ratio

The third example scenario represents the situation where the local danger level is fixed at 2m (very dangerous) and the area vulnerability is low (the value=1). In this scenario, the NTE varies with the global flood forecast level and the evacuee ratio shown in Figure III-37. When the estimated evacuee ratio is less than 40%, regardless of the increase of the global flood forecast level, the NTE is no more than 50%, like in scenario n° 2

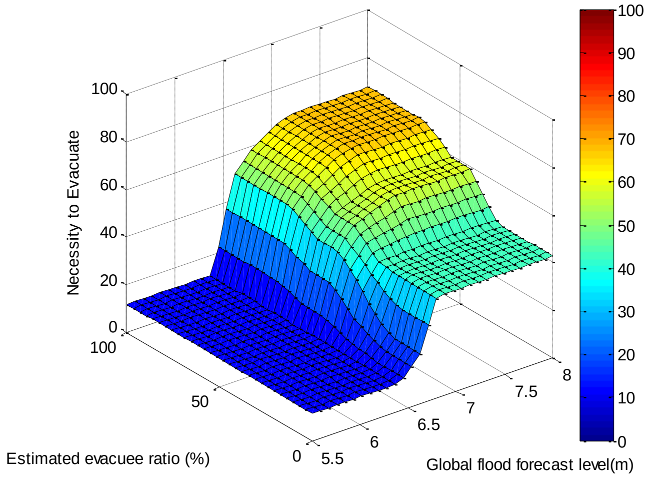


Figure III-37 Fuzzy surfaces of NTE varying with the global forecasted level and the Evacuee ratio

In the last two cases (scenarios 2 and 3), it can be noticed that the low estimated evacuee ratio logically limits the NTE rate since the efficiency of the evacuation is limited.

The fourth scenario represents the situation where the local danger level is fixed at 2m (very dangerous) and the evacuation capacity and safety is very high (the value=80%). Figure III-38 shows how the NTE varies with the global forecasted level and the area vulnerability. In this case, the NTE does not change significantly with the area vulnerability, because the area capacity of preventing from floodwaters is logically very limited, especially faced to a catastrophic event.

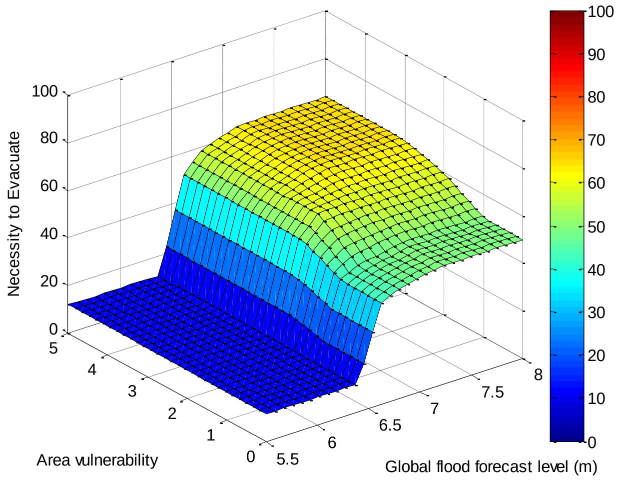


Figure III-38 Fuzzy surfaces of NTE varying with the global forecasted level and the area vulnerability

In conclusion, the fuzzy 3D surfaces synthesize and reflect fairly well the original information included in the shape of the fuzzy relations between decision criteria and the NTE. They enable to analyze the relative influence of two parameters on the output.

Moreover, this sensibility analysis both helps to calibrate the fuzzy non-linear model and to study and compare different scenarios and strategies of evacuation. In this perspective, the fuzzy decision model can also be used as a tool for evacuation plan preparation.

4.8. Fuzzy system application to the spatial dimension

Spatial data about topography and other specific topics of the territory is a major ingredient in almost all public decision making (Burrough & McDonnell 1998, Cornélis & Brunet 2002). Oort & van Bregt (2005) estimated that 80% of data used by policy-makers in public decisions is spatial. Obviously, the spatial data about topography, flood hazard, land use, roadways network etc. plays an important role in public decision for flood evacuations (Shaw et al. 2011). Geographical Information Systems (GIS) are generic software tools that offer a set of ready-made services for spatial analysis and decision support. These services can be adapted to specific topics and problems including a spatial component like risk management, crisis management and mass evacuation. GIS can provide maps, spatial database, statistics, data analysis and decision support. Maps are the graphical visualization of the area's geographic features; the database contains the georeferenced information displayed on the map; statistics is the information resulting from the database that has been processed and analyzed to display particular trends, and decision support is the final step of the interpretation of those analyses. When integrated into a GIS, the maps, the database and statistics become very powerful tools, especially for emergency management. A lot of studies and research can be found especially in the fields of flood risk analysis and evacuation planning (Meyer et al. 2007, Zhou et al. 2010, Wang 2005).

This section will address the way by which the fuzzy logic evacuation decision model can be applied to the spatial dimension. Here, spatial data is processed with the ArcGIS platform, one of the most used GIS in the world. According to the local characteristics of the territory and the city, the local necessity to evacuate (NTE) can be analyzed by the fuzzy model and the final results displayed on maps, which make the NTE for decision makers more intuitive to understand and interpret. The spatial application is detailed in the case study of the Chapter IV.

4.8.1. **Data preparation with the ArcGIS platform**

Firstly, it is necessary to prepare the spatial data about quantitative values of decision input criteria, which are organized in a series of thematic layers (e.g. local forecast water levels, area vulnerability, estimated evacuee ratio etc.) Figure III-39 shows the examples of decision criteria organized by thematic layers. It must be noticed that some input parameters can remain constant, and it is the case in our simplified model for the two parameters of the global flood forecast and the evacuee ratio criterion which does not vary in space. So, in the case of our model, the spatial operation for data preparation mainly concerns local hazard (local water levels) and area vulnerability (ground occupation). In a future evolution of the model, we can imagine that the evacuee ration could vary in different district of the cities.

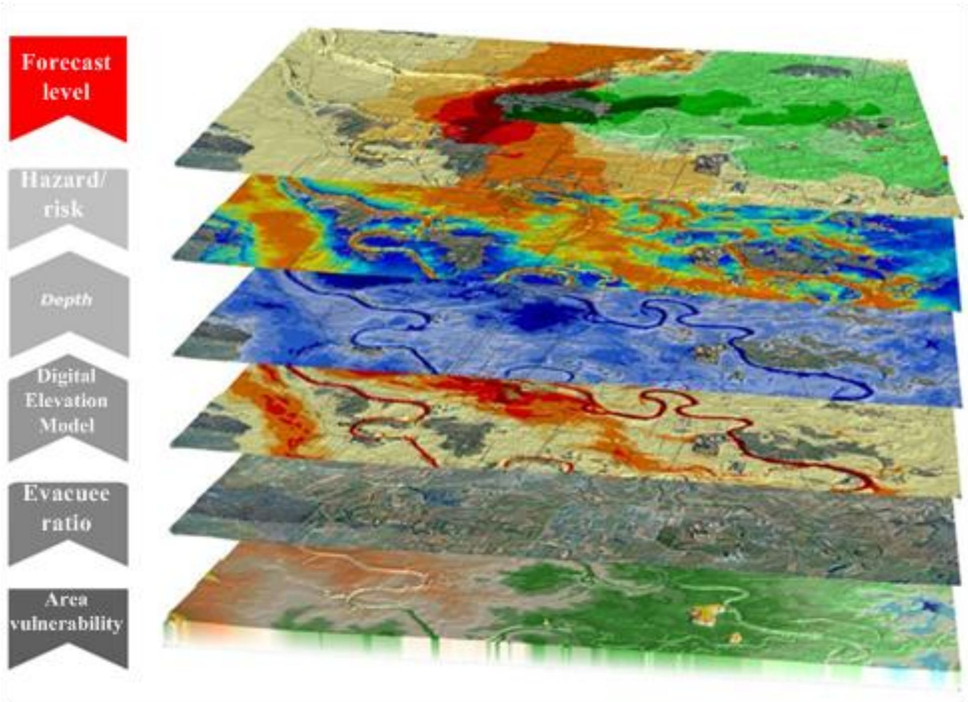
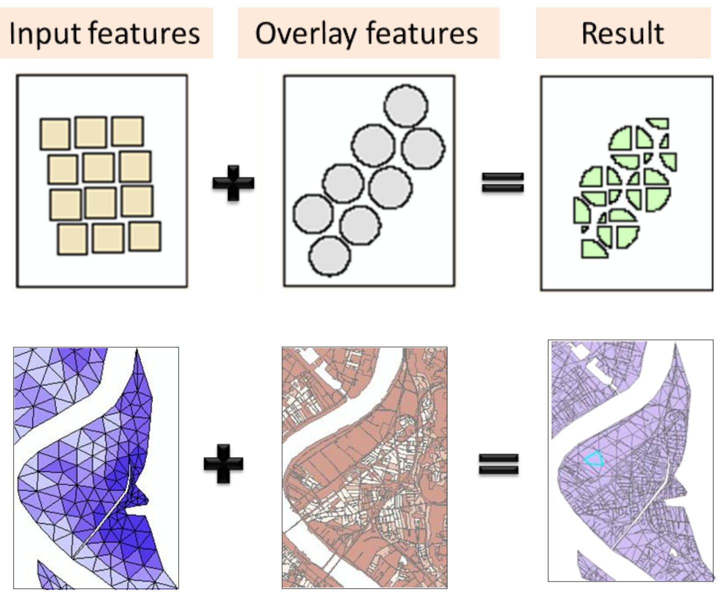


Figure III-39 Spatial decision criteria organized by layers

In order to create a new vectorial map which homogenizes the decision criteria data, it needs to overlay the corresponding thematic layers. The new map of the overlain data must locally aggregate the characteristics of the decision criteria into one dataset before being processed by the fuzzy algorithm. This spatial first step needs to determine the new topology of intersected geometric entities where the sets of values of the decision criteria can be defined.

The intersection overlay tool of ArcGIS is used to cross the two vector layers of flood water levels (polygons) and area vulnerability (polygons). The water levels polygons are split where two kinds of polygons of the area vulnerability layer are intersected and the new polygons are assigned the attributes of both original layers, as shown in Figure III-40. Then, the resulting overlain vector layer includes the attributes of the two layers: flood water levels and the area vulnerability. The same process could be extended to more criteria if needed.

Overlay operation: intersection



ArcGIS vector overlay tool:
Intersection

Example: overlay flood hazard layer
and area vulnerability layer

FID	Shape *	ID	VAL0	VAL1	VAL2	VAL3	VAL4
0	Polygone	1	0.074787	0.100754	2.13399	3.82899	1.695
1	Polygone	3	0.054361	0.080736	2.051278	3.829278	1.778
2	Polygone	5	0.047093	0.052716	1.982518	3.826852	1.844333

+

FID	Shape	CITIES	CODE	PROD DATE	SHAPE AREA	AREA VUL
0	Polygone	Bordeaux	12220	2010	0.279328	3
1	Polygone	Bordeaux	12220	2010	0.13249	3
2	Polygone	Bordeaux	12220	2010	0.194165	3
3	Polygone	Bordeaux	12220	2010	0.054241	3

FID	Shape *	VAL0	VAL1	VAL2	VAL3	VAL4	CITIES	LUZ OR CIT	CODE	PROD DATE	SHAPE AREA	AREA VUL
0	Polygone	0.009916	0.0239	0.095293	5.095293	4.999999	Bordeaux	FR007L	12100	2010	0.268181	3
1	Polygone	0.009916	0.0239	0.095293	5.095293	4.999999	Bordeaux	FR007L	20000	2010	18.678097	3
2	Polygone	0.030162	0.028873	0.082013	5.082013	5	Bordeaux	FR007L	20000	2010	18.678097	3
3	Polygone	0.030162	0.028873	0.082013	5.082013	5	Bordeaux	FR007L	30000	2010	8.535571	3

Figure III-40 Example of overlay thematic layers on decision criteria

In the example, the overlain vector layer table includes polygon geometrical features and each polygon has the attributes about decision criteria (e.g. flood hazard and area vulnerability). As the global flood forecast level and estimated evacuee ratio is supposed to keep the same value at the regional scale, their value also remains constant in the spatial projection of the fuzzy model

4.8.2. **Importing spatial data into the evacuation decision fuzzy model**

Since the evacuation decision fuzzy model is built with the Matlab Fuzzy Logic Toolbox^{TM}, the spatial data of the decision criteria need to be exported from ArcGIS to Matlab. Before doing this import into the Matlab toolbox and in order to be processed by the fuzzy operational model, the table of attributes must first be transformed into an Excel file format. Then, the fuzzy complete algorithm implemented with Matlab can be applied on each row of the file corresponding to a geometric entity where the criteria values are constant.

Finally and inversely, the obtained output of the NTE with Matlab can be imported into ArcGIS to create the spatial distribution map of the NTE. Figure III-41 illustrates the process of the fuzzy logic model applied to the spatial dimension.

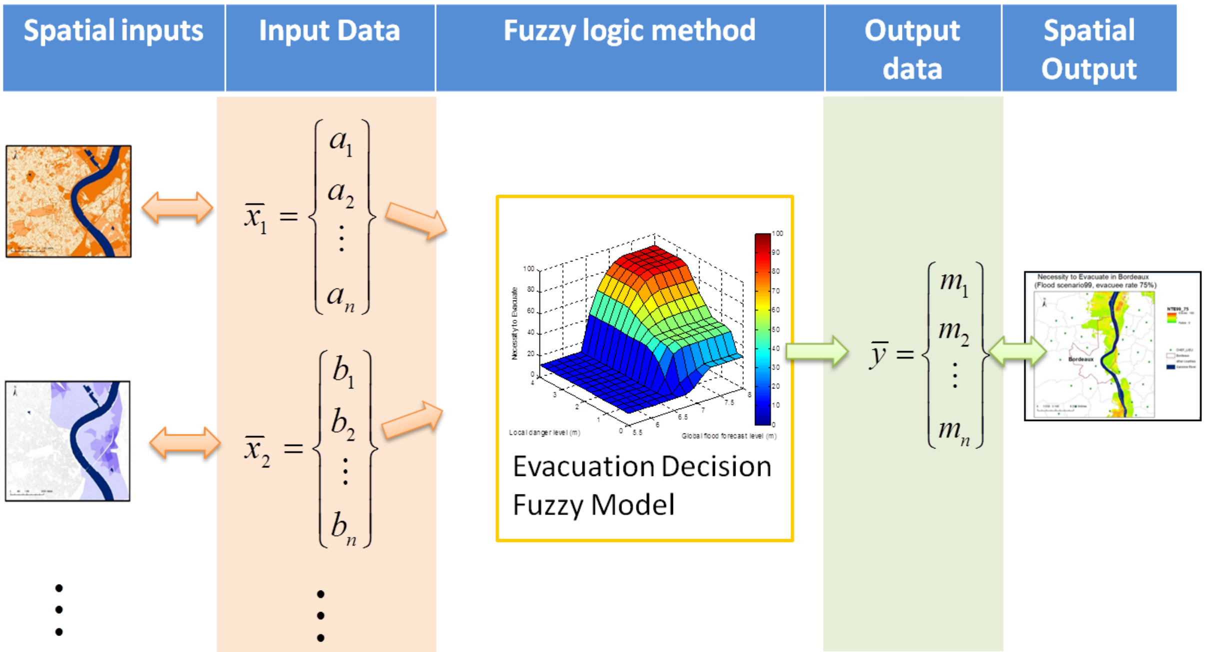


Figure III-41 Overview of the fuzzy logic process applied to the spatial dimension

4.9. Final interpretation of the NTE rate as decision support for mass evacuations

The fuzzy logic method and tool for evacuation decision presented in this chapter should greatly help develop a coherent and clear strategy to estimate the necessity to evacuate flood prone areas. This local necessity to evacuate is expected to help decision makers to better understand the context of the crisis, to identify the main information concerning a possible need of evacuation, and finally take a decision based on a multicriteria analysis.

In this perspective, we propose to make a link between the final numerical value of NTE (expressed in %) and a set of qualitative values like: very low, low, medium, high and very high. Then, these values can be interpreted in terms of evacuation decision strategies such as "no evacuation", "advisory evacuation" or "mild evacuation" and "urgent evacuation order" (Shaw et al. 2011). One possible solution for the corresponding suggested actions associated with the necessity to evacuate could be that listed in Table III-16 (Tapsell & Priest 2009, Priest et al. 2007, Shaw et al. 2011).

Evacuation option	Description	Necessity to evacuate (%)	
No evacuation	No additional actions are necessary	very low	(0, 15)
Watchfulness	Precaution of the flood risk including the preparation for evacuation	low	(15, 40)
Advisory evacuation	Partial evacuation, some people at risk are advised to evacuate (those too vulnerable to flood risk to life)	medium	(40, 65)
Mild evacuation order	Recommendation of full evacuation, majority of people at risk to evacuate	high	(65, 80)
Urgent evacuation order	Order of full evacuation, public at risk is strongly urged to leave the area affected.	very high	(80, 100)

Table III-16 Suggested actions associated with the necessity to evacuate

5. Conclusion

In this chapter, an evacuation decision fuzzy model has been proposed to assess the necessity to evacuate based on four decision criteria (the global flood forecast level, the local danger level, the area vulnerability and the capacity & safety of evacuations) and this model has been applied in the spatial dimension (Figure III-42).

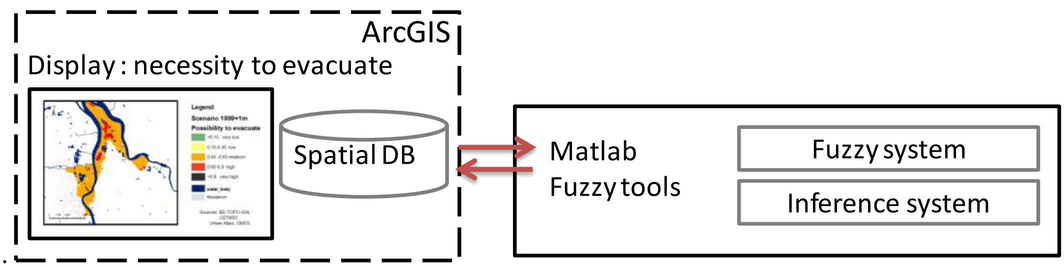


Figure III-42 Framework of the evacuation decision fuzzy model applied in the spatial dimension

Then, this conceptual fuzzy model has been firstly implemented with the Matlab Fuzzy Logic Toolbox™, which mainly includes the membership functions for the decision criteria and the NTE, and a rule base with an inference system to produce the NTE from the inputs, based on heuristic rules. Secondly, the data implying a spatial dimension about the decision criteria have being pre-processed with the ArcGIS platform, and then imported into the evacuation decision fuzzy model to evaluate the NTE of a specific area. Finally, the NTE spatial values can be imported into the ArcGIS platform to be displayed on maps. The NTE maps can be used as decision support for the evacuation management

The evacuation decision fuzzy model qualifies a non-linear relation between the decision criteria and the necessity to evacuate (NTE), based on the heuristic rules using fuzzy logic. It will provide a NTE assessment for officials in a specific area for different scenarios and circumstances. Therefore, according to the value of the NTE, the corresponding strategies (e.g. no evacuation, advisory evacuation, mild evacuation, urgent evacuation order) for the final evacuation decision can be suggested.

The limits and weaknesses of our model and tool are analyzed at the end of Chapter V and suggestions are made to improve them on this existing basis.

Chapter IV. Spatial application of the fuzzy logic method with ArcGIS in Bordeaux City

1. Introduction

In Chapter III, we developed a fuzzy logic system for evacuation necessity analysis. In this chapter, the method is applied to the French city of Bordeaux prone to a submersion coming from the Gironde estuary and/or the river Garonne. The objective of the following pilot study is to analyze the spatial distribution of the necessity to evacuate (NTE) in Bordeaux city for different historical and prospective scenarios of flood in order to help authorities to make a final decision based on the average NTE.

The results of the NTE visualized on a map are used to answer the following questions:

- Where is an evacuation actually needed in Bordeaux, given a certain forecast, scenario and other hypotheses?
- To which extend is it really possible to successfully and safely evacuate a risk prone area?

Even if this decision support method was initially envisaged for real-time crisis management, the results described in this chapter can be exploited both for evacuation planning (calibrating evacuation scenarios) and emergency response measures (decide and manage an action plan).

This chapter begins with a brief description of the pilot city of Bordeaux in section 2 (a more complete one on the regional and local context can be found in Appendix D.). Then, section 3 gives a description of the input data which is the basis of the case study. In section 4, the NTE results in Bordeaux, obtained from historical flood events and future climate change scenarios by the fuzzy logic method, are analyzed and visualized on maps.

2. Study areas: Bordeaux city

Bordeaux is a city in the South-West of France which is prone to submersion in case of the conjunction of a big maritime storm and a high tide in the Gironde estuary, which has already happened in 1999 (Lothar-Martin storm) and 2010 (Xynthia storm) also in 1981, in a limited extent. In the future, this kind of exceptional event and sea level rise can be worsened by the long-term consequences of climate change. Potential more severe scenarios including climate change and see level rise have been studied in the framework of the THESEUS FP7 EU project (Laborie et al. 2012). Thanks to this project and previous studies, we could use existing maps of floods (given by a hydraulic 2D model), vulnerability and evacuation plans to experiment our proposal. A maximum extent of sea level rise by 1 meter is also taken into account in this study (IPCC 2007, ONERC 2010).

3. Data description of the case study

3.1. Forecast and flood data

Data on the forecasted water levels and flood alert can be obtained from Météo-France and Vigicrues 12 hours in advance. Flood maps corresponding to this data were calculated by a hydraulic 2D model called TELEMAC, which is developed by CETMEF/EDF/SOGREAH. The Gironde model on TELEMAC was made by SOGREAH. (SOGREAH 2009a).

Three flood scenarios were tested in this study (the flood of 1981, the flood of 1999 and a hypothetical exceptional flood including a 1m sea level rise corresponding to 1999 scenario+1m).

3.1.1. **The flood of 1981**

The flood event of 1981 happened on 13 December 1981 in Bordeaux. It was mainly caused by a high tide (tidal coefficient 106) and strong winds (86km/h). The maximum water level of the tide gauge of the services of the Port Autonome de Bordeaux (PAB) was estimated at 5.04m NGF in Bordeaux on 13 December 1981 (SOGREAH 2009b). The return period of this flood event was estimated between 50 and 100 years.

Figure IV-1 shows the flood map corresponding to this scenario, rebuilt by CETMEF and CETE (Centre d'Etudes Techniques de l'Equipement) of Bordeaux with the TELEMAC model. It can be seen that the north of Bordeaux and the right bank of the Garonne were flooded, with flood water levels in most of the flooded areas inferior to 0.25m, some places over 0.5m on the right bank, but no place over 1m. If we only analyze this flood map and before applying our method, it seems that it is needed to evacuate in no places, except may be for non autonomous people like elders, children, disabled in the flooded outdoors/one-story-house.

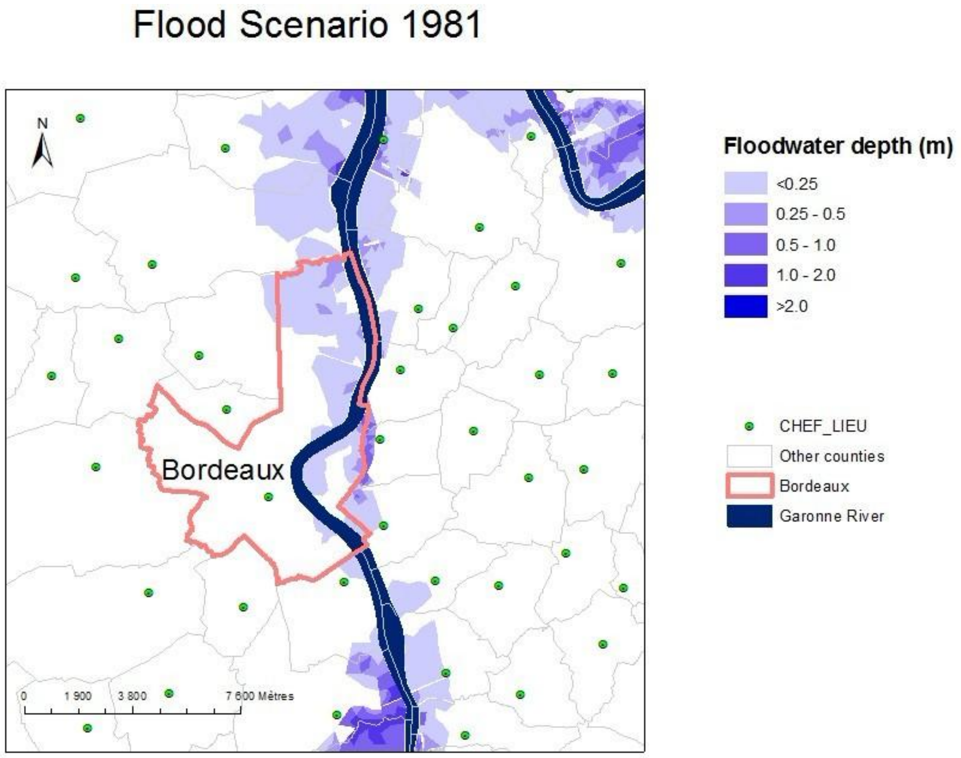


Figure IV-1 Flood water depths of the 1981 flood (source: SOGREAH, BD TOPO)

3.1.2. **The flood of 1999**

The flood event of 1999 happened on December 27th, 1999 in Bordeaux. It was mainly caused by a storm surge despite a low tide coefficient and a low discharge of the Garonne. The amplitude of the storm surge reached 2.25m in Bordeaux and the speed of storm winds reached 194km/h. This storm caused a great flood, which happens less than once every century. The maximum water level of the tide gauge of Bordeaux was estimated as 5.24m NGF in Bordeaux on 27 December 1999 (SOGREAH 2009b).

It can be seen on Figure IV-2 that the north and all the right bank of Bordeaux were flooded. The flooded areas by the 1999 flood are obviously more important in the right bank compared to the 1981 situation, and the flood water depth of some places was even over 1.0m. The eastern border of Bordeaux on the right bank suffered from the deepest flood, most of which was between 0.5 and 1m. From this single flood hazard map, it tends to be reasonable to evacuate people in the border of Bordeaux in the right bank (the community of the Bastide). It is also suggested to evacuate vulnerable people (elders, children, disabled etc.) or in the outdoors/one-story-house in the north with flood waters over 0.5m.

From the flood hazard maps of 1981 and 1999, it can be seen that the areas on the right bank of the Garonne in Bordeaux are the one most prone to floods, especially because of the low topography of these areas. Therefore, these areas on the right bank are also the one most prone to be evacuated, especially during an extreme flood event. This analysis is confirmed by the Plan Communal de Sauvegarde (PCS) of Bordeaux city (2008), which indicates these areas as the zones to be evacuated during a flood crisis.

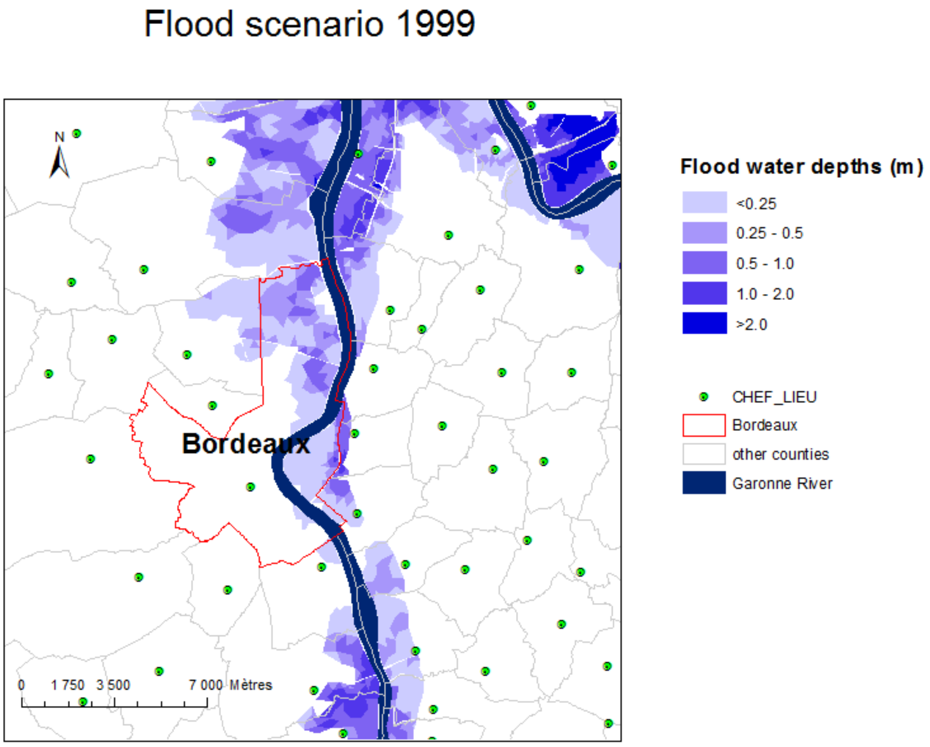


Figure IV-2 Flood water depths of the 1999 flood (source: SOGREAH, BD TOPO)

3.1.3. **The hypothetic flood based on a 1m-sea-level-rise (the flood of 1999+1m)**

The most recent report from the International Panel on Climate Change (IPCC 2007) estimated that the global average sea level will rise between 0.18m and 0.59m during the 21st century. More recent predictions from scientists at a climate change conference say that the melting of the polar ice sheets could raise sea levels by a meter or more by 2100 (Nicholls et Cazenave 2010). The studies of sea level rise in Gironde estuary (THESEUS EU FP7) indicated that the extreme scenario of sea level rise could be 1m. Therefore, the flood scenario 1999+1m has been assumed and chosen to represent a pessimistic but realistic flood hazard scenario in the context of climate change in the perspective of the 21st century.

Figure IV-3 shows the flood map corresponding to this scenario 1999+1m, which takes the input conditions of the 1999 flood and adds a sea level rise of 1m. It can be seen that a 1m sea level rise would significantly increase the flooded areas and the average depth of flood waters in urbanized prone areas. The flood waters could spread closer to the downtown of Bordeaux. The entire of the right bank would be flooded and the maximum depth of flood waters in the border areas of the right bank reaches 1.6m. It could be very dangerous for the people who live/work in these areas and this situation would certainly justify a mass evacuation of the north and east part of the city.

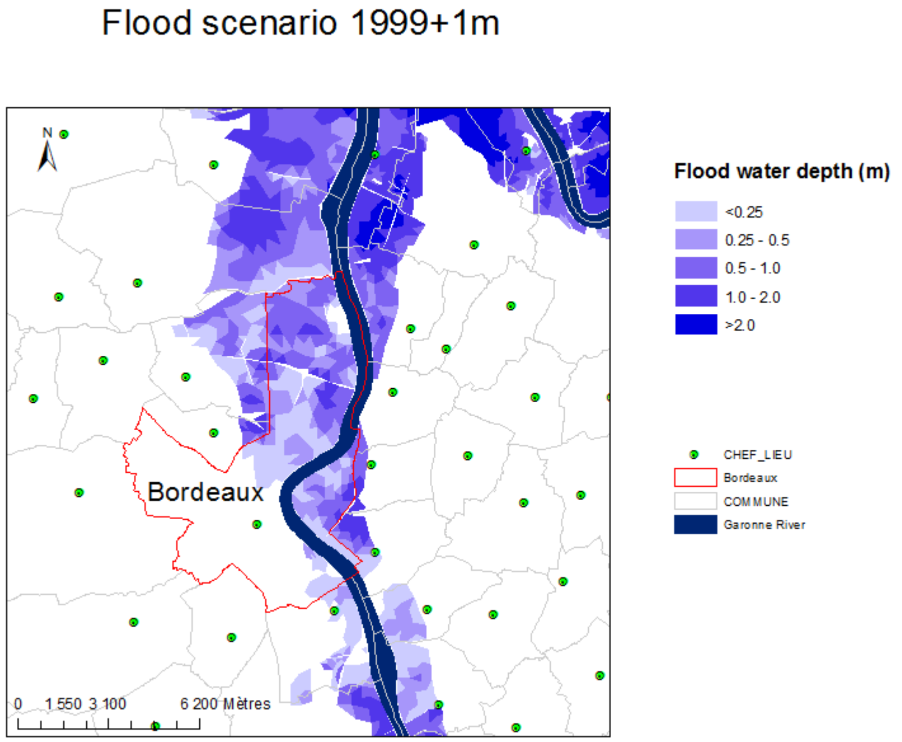


Figure IV-3 Flood water depths of the flood of 1999+1m (source: SOGREAH, BD TOPO)

As the climate change impacts the sea level rise and the extreme weather event, the conjunction of both can largely increase the flood risk for coastal and estuarine cities like Bordeaux. According to the experience, the flooding due to storm surges could bring much bigger damages. The real situation is more complicated since interactions of multiple phenomena increase the uncertainty. In the 1999+1m flood, it tends to be necessary to leave the flooded areas of Bordeaux city for safer areas in the neighborhoods.

3.2. Area vulnerability data

The vulnerability criterion for the evacuation model is based on the type of buildings that can be found in an area, which can provide different kinds of protection for people during the flood (see Chapter III, section 4.3). For example, tall buildings can endure higher flood water depths. As aforementioned, three levels (low, medium and high) are classified in the definition of this criterion. Then, this qualitative vulnerability must be represented in the spatial dimension.

Spatial information usually available includes the type of land-use, such as residential area, industrial and commercial areas, forest etc. For example, an open field or a campsite would be highly vulnerable as there is no shelter on the site. However, to define the degree of vulnerability for certain types of land-use, it is sometimes necessary to use expert knowledge on the type of buildings that can be found. The vulnerability could change depending on the activities within an area e.g. the presence of schools, hospitals or care homes. In the case of Bordeaux city, the vulnerability map has first been defined from the Urban Atlas, GMES (2006). The land use map distinguishes the types *continuous urban fabric*, *discontinuous urban fabric* and *others types of land use* like roads, forests, green areas etc. According to the *Urban Atlas 2006 Mapping Guide,* continuous urban fabric is mainly made of residential areas with a high degree of soil sealing, independent of their housing scheme (single family houses or high rise dwellings, city centre or suburb). Included are downtown areas and city centers, and central business districts as long as there is partial residential use. Discontinuous urban fabric is mainly made of residential areas containing 20-80% of non-sealed areas, independent of their housing scheme (single houses or high-rise dwellings, city center or suburb). The non-sealed areas might be private gardens or common green areas.

In this study, in order to simplify the representation of the vulnerability, the method for modeling the area vulnerability in the spatial dimension (Priest al et. 2007) assumes that:

- Continuous urban fabric has a low vulnerability;
- Discontinuous urban fabric has a medium vulnerability;
- The others (e.g. open areas, roads, special spots like schools, camp sites, hospitals etc.) have a high vulnerability.

The resulting vulnerability map is illustrated in Figure IV-4. It can be seen that the downtown of Bordeaux is mainly located in the left bank of the Garonne. However, there are still some residences located in the flood prone areas (the low-lying areas in the right bank and in the north). In particular, the industrial zones (e.g. ZAC Coeur) along the right bank of the Garonne River have a high vulnerability. The downtown of Bordeaux and the residences in the right bank have a low vulnerability based on the assumption that the buildings can provide a certain resistance to the flood waters in theory. As mentioned in section 2.2.3, in Bordeaux, about 200 000m^2 of the single one-stage houses face flood risk, with no possibility to get secure in a second stage. However, in this study, they are not distinguished from the multi-stage residences and this simplified vulnerability model is used to test the fuzzy method for the evacuation decision. In future researches, a more accurate and realistic vulnerability model is expected including more details about the buildings such as heights, situations etc.

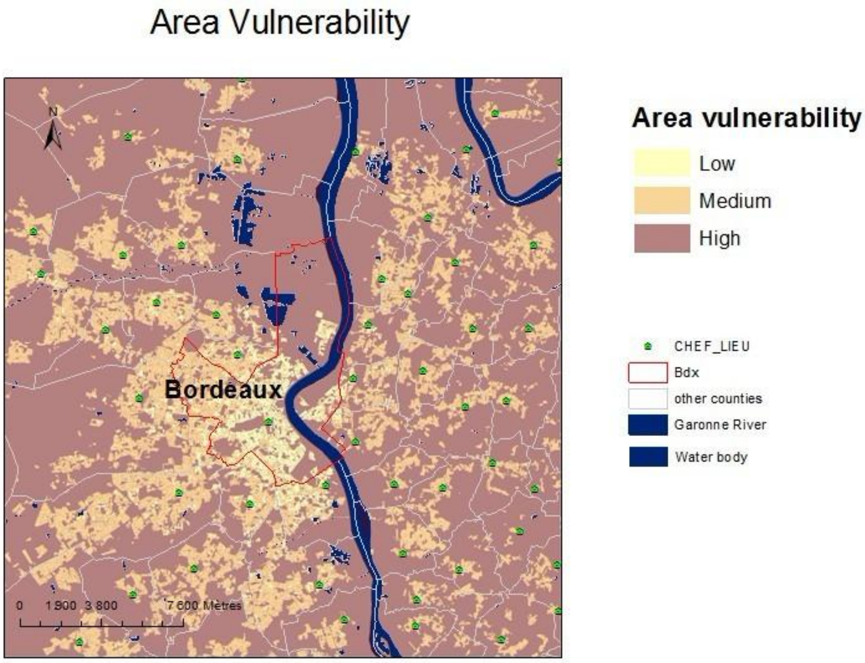


Figure IV-4 Area vulnerability map in Bordeaux according to our classification of land use (source: Urban Atlas, GMES, BD TOPO)

3.3. Data bout evacuation feasibility

Previous studies led within the THESEUS project (evacuation planning methodology, evacuation plans of Bordeaux) provide abundant information on the evacuation preparation and capacity (UTC-GSU 2011a). They also include a roughly estimation of the number of people to evacuate and the evacuation times using the Evacuation Calculator tool (Hissel 2011). However, there is no local return of experience and available data on evacuations in Bordeaux. That's why we propose to make a hypothesis about the global ratio of people who would achieve the evacuation. For that, three options were assumed: 25%, 50% and 75%, which respectively represents a low, medium and high estimated evacuee ratio (details are discussed in section 4.3.4 of Chapter III). These assumptions can be considered as three levels of possible situations (evacuation safety and capacity is low, medium and high) of the evacuation implementation on the ground.

4. Results and discussions

This section gives the results of the local NTE calculated values, based on the four input criteria discussed in section 3 and using the fuzzy logic method and their distribution on maps. In a specific area, the area vulnerability is relative stable in time, but the other three criteria depend on the actual situation over time. The local danger criterion is largely associated with the global forecast criterion. The global flood forecast criterion is considered as a constant value in the study area for each flood scenario. The local danger/water levels are given on maps by the hydraulic TELEMAC model outputs for the three scenarios (1981, 1999, and 1999+1m). The area vulnerability criterion is shown on the map in Figure IV-4. The estimated evacuee ratio has three hypothetical values (25%, 50%, and 75%). The criteria maps are overlaid with the ArcGIS platform. Then, the fuzzy method is applied to obtain the final NTE maps (see section 4.8 in Chapter III).

In this case study, the typical criteria scenarios are chosen to give comparative analysis of local NTE values. The resulting NTE maps are discussed within two groups of scenarios. Firstly, the results of the NTE are calculated and compared for the three selected flood scenarios (1981, 1999, and 1999+1m) with a fixed value of the estimated evacuee ratio of 75% (see section 4.1). Secondly, the results of the NTE are calculated based on the three estimated evacuee ratio only in the case of the 1999 flood (see section 4.2). The application and interpretation of NTE maps to support final evacuation decision is discussed in section 4.3.

4.1. NTE analysis for different flood scenarios

4.1.1. **NTE values distribution for different flood scenarios**

Given the evacuation capacity and safety at a high level (with the estimated evacuee ratio of 75%), Table IV-1 and Table IV-2 respectively show the results of NTE typical values (max, min, average) or intervals distribution in percentage, for the total flooded areas and for the respective flood scenarios of 1981 (50-100 year flood), 1999 (>100 year flood) and 1999+1m (1999 + climate change scenario). Only the NTE for the flooded areas are noted in this study.

Scenarios	NTE extreme and average values		
	Maximal NTE	Minimal NTE	Average NTE
1981 flood	52.1%	13.3%	28.9%
1999 flood	61.9%	21.0%	36.8%
1999+m1flood	78.1%	26.5%	43.6%

Table IV-1 NTE values characteristics in different flood scenarios with 75% of evacuee ratio

<u>Scenario 1981</u>

In case of the 1981 flood (50-100 years flood), the NTE ranges between 13.3% and 52.1% (see Table IV-1), and 92.1% of the flooded areas have an NTE in the interval 15% - 40% (see Table IV-2). The average NTE is 28.9% (see Table IV-2). In such case, the global characteristics of NTE values indicate the low necessity for triggering a mass evacuation in the whole affected areas, but it is necessary to take some protective actions to mitigate the impact of the flood on vulnerable areas, stakes and people.

Scenarios	NTE intervals				
	<15%	15% - 40%	40% - 65%	65% - 80%	> 80%
1981 flood	7.1%	92.1%	0.8%	0	0
1999 flood	0	59.5%	40.5%	0	0
1999+1m flood	0	35.8%	62.3%	1.9%	0

Table IV-2 Relative percentage of NTE interval values for the flooded area

Scenario 1999

For the1999 flood event (>100 years flood), the NTE varies between 21.0% and 61.9% in Bordeaux with the highest NTE values significantly increasing by 18.8 % compared to the previous scenario (see Table IV-1). About 60% of the flooded areas have an NTE ranging between 15% and 40% (see Table IV-2), while the NTE values of the other 40% of flooded areas reach the interval between 40% and 65%. The average NTE value increases by 27.3% compared to the 1981 flood average value, but this average NTE (36.8%, see Table IV-2) remains at a relatively low level. Therefore, in such a case, the global characteristics of NTE values indicate no mass evacuation in the whole affected areas, but an advisory evacuation decision can be considered locally because of some local NTE values reaching between 40% and 65%.

Scenario 1999+1m

For the hypothetic scenario 1999+1m, the highest NTE increases up to 78.1% at a high level (see Table IV-1). Compared with the event 1981 and 1999, the highest NTE increases respectively by 49.9% and by 26.6%. Once the NTE values are over 65%, an evacuation decision must be seriously envisaged. Table IV-2 shows that about 35.8% of the flooded areas have an NTE ranging between 15% and 40% (no evacuation), whereas 62.3% of the flooded areas range between 40% and 65%, About 2% get a high NTE (between 65% up to 78.1%). Compared with the 1999 flood, a 1m-sea-level rise makes the average NTE value reach 43.6% with an increase by 18.5% (see Table IV-2). In such a case, the global characteristics of NTE values indicate an advisory evacuation decision in the whole affected areas.

Global analysis and conclusions about NTE values characteristics

In summary, given the evacuation capacity and safety at a high level, the NTE values are limited at a relative low level in the whole affected areas in Bordeaux for the historical floods of 1981 and 1999. A mass evacuation in the whole city does not seem necessary in these cases, which seems confirms by the return of experience. However, in the context of an increasing flood risk due to climate change and a 1m sea level rise (the 1999+1m flood), this situation can largely increase the NTE values in Bordeaux city. Therefore, it makes sense to elaborate guidance for the preparation and management of evacuation for the increasing flood risk in the context of climate change.

4.1.2. **NTE spatial analysis for different flood scenarios**

Given an estimated evacuate rate of 75%, the resulting NTE maps for the three flood scenarios (1981, 1999 and 1999+1m) are illustrated through Figure IV-5 to Figure IV-7. On the NTE maps, local NTE values from low to high are represented by gradual color changes from green to red in the scale between [0, 1].

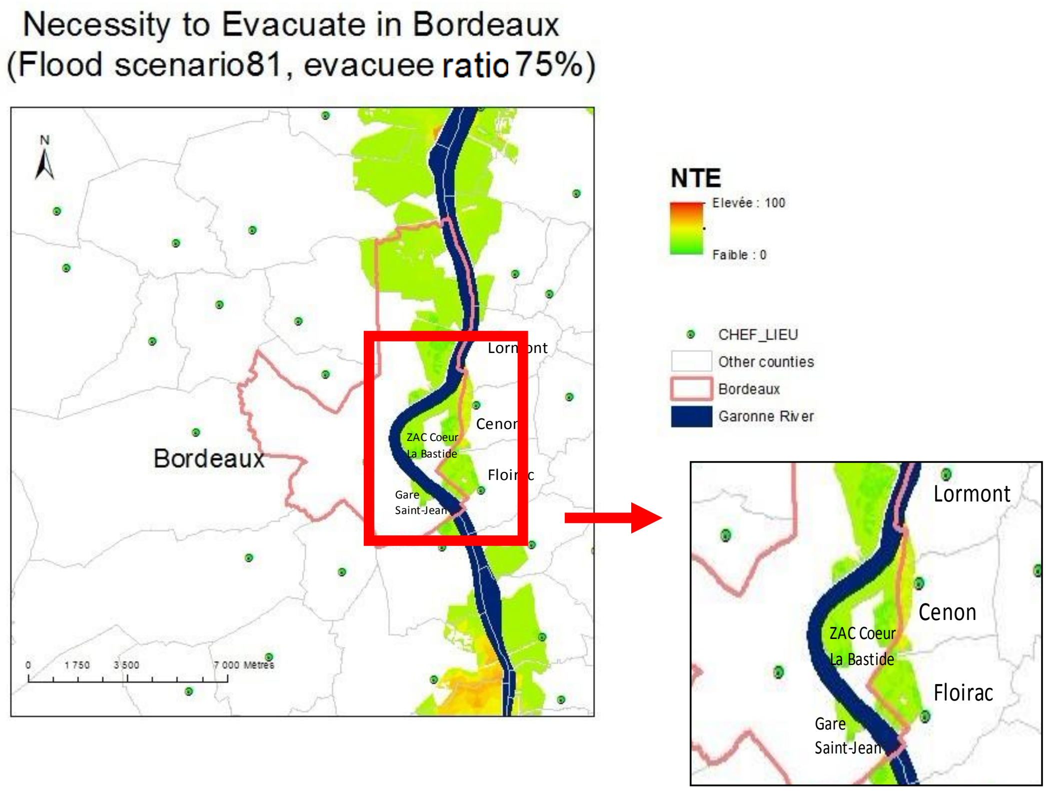


Figure IV-5 Local NTE of the 1981 flood in Bordeaux with 75% of evacuee ratio

<u>Scenario 1981</u>

Globally, the color discrimination of the local NTE is not significant in case of the 1981 flood (50-100 years flood) in the whole affected areas (see Figure IV-5(a)).

The highest NTE appears in the edges of la Bastide in the right bank, bordering the counties of Lormont, Cenon and Floirac (see Figure IV-5(b)). For the Bastide district in the right bank of the Garonne in Bordeaux, the altitude is very low (below 5m, see Figure D-5 in section 1.2.2 of Appendix D.) and below the embankments. Therefore, the Bastide district areas are the most vulnerable areas prone to evacuate facing a flood event, especially in the borders with other communes. Nevertheless, the 1981 flood event is not severe enough to envisage triggering an evacuation in neither this district, nor everywhere else in Bordeaux

Scenario 1999

In case of the event of 1999, the local NTE in the whole affected areas show bigger difference from one place to another, so that it can be easily distinguished by color. Compared with the flood of 1981, the flooded areas with NTE in yellow color (around 50% - see Figure IV-6) are visibly increasing in the north and at the border with the neighboring counties (Lormont, Cenon and Floirac) in the right bank (the Bastide district).

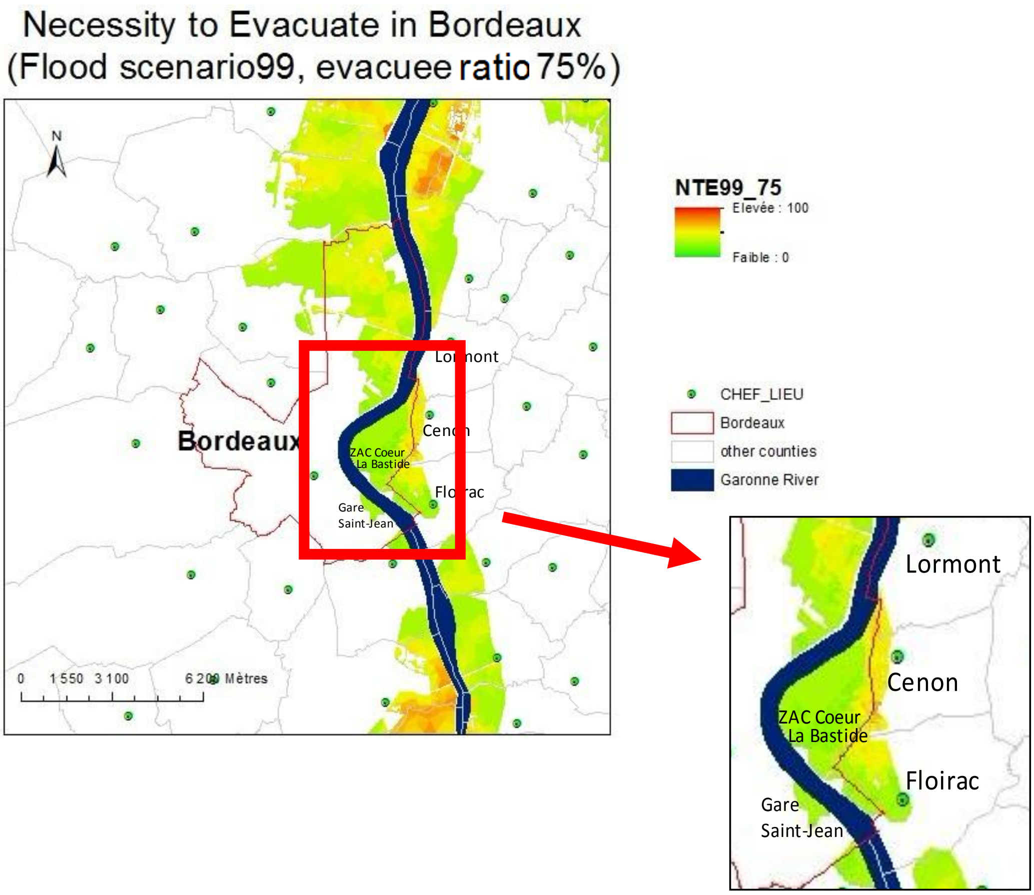


Figure IV-6 Local NTE of the 1999 flood in Bordeaux with 75% of evacuee ratio

Scenario 1999+1m

In such a hypothetical case, the local NTE reach values over 50% (orange and red color), in the Bastide district and in the north of the city which would certainly need an evacuation.

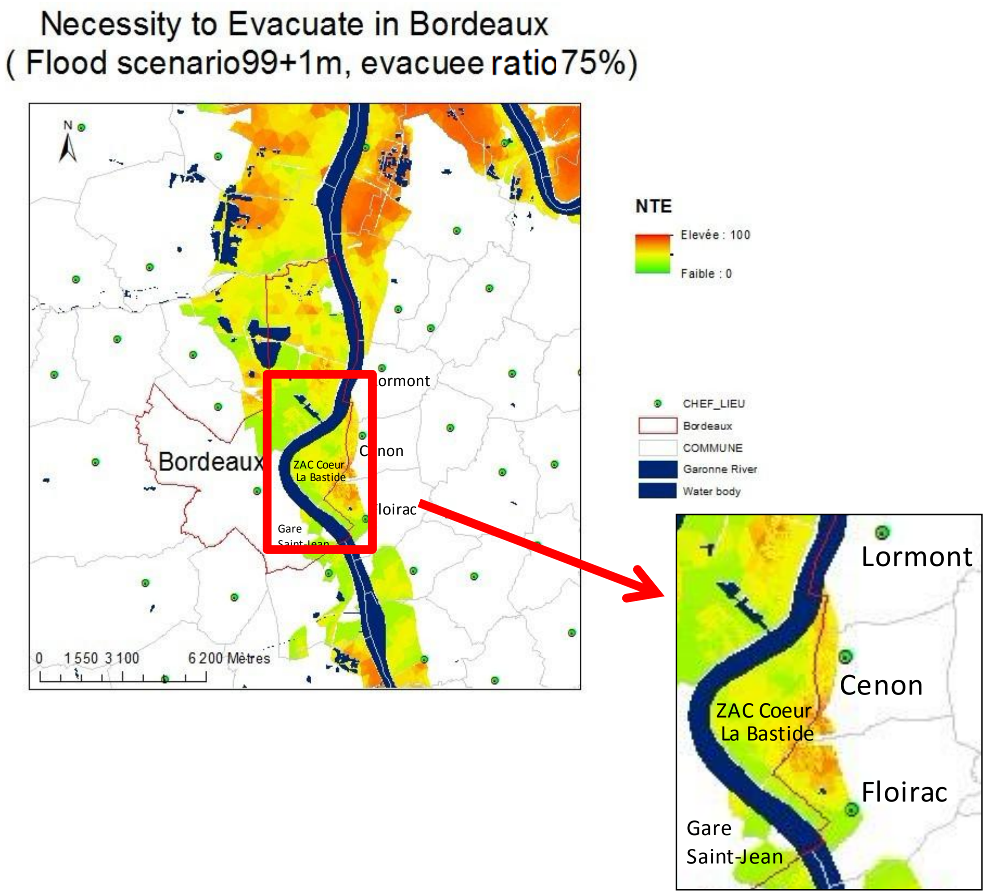


Figure IV-7 Local NTE of the 1999+1m flood in Bordeaux with 75% of evacuee ratio

<u>Global analysis and conclusions about the local NTE</u>

In this local NTE analysis, given the high level of evacuation capacity and safety, the color-coded local NTE maps for different flood scenarios can help distinguish visually the areas most prone to evacuation and identify the priority. The Bastide district and the north of the Bordeaux have a relative higher NTE than other affected areas. A way to link these maps with exact figures of NTE and to interpret it in terms of evacuation strategy is introduced in section 4.

4.2. NTE analysis for different estimated evacuee ratios

For a same flood scenario, the evacuation capacity and safety criterion can significantly affect the necessity to evacuate. For example, for the 1999 flood, three evacuation estimated evacuee ratio (25%, 50% and 75%) have been considered in order to analyze its relative influence on the NTE values characteristics (Table IV-3 and Table IV-4) and the NTE maps (Figure IV-8, Figure IV-9).

4.2.1. **NTE values characteristics for different evacuation scenarios**

In our study, we assume that an advisory evacuation can be suggested when the NTE reach values between 40% and 65%. Table IV-3 shows that the NTE varies significantly between a low capacity and safety of evacuation (25%) and a high one (75%), while the variation is more limited when the level of capacity and safety evacuation is already over 50%. In case of a crisis, it is not sufficient to say that it is not possible to evacuate and that other protective and alternative actions (rescue, shelters in place etc.) must be envisaged if the capacity to evacuate is low. In the long term, it is necessary to find out and clarify the very causes which prevent to evacuate, and to improve the evacuation plans in that perspective (infrastructures and equipments, crisis organization, available resources …). Crisis preparation and evacuation planning must permit to reach a good level of capacity and security of evacuation so that it is not a decisive criterion for evacuation decision in crisis management.

Estimated evacuee ratio	NTE values characteristics		
	Maximal NTE	Minimal NTE	Average NTE
25%	41.6%	21%	22.1%
50%	56.4%	21%	36.2%
75%	61.9%	21%	36.8%

Table IV-3 NTE values for three evacuation scenarios with 25%, 50%, or 75% of estimated evacuee ratio

Table IV-4 shows that that when the estimated evacuee ratio is at a low level (it can be for different causes that our method does not develop), the local NTE of 99.9% of the flooded areas ranges between 21% and 40%. Therefore, a mass evacuation is not recommended in this case, and other protective actions and interventions (e.g. rescues) must be considered, because the situation and the capacity of the organization do not enable to implement an efficient and successful evacuation.

Estimated evacuee ratio	NTE level characteristics	
	21% - 40%	40% - 65%
25%	99.9%	0.1%
50%	63.1%	36.9%
75%	59.5%	40.5%

Table IV-4 NTE level characteristics for the three evacuee ratios

With this indicator varying from low to high, the percentage of the affected areas with an NTE over 40% increases from 0.1% to 40.5% (Table IV-4). That means that 40.4% of the affected areas need other protective actions if the capacity and safety of evacuations is at a too low level to achieve an evacuation.

4.2.2. **NTE spatial analysis for different evacuee ratio**

As the estimated evacuee ratio decrease from 75% to 25%, the NTE maps for these two scenarios show that the north (e.g. Le Lac, Bacalan) and the edge of counties in the Bastide district (see Figure IV-8(c) in yellow), switch from yellow to green (see Figure IV-8(a) and (b)). These areas are the 40.4% of the affected areas (discussed in section 4.2.1) needing other protective actions if the capacity and safety of evacuations is too low to achieve an evacuation.

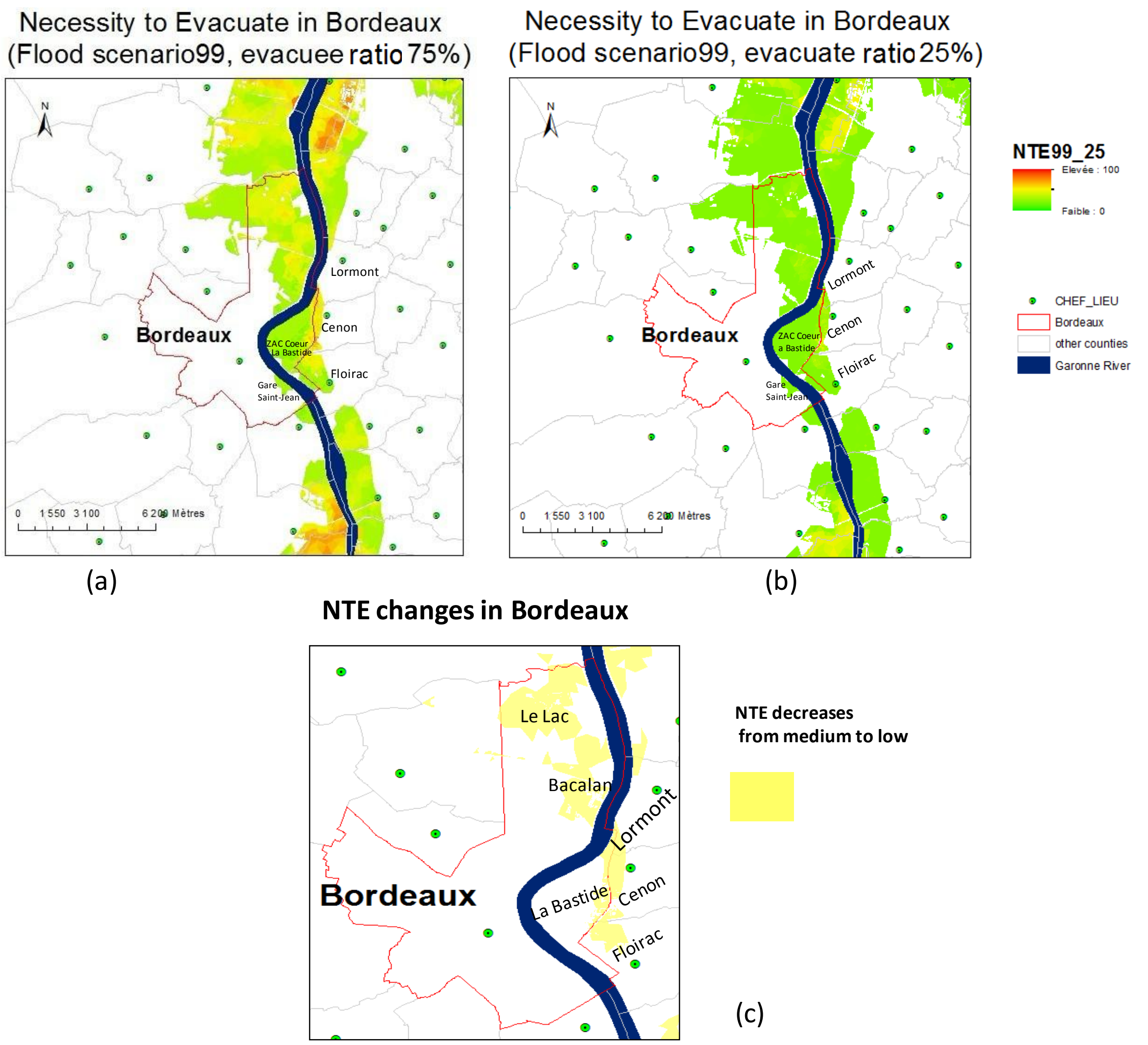


Figure IV-8 Comparison of the NTE for the 1999 scenario with 25% and 75% of evacuee ration ratio

When the estimated evacuee ratio decrease from 75% to 50% only, Figure IV-9 (a) and (b) show a small discrimination of NTE maps for these two scenarios. On the NTE variation map (Figure IV-9 (c)), more obvious reduction appears in the Bacalan and small areas in the east border of the Bastide. Therefore, these areas highly impacted by the evacuation capacity level need more detailed emergency plans including multiple alternative protections (rescue, shelters in place etc.), multiple emergency scenarios etc. in response to a crisis (this is not developed in this study).

In this local NTE analysis, given a flood scenario, the color-coded local NTE maps for different evacuation capacity and security levels make appear some changes of local NTE level, which can help decision makers locate the most risk prone areas to evacuate. This also can help adapt evacuation strategies.

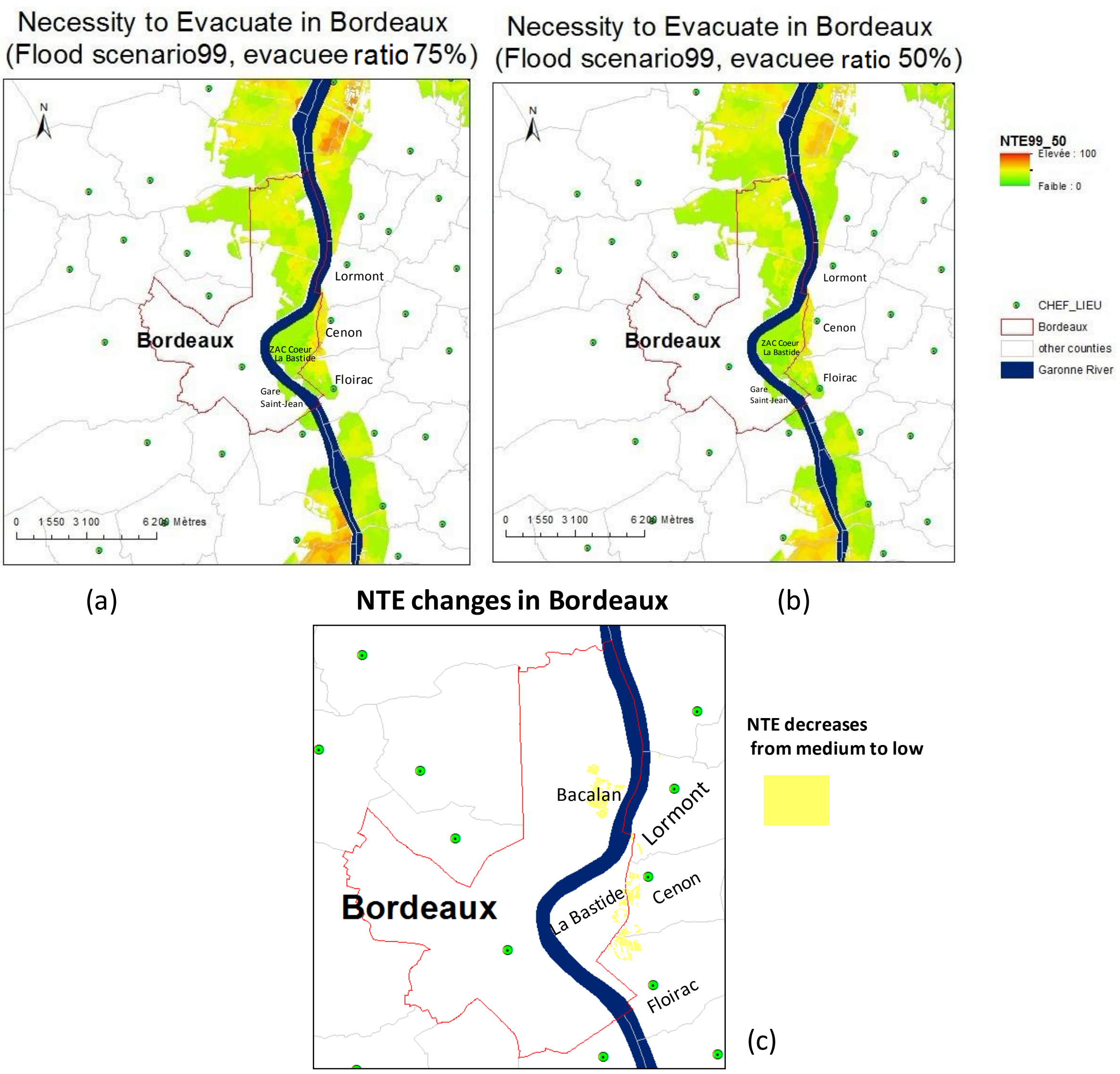


Figure IV-9 Comparison of the NTE for the 1999 scenario with 50% and 75% of evacuee ration ratio

4.2.3. **Global analysis and conclusions about the evacuation capacity and safety**

Indeed, the criterion of the capacity and safety of evacuation increases the complexity of the risk analysis and the evacuation decision. Moreover, compared with the flood scenario maps (see Figure IV-1 to Figure IV-3 in section 3.1), the criterion of capacity and safety evacuation introduces a major difference between NTE maps and classical risk maps which only take into account the level of hazard and the level of vulnerability, by adding a third layer about risk management. This new criterion should be developed in further research to precise the very content of this third layer. Our study sets the basis for mapping the risk including crisis management criteria.

Furthermore, the NTE map is quickly and easily read evacuation necessity by decision makers through color-coded level, so that help them judge how critical the local situation is facing an imminent flood. And it also can be used to prioritize the evacuation zones and to support the evacuation planning according to the different NTE levels.

4.3. Application of NTE maps to support evacuation final decision

The results of the NTE map calculation represents a comprehensive and synthetic evaluation of the decision circumstances including the flood risk, potential dangers, the vulnerability of the territory and people and the evacuation safety and capacity. Finally, following the same logic than the flood vigilance maps produced by French authorities, the NTE rate can be categorized in five colors (green, yellow, orange, red and dark red) corresponding to five necessity levels from “very low” to “very high” (see Table IV-5). Each level also corresponds to an evacuation decision option that could possibly be adapted to each local case.

Evacuation option	Description	Necessity to evacuate (%)	
No evacuation	No additional actions are necessary	very low	(0, 15)
Watchfulness	Precaution of the flood risk including the preparation for evacuation	low	(15, 40)
Advisory evacuation	Partial evacuation, some people at risk are advised to evacuate (those too vulnerable to flood risk to life)	medium	(40, 65)
Mild evacuation order	Recommendation of full evacuation, majority of people at risk to evacuate	high	(65, 80)
Urgent evacuation order	Order of full evacuation, public at risk is strongly urged to leave the area affected.	very high	(80, 100)

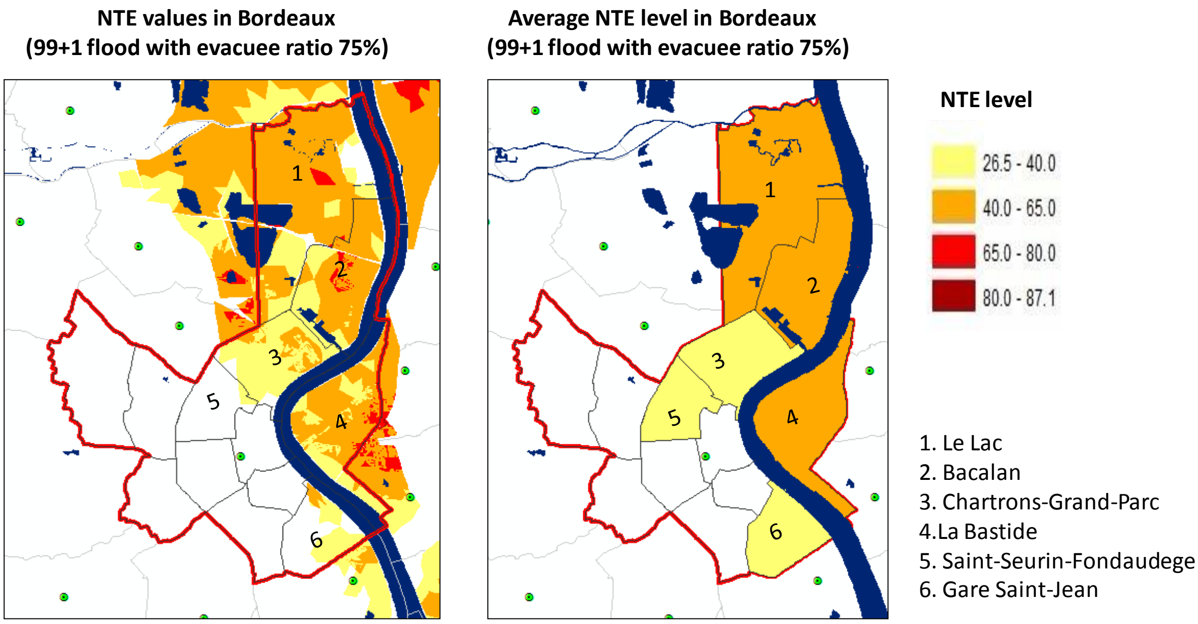
Table IV-5 Suggested actions associated with the necessity to evacuate

For example, Figure IV-10 shows the spatial distribution of the NTE values in Bordeaux for the scenario of 1999+1m, with a 75% rate for the evacuee ratio. Table IV-6 shows the characteristics (maximal, minimal and average values) of NTE values in the different districts.

Communities	NTE values characteristics		
	Maximal NTE	Minimal NTE	Average NTE
Le Lac	75.2%	28.9%	47.6%
Bacalan	77.7%	30%	47%
La Bastide	78.1%	26.5%	43.8%
Chartrons-Grand-Parc	55.7%	26.5%	32.8%
Gare Saint-Jean	48.6%	26.5%	32.4%
Saint-Seurin-Fondaudege	30%	26.5%	28.8%

Table IV-6 NTE values for the scenario of 1999+1m with 75% for the evacuee ratio

In this study, the average NTE is chosen as a global indicator for the final decision and the local NTE map as a complementary tool to identify which areas have to be evacuated in priority. Thus, in this case, for the Bordeaux city, six communities (Le Lac, Bacalan, Chartrons-Grand-Parc, La Bastid, Saint-Seurin-Fondaudeg, Gare Saint-Jean) are impacted by the flood event, three of which (Le Lac, Bacalan, La Bastide) are at a medium average NTE rate (see Figure IV-10 (b)). So, these three communities can be given an advisory evacuation, and inside these districts, the partial evacuation should be focused on the zones with a high NTE level in red color (Figure IV-10 (b)). On the contrary, a delay decision is suggested for the other three communities (Chartrons-Grand-Parc, Saint-Seurin-Fondaudeg, Gare Saint-Jean) because of a relatively low average NTE, but it requires keeping watching to the evolution of the event and preparing for a possible more serious situations.



(a) (b)

Figure IV-10 Map of necessity to evacuate in Bordeaux in case of flood of 1999+1m, 75% of evacuee ratio

4.4. Discussion about the results of NTE

There are few evacuation experiences and data to evaluate the results of the local NTE values in Bordeaux. However, comparing the local flood data resulting from the hydraulic model with local flooding experience can help roughly assess the resulting NTE.

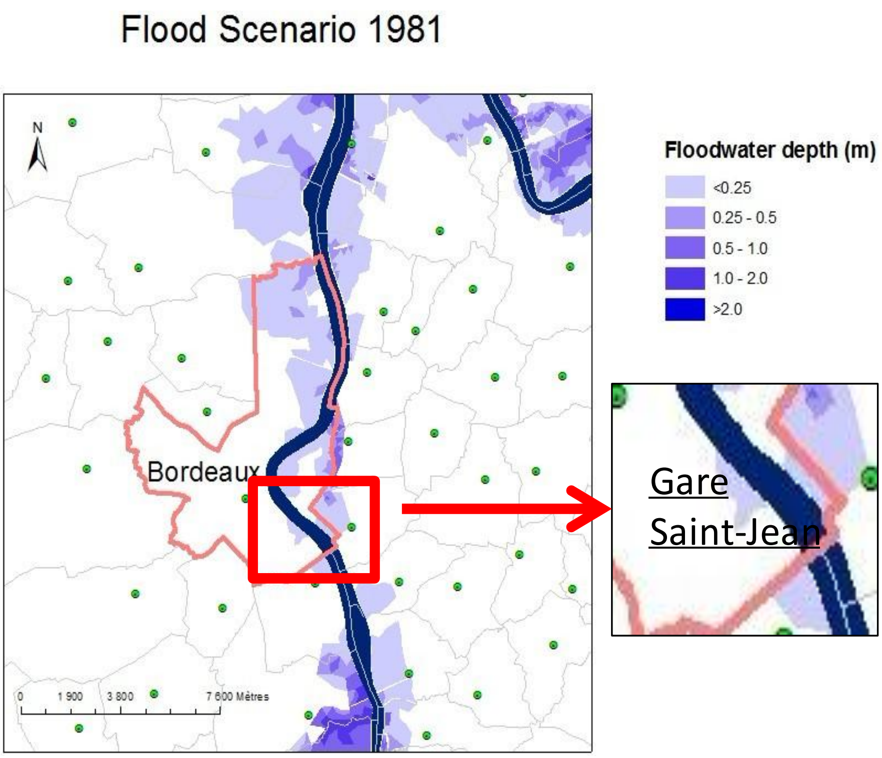


Figure IV-11 Local flood water depths modeled by TELEMAC for the 1981 flood in Bordeaux (source: SOGREAH, BD TOPO)

For example, according to historical data (PPRI de Bordeaux 2005), the low-lying communities were flooded in the afternoon of December 13th 1981 due to the high tide; all the countryside surroundings were flooded due to continuous heavy rainfall for four days. Because of the high tide and high discharge of the Garonne River, the depths of the flood waters reached 0.5m in the train station district (le quartier de la gare). The flooded areas spread on December 14th. In this study, the results of the flood water depths in the train station district modeled by TELEMAC (a 2D hydraulic model) were less than 0.25m (see Figure IV-11), while the recorded estimation was over 0.5m, so the results of the NTE probably underestimate the real risk. Therefore, the precision of the NTE values largely depend on the precision of input data. It is thus important to improve the data quality in the evacuation decision making, especially the global and local forecasted water levels which remain the main quantitative criteria.

Another example, according to the records of the 1999 flood event (PPRI de Bordeaux 2005), the flood waters were overflowing very quickly in Bordeaux (especially in la Bastide areas), due to the storm surge. The estimated velocity of the flood waters could be superior to 2m/s, which would significantly increase the danger for people. In our model and study, the velocity has no direct contribution to the NTE values, but is implicitly and partially included in the area vulnerability criterion because during a flood, the velocity can be decreased by the presence of obstacles (e.g. buildings), that is to say, open field is more vulnerable than downtown areas (Priest et al. 2007). However, compared with the actual situation of the quick rising of the flood water, our calculated NTE is likely to be underestimated based on such assumptions.

As a matter of fact, the NTE is an estimated value based on the existing data and resources. The accuracy of the NTE depends on the relevance of the values of the input criteria (that can be obtained by measurements, simulations, return of experience …) and the fuzzy model itself for the evacuation decision. The objective of the NTE is to help assess a complex situation of crisis management and its translation in terms of necessity to evacuate, which in any case can’t be an exact value. Given that the values of the input criteria are reliable, the results can be adjusted through modifying the rules according to the return of experience. In this study, the fuzzy model for evacuation decision is a first exploring proposal and experimentation for helping local officials to better understand the situation and make the final evacuation decision. The proposed fuzzy logic method is able to synthetically assess the necessity to evacuate through combining various or even conflicting criteria.

Chapter V. Conclusion and perspectives

1. General conclusion

Climate change and growing urbanization, sea level rise and extreme climatic events increase the risk of flood for coastal cities. Preventive evacuation as an effective measure can help reduce the loss of lives and properties. This thesis analyzed the procedure and characteristics of a mass evacuation in an urban area, reviewed existing methods and tools and introduced a fuzzy logic method to evaluate the decision circumstances by merging multiple criteria, integrating empirical experience and mitigating uncertainty impacts. The necessity to evacuate (NTE) with a value ranging in [0, 1] represents the final result of the crisis situation assessment. This rate can be associated to a qualitative level in the set (very low, low, medium, high, or very high) to support the decision. The NTE can also be visualized on maps thanks to a GIS so that the high or very high risk areas prone to evacuate can be easily identified. Therefore, our method can help authorities to understand how critical the situation is at a specific time of the crisis and make an evacuation decision: no evacuation, delay the decision, advisory evacuation, mild evacuation, or urgent evacuation. In the long term, the NTE levels can also help managers to improve and adapt the evacuation strategies and optimize the levers of actions.

The case study in Bordeaux city shows that a mass evacuation does not appear necessary with a relatively low local NTE for the flood scenarios of 1981 (50-100 years flood) and 1999 (>100 years flood). On the contrary, when the flood risk is worsened by climate change (given a 1-meter-sea-level added in the Gironde estuary, once a flood similar to the 1999 flood occurs), the local NTE values of 65% of flooded areas increase obviously, especially in the Bastide district areas. Therefore, it seems necessary to anticipate the impact of climate change by reinforcing the dikes infrastructures and by preparing mass evacuation procedures, especially in the areas with a high NTE level such as the Bastide district.

In summary, through its implementation and its applications in the case study of Bordeaux, the proposed decision making method based on fuzzy logic and coupled with the GIS offers the following advantages:

- First, such an approach considers the heterogeneity of input data and their interaction to produce a single and simple output for the decision. The evacuation decision takes into account multifaceted factors such as the hazard forecast, the local danger level, the territory and population characteristics and vulnerabilities, and evacuation characteristics. Since each of them has a different unit, it is usually difficult to deal with them all together. The existing methods using money as a common unit to represent a substitute variable clearly have limitations. Fuzzy logic methods can respect each criterion and its unit as well as integrate them by the concept of degree of membership, thus avoiding the problem of heterogeneity. The final integrated result provides the information needed for choosing the scenarios and the priorities.

- Secondly, our method can provide more precision compared to other methods: the NTE is a continuous variable, instead of binary ones whose value is 'yes' or 'no'. Facing most incoming flood hazard, it is rare to get all the people out of the city with a global 'yes' or 'no' solution. Evacuating only high risk parts of the city is sufficient for protecting people lives from flood. The NTE provides the possibility to analyze such situation and identify the high risk areas, so to give adapted solutions, such as partial evacuation and shelters location choice.
- Thirdly, the method offers more tolerance to uncertainty. Since uncertainty is unavoidable in hazard forecast, the method should be robust with uncertainty. Using a conventional decision making method, such as a decision tree method to get a 'yes' or 'no' solution, even a slight uncertainty around some critical values could result in a totally different decision between 'yes' or 'no'. For a fuzzy logic application, the uncertainty only results in a fluctuation of the NTE rate. The result does not change dramatically as long as the uncertainty is reasonable. So the proposed method is more robust to handle uncertainty.
- Fourthly, the qualification of the inputs/outputs of the model gives a common decision support framework for experts and decision makers and helps to convey a kind of "know-how" in a common language. The common language enables to express and to process the inputs and the outputs of the knowledge model in a range of qualitative values which takes into account the uncertainty of the situation and well fits the existing levels of dangers and alerts. It is a simple way to reason with vague, ambiguous, and imprecise input in the evacuation decision process based on linguistic (qualitative) descriptions and conditional reasoning by an 'IF-THEN' rule system. Each IF-THEN rule is one part of the diagnoses and the fuzzy logic method can automatically aggregate them to establish a global result. With such a reasoning system, experience and experts judgment for different scenarios can be merged.

However, the shortcoming of the method is that the rule number increases dramatically with the number of inputs. Even if the method and the tool can theoretically handle hundreds of factors and thousands of rules at the same time, it is recommended to use cascade structures to avoid too many rules at one time. It means that by dividing input criteria into different groups, each group can get an output value through a fuzzy logic subsystem, and then the outputs of the groups are synthesized to get the final NTE, as discussed in Chapter III.

- Fifthly, the proposed fuzzy method also shows a good extensibility. In the preparation phase, this kind of NTE maps made from scenarios can be analyzed and criticized by experts and decision makers in order to modify and calibrate the fuzzy logic model (rules and membership functions) until it gives coherent results. Then, we can expect to progressively calibrate a general fuzzy model by confronting it to several different but similar cases in France and Europe.
- Finally, the final output of the model, a map of evacuation necessity, is a real new contribution to evacuation decision making process, and it extends the existing maps of hazard and risk in terms of crisis management.

2. Limits of the proposal and orientations for future works

The experimentation of a fuzzy logic approach mixed to a GIS multicriteria analysis and applied to mass evacuation in case of coastal submersion showed some interesting results and advantages as underlined in section 1 but also some drawbacks and difficulties. Thus, the following recommendations are proposed from this research to take into account the return of experience, to correct the weaknesses of the method and to progress towards an operational tool for decision makers:

- Firstly, due to a lack of data and a limited time to conduct this work, the thesis has chosen a limited set of criteria to implement the fuzzy logic method, with the primary purpose of proving the feasibility and advantages of the proposed new approach. As a matter of fact, it is important to set up and validate a complete and exhaustive panel of decision criteria with experts, decision makers and stakeholders, including planners, managers and even the public involved in the evacuation. Such complex criteria involving evacuation decisions can be organized in a hierarchical form.

  As aforementioned, with more criteria/indicators, a multi-level fuzzy method could be established in the future.

- Secondly, in this study, the input data of the territory vulnerability, representing local protection ability, is simply defined based on the types of land use for an easy manipulation in the spatial dimension. It represents a large region of land characteristics for protection at a wide scale, but for an evacuation, one requires more precision regarding the characteristics at the local scale like buildings characteristics (e.g. height, density, category, age etc.), population distribution (e.g. density, location, social characteristics etc.) and other relative aspects. Therefore, the area vulnerability should be modeled in a more detailed and comprehensive way.
- Thirdly, in this evacuation decision fuzzy model, the defuzzification process produces NTE values systematically limited in the range [10% - 90%], while the NTE rate is associated to five qualitative levels covering the whole range [0, 100]. In the future, it requires finding a solution to correct this range narrowing problem.
- Fourthly, input data and thus the NTE can evolve during the flood event. A supplementary method could be developed to estimate the dynamic evolution of the NTE (the gradient), which would be useful for the evacuation decision assessment in real time.
- Fifthly, how to calculate the NTE is discussed in this study, but the NTE value varies spatially and also timely within the forecast. Therefore, it is necessary to analyze the NTE sector by sector, and its evolution with the forecast (see the previous point), in order to better prioritize the evacuation in space and time.
- Sixthly, the NTE values (rate) and categories (5 classes of decision) represent an experimental effort for systematically evaluating situations and help evacuation decision making. Therefore, the calibration of the model and the validation of the method still have to be confronted to several examples in different contexts before concluding that they can be conveyed into an operational tool for decision support. The computation functions of the inference system and the membership functions for evacuation decision should be verified through the feedback of pilot sites and decision makers in practice. The heuristic rules and the output NTE must be well understood and adjusted together with experts and decision makers.
- Finally, the application of this fuzzy methodology as decision support associated with a GIS is promising for improving crisis management in the case of severe disasters threatening people's lives. An Evacuation Fuzzy Decision Module as one part of an Evacuation Management Decision Support System (Figure V-1) is

expected to be developed in the future on the basis of our proposal. The results of the evacuation fuzzy decision analysis can be imported into a geographic information system (GIS) for spatial analysis and generally could be integrated in a flood preparation and management platform like OSIRIS (Morel et al. 2010b) to complete and specialize the general action plan. Different layers of information such as topography, demography, etc. can be incorporated to facilitate the process and to update a large quantity of information and the understanding of the results. The information on flood risk and evacuation with the complement of the NTE information is expected to better support the evacuation decision making during a flood crisis.

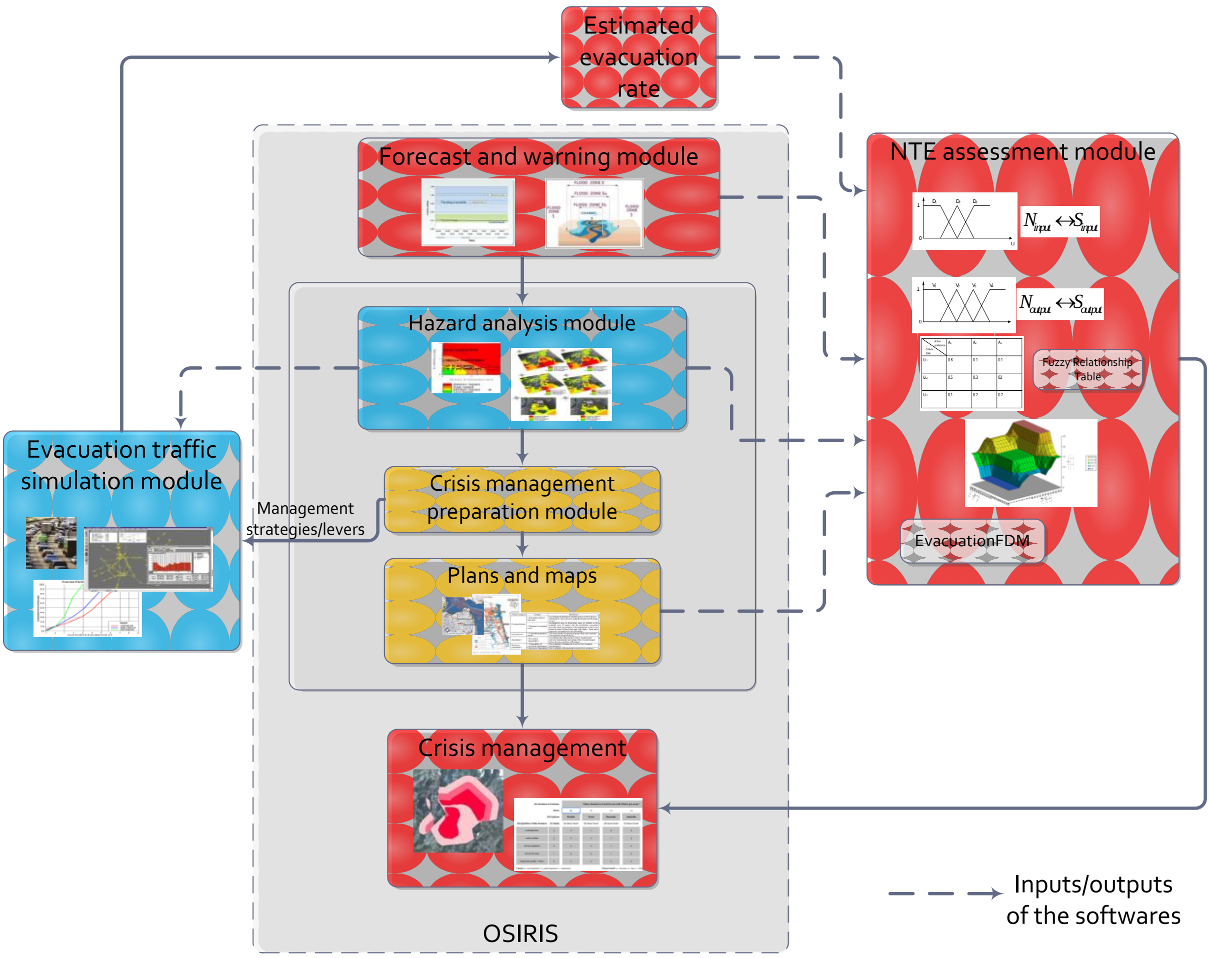


Figure V-1 A schematic view of an evacuation fuzzy decision module integrated into the OSIRIS platform

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Appendix A. Explicit evacuation decision criteria table

	Titre	Données de sortie	Description	Importance
A1	**<u>définir les paramètres, scénarios et cartes de submersion</u>**	un jeu de scénarios et cartes de submersion	identifier les zones inondables pour décider les zones à évacuer; influences vulnérabilité des populations au risque	3
A1-1	**identifier les paramètres de la prévision permettant d'établir des scénarios de submersion**			
		fiche de synthèse des paramètres de prévision maritimes, météorologiques et hydraulique	références pour identifier le risque inondation	3
		marée astronomique		
		surcote	identifier les zones inondables pour décider les zones à évacuer	3
		houle et vague		
		données fluviales	identifier les zones inondables pour décider les zones à évacuer	3
		paramètres météorologiques	influencer la sécurité de transport	3
A1-2	**définir des jeux de paramètres**	**liste des jeux de paramètres de prévisions maritime, météorologique et hydraulique**	hiérarchisation des scénarios de submersion; choix le plan selon scénarios	3
		marée astronomique		
		scénario 1		
		scénario 2		
		scénario 3		
A1-3	**établir les cartes de submersion**	**cartes de submersion (étendue, hauteurs d'eau, vitesse, durée) et paramètres de la prévision de l'aléa associés**	évidence l'étendue de l'inondation les hauteurs d'eau, les vitesses et les durées de submersion	3
A2	**<u>caractériser la vulnérabilité et le risque affectant le territoire et la population</u>**			

A2-1	**définir la vulnérabilité et le risque du bâti et de la population**	**carte du bâti selon ses usages et en fonction des différentes hauteurs d'eau de l'aléa**	identifier les zones les plus exposées aux risques pour estimer le nombre de personnes à évacuer	3
A2-2	**définir la vulnérabilité et le risque affectant les réseaux**	**carte des réseaux de transport en zone inondable**	identifier les réseaux vulnérabilité pour décider les tronçons sécurisés empruntés	3
		carte des réseaux de servitude en zone inondable		1
		carte des réseaux impactés		0
A3	**<u>identifier les autres données stratégiques et les leviers d'action</u>**			0
A3-1	**identifier les leviers d'actions**	**liste des leviers relatifs aux transports, aux déplacements et à la communication à la population**		
		modification du plan de déplacement		
		planification des itinéraires d'évacuation		
		utilisation des bus		
		utilisation des réseaux de tramways, métros et trains		
		réorganisation des plans de feux tricolores		
A3-2	**définir des données stratégiques relatives aux moyens humains et matériels potentiellement mobilisables**			
A3-2.1	définir les moyens matériels et humains potentielles ment mobilisables	**identité et nombre de personnes potentiellement mobilisables pour assurer la gestion de la crise**	les ressources assurer la réalisation d'évacuation	2
		Nature et nombre de moyens de matériels propres à la gestion de crise		0

A3-2.2	définir les moyens de communication et de signalisation potentiellement mobilisables	**nature et nombre de moyens de communication à la population et de signalisation potentiellement**	couvertures de communication influencer la réponse à décision d'évacuation	1
A3-3	**définir des données stratégiques relatives aux structures d'accueil potentiellement mobilisables**	**carte des refuges horizontaux potentiellement utilisables**	capacité d'accueil assurer la réalisation d'évacuation	2
		carte des bâtis permettant un transfert vertical	évacuation vertical décision-très important	2
A3-4	**définir des points de sortie et évaluer la population évacuable par les réseaux de transport**	**capacité horaire d'évacuation des moyens de transport**	pour estimer temps d'évacuation	2
		points de sortie de la zone submergée pour chaque moyen de transport	points critiques à évacuer	3
A4	**<u>définir la stratégie d'évacuation</u>**			
A4-1	**choisir les modalités d'évacuation espace-temps**			2
A4-1.1	définition des modalités d'évacuation spatiale (verticale/horizontale)	**carte par secteur des bâtiments évacués horizontalement ou verticalement**		1
A4-1.2	définition des modalités d'évacuation temporelle pour l'évacuation horizontale			0
A4-1.3	définition des points de rassemblement, des itinéraires et des refuges pour l'évacuation horizontale	**carte des points de rassemblement, des itinéraires vers les structures d'accueil et des refuges selon les secteurs d'évacuation**		1
		nombre de personnes à évacuer verticalement ou horizontalement, individuellement ou collectivement, par secteur	influence temps d'évacuation	3

		carte des points de sortie de la zone inondée et des itinéraires d'accès aux refuges	points critiques à évacuer	3
A4-2	**choisir les moyens de transport pour l'évacuation collective et les acteurs pour gérer les déplacements**	**choix des moyens de transport collectif à mettre en place et identification des acteurs à mobiliser et leurs rôles**		
A4-2.1	définir les moyens de transports à utiliser pour chacune des zones à évacuer, en fonction des moyens humains et matériels à disposition, de la capacité des moyens de transport, et du nombre de personnes à évacuer collectivement			
A4-2.2	identifier le nombre d'acteurs à mobiliser et leurs actions		ressource à évacuer pour assurer la réalisation d'évacuation	3
A4-2.3	parmi les acteurs et les moyens de transports mobilisables, prévoir d'en affecter certains à la gestion des aléas spécifiques à l'évacuation		très important durant l'évacuation	1
A4-3	**choisir la stratégie et les moyens de communication**	**moyens de communication et messages d'alerte**	influence la réponse de l'alerte d'évacuation	2
A4-3.1	mettre en place une démarche de concertation avec les acteurs (services de la mairie, pompiers, SAMU…)			0
A4-3.2	mettre en place une démarche d'information préventive auprès de la population			0
A4-3.3	messages d'alerte lors du risque d'inondation		influence la réponse de l'alerte d'évacuation	2

A5	**<u>définir les scénarios d'évacuation et vérifier leur faisabilité</u>**			
A5-1	**vérifier la faisabilité de la stratégie d'évacuation**	**validation de la stratégie d'évacuation**	Très important pour la gestion d'évacuation	0
	déterminer le nombre de personnes évacuables par réseau et par heure			
	prévoir des itinéraires de remplacement aux itinéraires définis dans la boite A4 en cas de travaux de voiries			
		critère de décision	ne pas trouver	3
A5-2	**vérifier la faisabilité de la stratégie de communication**	**validation de la stratégie de communication**		
	moment de l'alerte à la population			1
	validation du plan d'évacuation par l'ensemble des représentants officiels		important pour gérer l'évacuation	0
	vérifier que la stratégie de diffusion du message d'alerte touche toute la population		important pour gérer l'évacuation	0
	informer la population de l'existence d'un plan ainsi que de l'attitude à adopter en cas d'évacuation		important pour gérer l'évacuation	0
A6	**<u>optimiser la stratégie et la mettre en forme</u>**		évaluation de plan d'évacuation	1
A6-1	**effectuer une itération**	**stratégie optimisée**		
A6-2	**mettre en forme le plan d'évacuation**	**un plan d'évacuation pour chaque scénario d'inondation traité**		
A7	**<u>choisir un plan d'évacuation et</u>**		il faut approfondir	

	<u>gérer en temps réel</u>			
A7-1	**choisir le plan d'évacuation correspondant**	**choix d'un des plans d'évacuation à appliquer**		
A7-2	**appliquer le plan d'évacuation et communiquer**	**adaptation du plan d'évacuation avec les données obtenues en temps réel concernant les bâtiments, les réseaux, la population, les acteurs**		
		énumération d'actions à mener en termes de communication afin de gérer la crise en temps réel		

Appendix B. Refined decision criteria list

Indicateurs d'aide à la décision pour l'évacuation d'un secteur urbanisé

Aléa et prévision (risque de 1er niveau – submersion)

1. Dépassement de seuil des paramètres de prévision
2. Existence d'un scénario d'aléa proche de la prévision
3. Références historiques de conditions climatiques et de submersion
4. Carte d'inondation et hauteurs d'eau prévues dans le secteur (moyenne et max)
5. Temps de submersion estimé

Risques de second niveau

6. Risques de ruptures de digues de protection
7. Etat des réseaux vitaux et risques de dégradation (risque direct et indirect pour le secteur)
    a. Electricité et chauffage
    b. Eau et assainissement
    c. Réseaux de communication
8. Conditions météo et conditions de sécurité pendant la période d'évacuation envisagée
9. Etat actuel et prévisible des itinéraires d'évacuation

Données du territoire

10. Population totale à mettre en sécurité
11. Population vulnérable à évacuer
12. localisation de la population au moment supposé de l'alerte
13. Possibilités de refuges / capacités d'accueil à l'intérieur du secteur au regard du risque et des besoins

Données temporelles de l'évacuation

14. Délai avant l'arrivée de la submersion et temps total d'évacuation supposé
15. Heure de début et fin d'évacuation souhaitable

Disponibilité des ressources

16. Disponibilité des personnels pour la gestion de crise et la mise en œuvre du plan
17. Disponibilité des personnels et des matériels pour l'évacuation collective (transports en commun)
18. Réserves en carburant et capacités des stations d'essence pour l'évacuation individuelle
19. Capacité d'accueil hors zone pour les personnes vulnérables
20. Capacité à évacuer les personnes une fois le secteur inondé
21. Capacité routière

Appendix C. Decision matrix to design the rule base for the evacuation decision fuzzy system

Necessity to evacuate (NTE)				
Global forecast	Local danger	Area vulnerability	Evacuee Ratio	Necessity to Evacuate
Red	Zone a	High	Very high	Very high
			High	Very high
			Medium	High
			Low	Medium
			Very low	Medium
		Medium	Very high	Very High
			High	Very High
			Medium	High
			Low	Medium
			Very low	Medium
		Low	Very high	Very High
			High	Very High
			Medium	High
			Low	Medium
			Very low	Medium
	Zone b	High	Very high	Very High
			High	High
			Medium	High
			Low	Medium
			Very low	Medium
		Medium	Very high	High
			High	High
			Medium	Medium
			Low	Medium
			Very low	Medium
		Low	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low

			Very low	Low
	Zone c	High	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Low
		Medium	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Low
		Low	Very high	Medium
			High	Medium
			Medium	Low
			Low	Low
			Very low	Low
	Zone d	High	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Low
		Medium	Very high	Medium
			High	Medium
			Medium	Low
			Low	Low
			Very low	Low
		Low	Very high	Low
			High	Low
			Medium	Low
			Low	Low
			Very low	Low
	Zone e	High	Very high	Low
			High	Low
			Medium	Low

			Low	Low
			Very low	Low
		Medium	Very high	Low
			High	Low
			Medium	Low
			Low	Low
			Very low	Low
		Low	Very high	Low
			High	Low
			Medium	Low
			Low	Low
			Very low	Low
Orange	Zone a	High	Very high	High
			High	High
			Medium	High
			Low	Medium
			Very low	Medium
		Medium	Very high	High
			High	High
			Medium	High
			Low	Medium
			Very low	Medium
		Low	Very high	High
			High	High
			Medium	High
			Low	Medium
			Very low	Medium
	Zone b	High	Very high	High
			High	High
			Medium	Medium
			Low	Medium
			Very low	Medium
		Medium	Very high	High
			High	High

			Medium	Medium
			Low	Medium
			Very low	Low
		Low	Very high	Medium
			High	Medium
			Medium	Low
			Low	Low
			Very low	Low
	Zone c	High	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Very Low
		Medium	Very high	Medium
			High	Medium
			Medium	Low
			Low	Low
			Very low	Very low
		Low	Very high	Low
			High	Low
			Medium	Low
			Low	Low
			Very low	Very low
	Zone d	High	Very high	Low
			High	Low
			Medium	Low
			Low	Very low
			Very low	Very low
		Medium	Very high	Low
			High	Low
			Medium	Low
			Low	Very low
			Very low	Very low
		Low	Very high	Very low

			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
	Zone e	High	Very high	Low
			High	Low
			Medium	Low
			Low	Very low
			Very low	Very low
		Medium	Very high	Low
			High	Low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Low	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
Yellow	Zone a	High	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Low
		Medium	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Low
		Low	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Low

	Zone b	High	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Low
		Medium	Very high	Medium
			High	Medium
			Medium	Medium
			Low	Low
			Very low	Low
		Low	Very high	Medium
			High	Medium
			Medium	Low
			Low	Low
			Very low	Very low
	Zone c	High	Very high	Medium
			High	Medium
			Medium	Low
			Low	Low
			Very low	Very low
		Medium	Very high	Medium
			High	Medium
			Medium	Low
			Low	Low
			Very low	Very low
		Low	Very high	Medium
			High	Low
			Medium	Low
			Low	Very low
			Very low	Very low
	Zone d	High	Very high	Low
			High	Low
			Medium	Very low
			Low	Very low

			Very low	Very low
		Medium	Very high	Low
			High	Low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Low	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
	Zone e	High	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Medium	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Low	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
Green	Zone a	High	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Medium	Very high	Very low
			High	Very low
			Medium	Very low

			Low	Very low
			Very low	Very low
		Low	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
	Zone b	High	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Medium	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Low	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
	Zone c	High	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Medium	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Low	Very high	Very low
			High	Very low

			Medium	Very low
			Low	Very low
			Very low	Very low
	Zone d	High	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Medium	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Low	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
	Zone e	High	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Medium	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low
		Low	Very high	Very low
			High	Very low
			Medium	Very low
			Low	Very low
			Very low	Very low

Appendix D. Flood risk management in Bordeaux

1. Floods and flood risk in the Gironde estuary and the city of Bordeaux

1.1. General description of Bordeaux

As a pilot site, we have chosen the city of Bordeaux, which is located in the north of the Aquitaine region in the southwest of France (see Figure D-1). It is a port city on the banks of the Garonne River, less than 100km from the Atlantic Ocean. The Gironde estuary is formed at the confluence of the rivers Garonne and Dordogne just downstream of the centre of Bordeaux.

Bordeaux is the capital of the Gironde department as well as the Aquitaine region. There were 236 725 inhabitants according to the census in 2009 (INSEE).

Bordeaux is famous all over the world for its red wines and is qualified as “pearl of Aquitaine”. It is also an important transportation hub on the Atlantic coast, which is the only linkage between Paris as well as the northern Europe and the Atlantic coast of Spain.

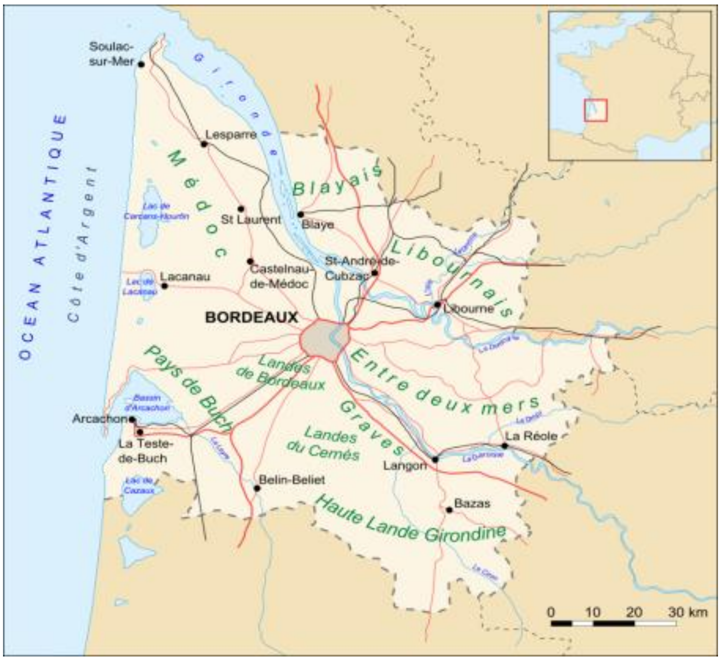


Figure D-1 Study area: Bordeaux located less than 100km from the Atlantic Ocean in Gironde (source: http://fr.wikipedia.org/wiki/Bordeaux)

1.2. Territory characteristics

1.2.1. **Dense urbanization**

Due to the increased urbanization and population growth, many settlements are built along the river banks in the flood-prone areas (see Figure D-2 and Figure D-3). According to Figure D-3, it is estimated that the population in Bordeaux is still going to increase by 10%-

15% in the next two decades. The city is built on a bend of the river Garonne, and is divided into two main parts: the right bank towards the east and the left bank in the west. Historically, the left bank is more developed with a very high density of population (see Figure D-4). Until the nineteenth century, the arrival of the railways brought a full urban development of the right bank, where main industrial areas have been (Godier & Mazel 2009). Therefore, if a catastrophic flood occurs in these highly populated areas, the damages are likely to be dramatic, including a serious risk for people lives.

Figure D-2 The ZAC Coeur of Bastide in Bordeaux in the flood-prone areas (source: http://www.vues-aeriennes-bordeaux.fr/2008_12_01_archive.html)

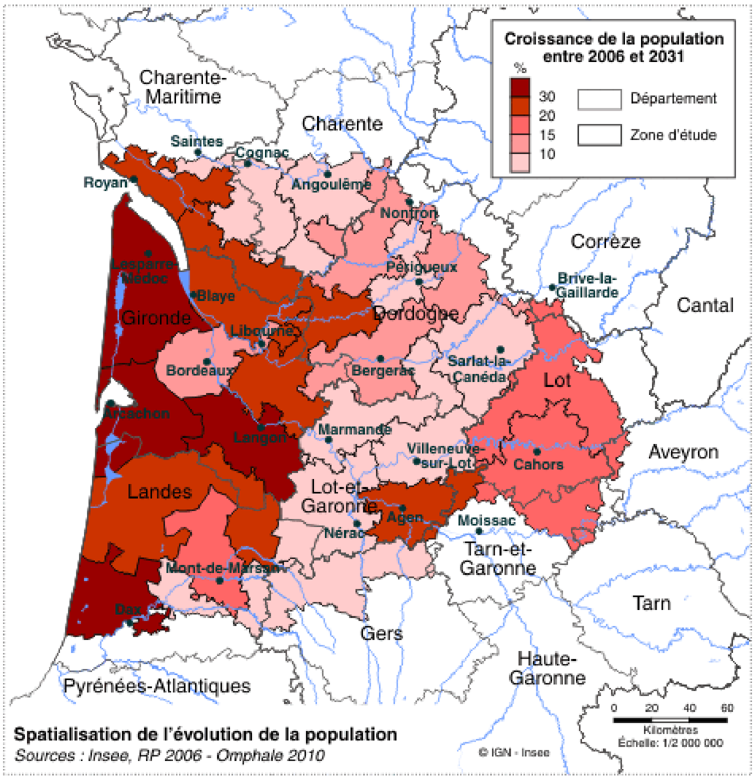


Figure D-3 Population growth rate in Gironde between 2006 and 2031 (Source: INSEE)

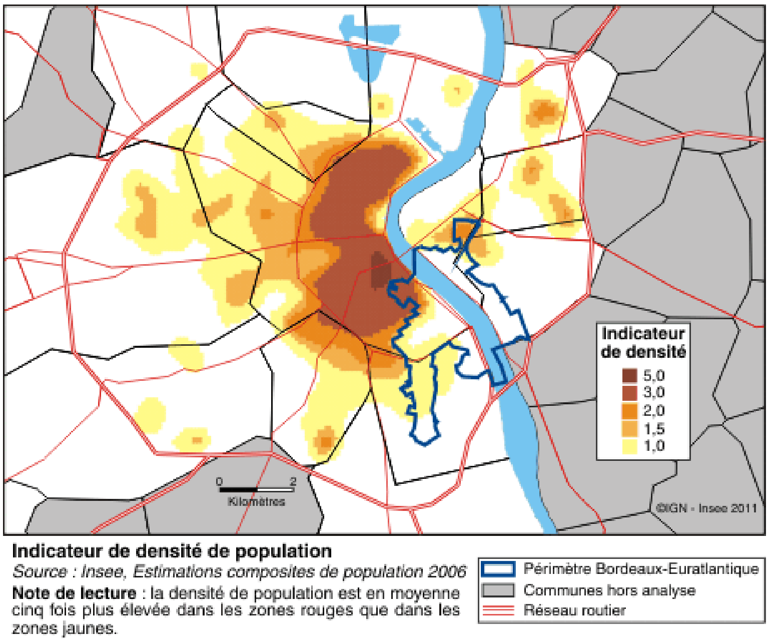


Figure D-4 Population density in Bordeaux city (Source: INSEE)

1.2.2. **Low topography**

The left bank of the Garonne, where the downtown of Bordeaux is situated, is a low-lying, often marshy plain, for example from the north towards Bordeaux-Lac. The right bank is very different since it goes almost directly from the plain to a limestone plateau with an abrupt increase of the altitude above 60m (see Figure D-5).

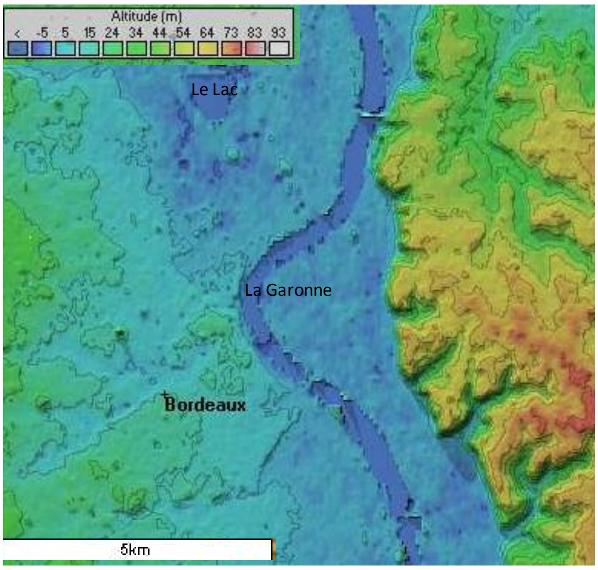


Figure D-5 Topographical view of the Bordeaux area
(adapted from http://fr.wikipedia.org/wiki/Bordeaux)

It was frequently flooded (e.g. flood of 1999) in the low-lying and plain areas with an altitude below 5m, especially in the north of Bordeaux and the plain areas of the right bank (see the 1999 flood map in Figure D-6). The low altitudes clearly increase the flood risk in these areas.

Figure D-6 Flooded areas in the right bank of the Garonne and in the north of the city according to the historical flood of 1999

1.2.3. **Maritime and river flood origin**

This area is heavily affected by the flood risk either from two rivers (the Garonne River and the Dordogne River) or/and the Gironde estuary (maritime causes). The Gironde estuary is subject to very strong tidal currents. The maximum water levels in the estuary, that generally cause a submersion, are due to a conjunction of a high maritime tide and a severe storm (wind, depression). In the future, this maritime water level over height can be worsened by a progressive sea level rise due to climate change. The fluvial-maritime complex phenomena (including combination of fluvial flooding, tidal, storm surges and sea level rise) make it more difficult to prevent, forecast and manage the flood risk in Bordeaux. This issue is developed in the next section.

1.3. Principal causes and types of floods in Bordeaux

The hydraulics of floods in Bordeaux is extremely complex. It is necessary to consider the interaction of the different parameters that contribute to a severe flood, including the discharge of the upstream of the Garonne (e.g. Lot, Tarn), the tidal coefficient, the northwest wind, the Atlantic barometric pressure, etc.

1.3.1. **Maritime causes (high tide or/and storms)**

Even when the fluvial flow of the Garonne is not with a high discharge (actually 700 m^3/s), serious floods may happen in Bordeaux (for example, the flood of 1999), caused by a storm surge coupled with a high tide.

While tides are usually the largest source of the short-term sea-level fluctuations, sea levels are also subject to forces such as wind and barometric pressure changes, resulting from storm surges, particularly in shallow seas near the coasts and in estuaries like the Gironde one. Storm force winds combined with the low barometric pressure cause the water to pile up higher than the ordinary sea level, which represents the most common cause of storm surge flooding problems in Bordeaux (see Figure D-7). For example, the storm surge of 1999 was the most serious recorded flood in the Garonne department during the period from 1879 to 2003. The highest water level of 5.05m NGF (General Leveling of France) was measured at Bordeaux (tidal coefficient 77 and storm surge levels at 2.25m).

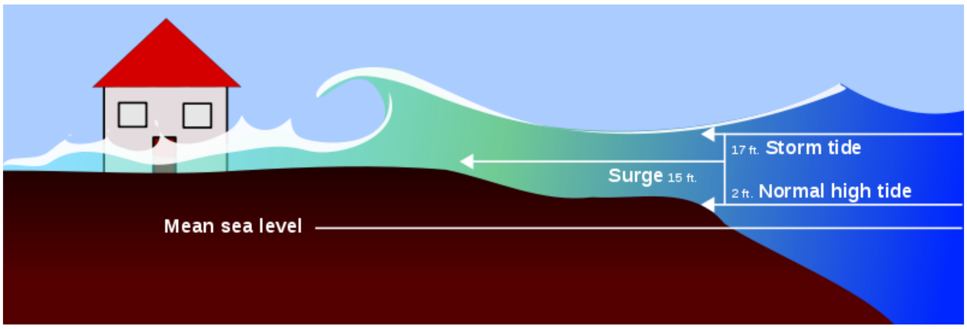


Figure D-7 Graphical illustration of the rise of the sea level caused by a storm surge (extreme strong winds and low barometric pressure)

1.3.2. **River causes**

Fluvial floods are mainly caused by heavy rainfalls which affect the whole or part of the Garonne basin (see Figure D-8). Bordeaux sits at the downstream of the Garonne, which is also affected by the discharge coming from the upstream of the basin. For example, a great flood called “Grand Souberne des Rameaux” happened in April 1770 when a heavy rain lasted for nine days and the snow was melting from the Pyrenees in the beginning of April. The sector of the Bastide was inundated on the right bank of Bordeaux (PPRI, 2005), and it is still today one of the most flood prone area of Bordeaux

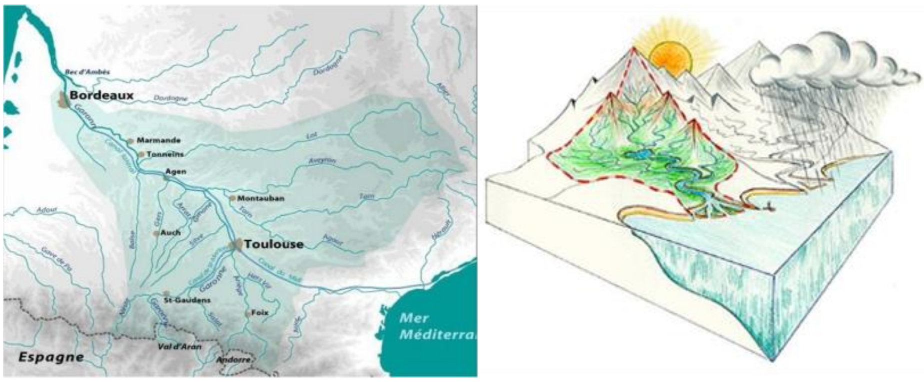


Figure D-8 Graphical illustration of the rise of water levels in Garonne caused by heavy rains in the basin

1.3.3. **Types of floods**

SOGREAH (2009b) analyzed the historical floods in the estuary and in Bordeaux and defined three categories of great events as follows:

- Floods due to storms: tide coefficient between 75 and 99 and wind speed superior to 100km/h,
- Flood due to tides: tide coefficient superior to 100 and wind speed superior to 50km/h,
- Flood due to river waters: return period of the crest discharge superior to 10 years.

However, no matter how many parameters (tide, discharges, wind, low pressure etc.) generate the event, the interaction and combination of them generates a high water level, which directly causes overflowing.

1.4. Historical floods in Bordeaux

Table D-1 shows the 12 most severe recorded floods in Bordeaux in the 20th century. The highest water levels of the river were observed by the services of the Port Autonome de Bordeaux (PAB).

Date	Local river levels (m)	NGF level (m NGF)	Storm surge levels (m)	Volumetric flow rate of the Garonne River (m^3/s)	Tidal coefficient
27 Dec. 1999	7.05	5.24	2.25	700	77
13 Dec.1981	6.85	5.04	1.70	1500 to 2000	99
19 March 1988	6.84	5.03	0.94	4000	115
7 Feb. 1996	6.77	4.96	1.77	1000	87
28 April 1998	6.73	4.92	1.03	2700	113
7 Feb 1974	6.68	4.87	1.38	2500	103
23 De. 1995	6.67	4.86	0.37	700	108
4 March 1923	6.63	4.82	-	3500	115
15 Feb. 1957	6.64	4.83	-	1300	114
27 March 1979	6.61	4.80	0.32	900	105
30 Jan. 1975	6.57	4.76	-	3200	105
14 March 1937	6.57	4.76	-	1600	112

Table D-1 The 12 most severe recorded floods in Bordeaux in the 20th century (source: PPRI 2005, PCS 2008 et SOGREAH 2009b) (- : lack of data)

1.4.1. **Characteristics of the historical floods**

It can be seen that the historical floods in Bordeaux have the following characteristics:

- The floods often happen in winter (e.g. December, January, and February) or spring (e.g. March, April).
- Floods due to high tides occurred more often. When serious floods happened in Bordeaux, the tidal coefficient was often superior to 100 (representing very strong tides), except for floods due to storm surges in 1999 and 1996. In 1999 and 1996, storm surge levels were very great, respectively reaching 2.25m and 1.77m.
- Floods due to storm surges did not occurred as often as floods due to high tides. However, it seems that storm surges caused much more serious floods, like the floods of 1999, 1981 and 1996.

1.4.2. **Casualties and damages**

Precise statistics of casualties and damages caused by floods in the past are not available, but we have some information about the impact on people, houses, agricultural lands, forests, infrastructures, dikes etc.

For example, from December 10th to 15th 1981, it rained heavily in the Aquitaine and the Midi-Pyrénées regions (Météo-France). A great flood affected the Garonne basin and the Adour, which caused considerable damages. On December 13th, the combination of the heavy rain and the high tide made the water levels of the Garonne rise quickly in a short time, in Bordeaux and its suburbs in the lacustrine city. “Les quais de Bordeaux” disappeared in a few minutes under 2m depth of flood waters (Météo-France).

Another example, during the storm of December 1999, numerous houses and infrastructures were inundated in Charente-Maritime and Gironde. The flow passed “les quais de Bordeaux” and rushed away about 15 cars (EPRI 2011). The dike failure at Blaye inundated 5 000 ha of territory and there was a nuclear incident in Braud-et-Saint-Louis. The low height buildings were inundated by the flood waters (EPRI 2011).

1.5. Future flood risks worsened by climate changes

1.5.1. **Sea level rise**

The expected sea level rise should be the most important effect of climate change in the Gironde estuary (see Figure D-9). The rising sea levels will amplify the flood risk in coastal and estuarial cities like Bordeaux, while population and economic growth will increase the value of the assets at risk.

Scénario	Optimiste	Pessimiste	Extrême
Montée	+ 40 cm	+ 60 cm	+ 1 m

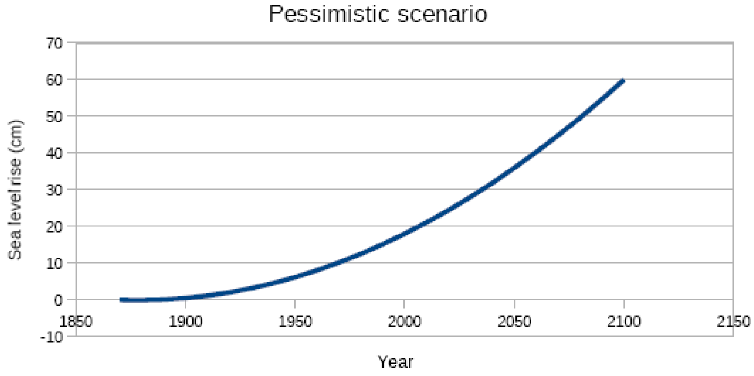


Figure D-9 Sea level rise in Gironde estuary (source: THESEUS EU FP7 project)

1.5.2. **Extreme meteorological events**

Climate change tends to increase the frequency and intensity of extreme natural hazardous events, especially in coastal zones, such as flooding due to severe storms, cyclones, or tsunami (Anderson & Camilla 2006). In Western Europe, a recent event like the storm Xynthia hit the French Atlantic coast on the 28th of February 2010 at 2 a.m. (Figure D-10). The storm surge combined with the high tide and high waves caused flood defenses failure along the coastline from the Gironde (Bordeaux) to the Loire Estuary. A significant amount of land (>500,000 ha) was consequently flooded and 47 people died as a result of the storm, most of them because of the flooding. This kind of extreme maritime storm leads to high-risk for people's life, especially in coastal and estuarial areas. Therefore, such events pose the problem of initiating proactive actions such as evacuation before the disastrous event strikes.

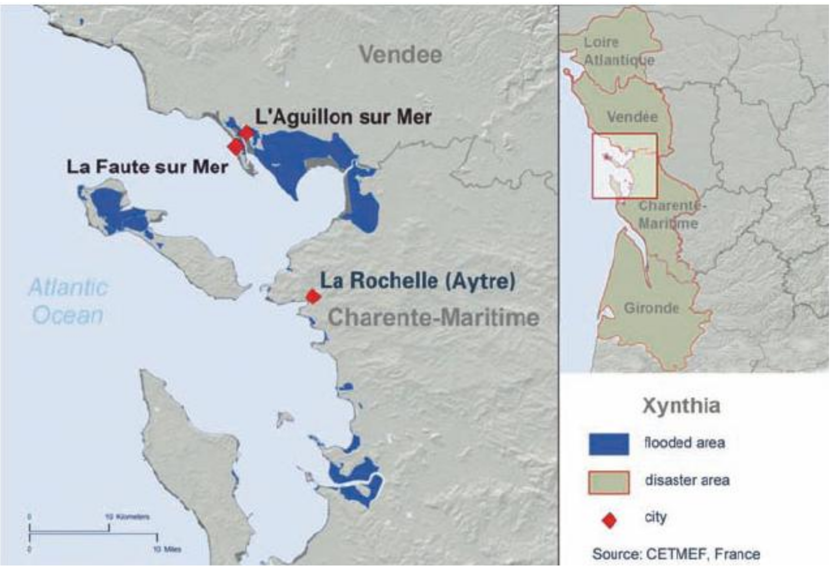


Figure D-10 French Atlantic coastline hit by the storm Xynthia

Moreover, local and big rainfalls are likely to occur during extreme events due to the effects of inland climate (Jeroen et al. 2011). Because cities sit on the coast where long rivers end (e.g. le Havre city and the Seine river), a river discharge can contribute to worsen the flood locally.

2. Flood risk management in Bordeaux

This section is about the flood risk policy in Bordeaux, which concerns protective infrastructures, planning (Plan de Prévention du Risque Inondation - PPRI) and crisis preparation and management (Plan Communal de Sauvegarde - PCS).

2.1. Protective infrastructures

To prevent flooding in the risk prone areas, embankments have been widely built in the Gironde estuary and Bordeaux areas. Most dikes are designed to resist to at least a 100 years return period flood. The average elevation of dikes is 6.80 m (local river levels) on the right bank, and 7.05m on the left bank.

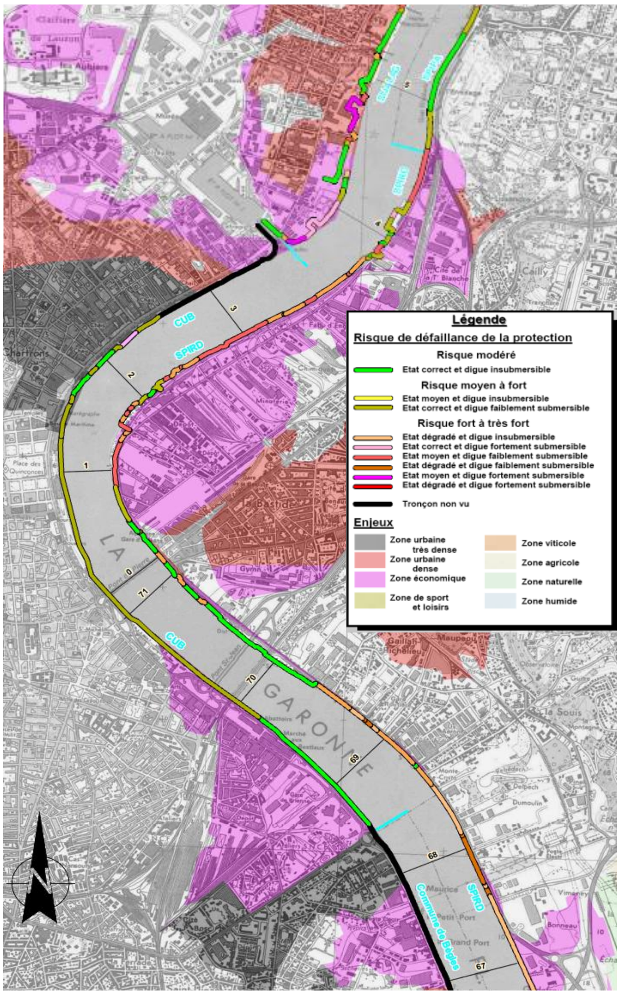


Figure D-11 River-embankment breach risk in Bordeaux Areas (source: SOGREAH 2009c)

However, it is necessary to take into account the risk of dike breach. In particular, the low-lying and plain areas with an altitude below 5m shown in Figure D-11 (e.g. north Bordeaux and the plain on the right bank) are below the height of the dikes, and the impact can be catastrophic in case of a dike breach. It seems that the disaster could be much bigger than the worst historical flood if the combination of a storm and a high tide is unfavorable. For example, the 1981 storm caused serious floods near Bordeaux because the wind and the waves made a dike breach.

The characteristics and state of dikes along the bank of the Garonne were marked on maps (SOGREAH 2009c). Figure D-11 shows different levels of dike breach risk depending on the local state of the protection. As a result of previous storms, especially in 1999 and 2010 (Xynthia), and the tendency of more extreme events due to climate changes, it is important to pay attention to reinforce the management and maintenance of flood defenses to limit the risk in the concerned areas.

2.2. The PPRI (Plan de Prévention du Risque Inondation) for Bordeaux City

In 1995, the Act on Environmental Protection became effective in France (Act 95-101 dated 2nd February 1995 – "loi Barnier"). Local flood prone prevention plans (Plans de Prévention des Risques Inondations - PPRI) are elaborated based on this Act. A PPRI is a tool to take into account the flood risk in the territory planning and management. It summarizes the local historical flood events, defines the reference flood event (ex: the 100 years return period event), and includes a series of thematic maps (e.g. flood hazard/risk maps, land use maps etc.). For example, the PPRI of the north and south of Bordeaux has been elaborated by the Préfecture of Gironde.

2.2.1. **References of flood events in Bordeaux**

There are two ways to measure water levels of the Garonne: NGF (General Leveling of France) and local river levels (see Figure D-12).

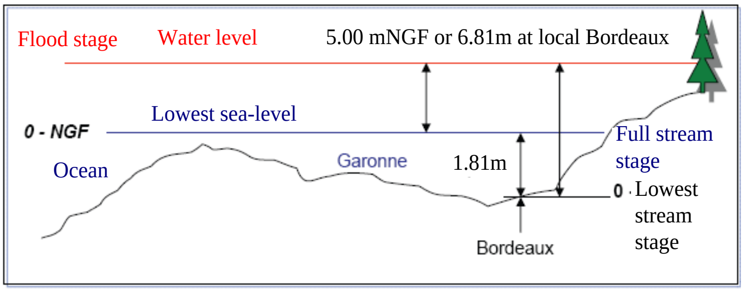


Figure D-12 Two ways of measuring water levels: NGF and local river level

The lowest sea level is defined as the zero in the NGF system. The lowest local stream stage is defined as the zero for the local river levels. In Bordeaux, the lowest stream stage of the Garonne is 1.81m below the 0-NGF (e.g. 5m NGF = 6.81m at the local scale).

Table D-2 shows the water level reference of an exceptional flood event (return period > 100 years) defined by the PPRI de Bordeaux.

Water levels	Tide Coefficient	Wind speed	Storm surge level at Verdon	Return period
5.10 m NGF	118	15m/s (54km/h)	1.19m	>100 years

Table D-2 Reference of an exceptional flood event (PPRI 2008)

According to the experiences of historical flood events and the reference of an exceptional flood event (return period > 100 years), the flood hazard/risk in Bordeaux was mapped and the contour of the flood prone areas was defined.

2.2.2. **Flood prone areas in the PPRI**

In Bordeaux, about 50% of the territory is located in flood prone areas according to the PPRI of Bordeaux. Figure D-13 shows the locations of these areas, which were determined according to the historical events. This map of the flood preventive plan distinguishes three intervals of water levels: below 1m, between 1m and 2m and over 2m.

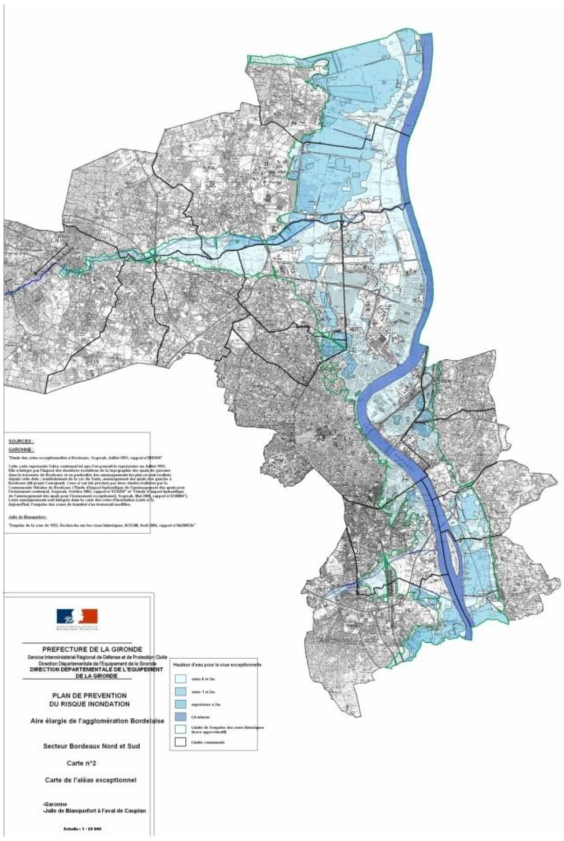
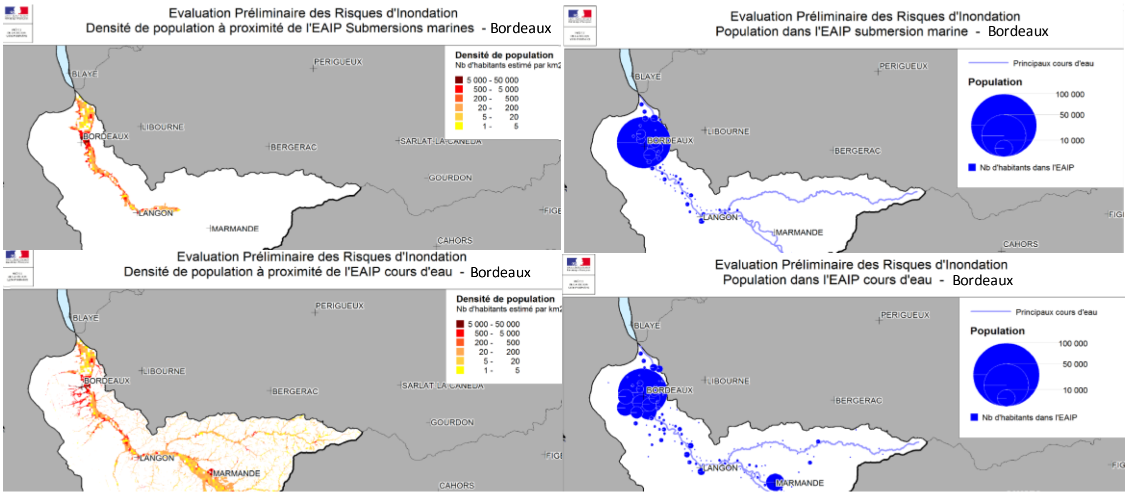


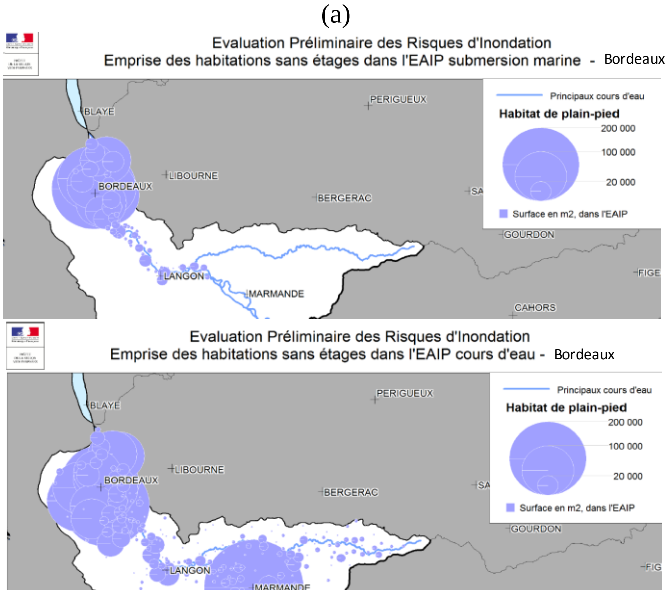
Figure D-13 Flood prone areas in Bordeaux and average water levels (Source: PPRI - Bordeaux 2005)

2.2.3. **Housing and total population in flood prone areas**

Globally, 10.5 to 16.9% of the housing in the Gironde department is located in flood prone areas according to the official data of the period 1999-2006 (SOeS 2010). In Bordeaux, according to EPRI 2011 (Première Evaluation Nationale des Risques d'Inondation – Principaux Résultats), more details about flood risk are given. For example, Figure D-14(a) shows the density and total number of the population living in the flood (fluvial-maritime) prone areas in Bordeaux. The downtown of Bordeaux has a high population density (>5000 per/km^2) and about 100,000 habitants live in the flood prone areas. Figure D-14(b) shows that about 200,000m^2 of the one-story houses are prone to fluvial-maritime floods.



(a)



(b)

Figure D-14 Overview of estimated population and one-story houses in flood prone areas in Bordeaux (adopted from: EPRI2011)

2.3. The PCS (Plan Communal de Sauvegarde) of Bordeaux city

The Plan Communal de Sauvegarde (PCS) has been introduced by the article 15 of the 2004 law on the modernization of the rescue services to help the mayor and the municipal services prepare and manage a flood crisis. Since 2004, municipalities have to elaborate the municipal safeguard plan (Plan Communal de Sauvegarde, PCS), including each identified natural and/or man-made risk. The goal of a PCS is to deal with crisis preparation and management. For example, in Bordeaux, there is an operational PCS for flood risk to describe possible scenarios and to help decision-making in case of a real event, which indicates preventive actions to be triggered in case of a flood alert including some evacuation information (PCS de Bordeaux).

The PCS de Bordeaux synthesizes existing procedures to save human lives, limit material damages and protect the environment. One part of the PCS can be devoted to the possible evacuation procedures. For example, the PCS of Bordeaux city indicates evacuation sectors and evacuation directions for the flood prone areas of Bastide and the Chartrons districts (see Figure D-15 and Figure D-16, the numbers 1 represent evacuation sectors and the arrows in green represent evacuation directions on the map). These evacuation forms and maps can provide useful information for local officials to take an evacuation decision and the basic elements to manage it. However, in case of a flood forecast and emergency, this information does not seem sufficient to evaluate the whole situation and the parameters in order to trigger an evacuation.

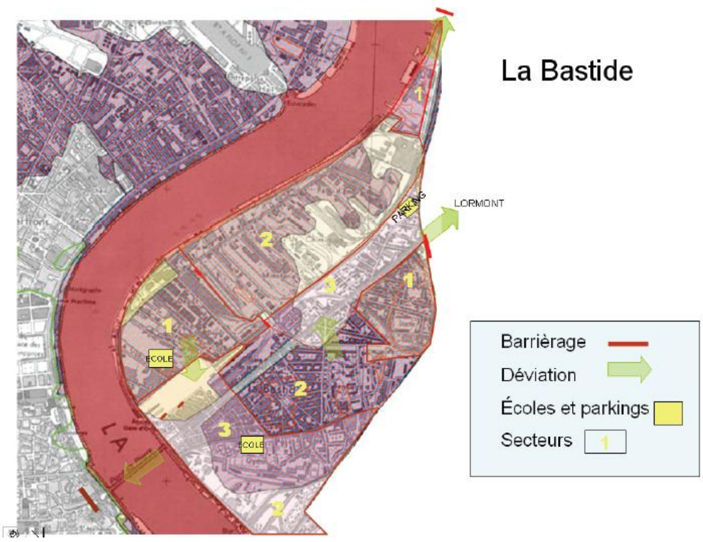
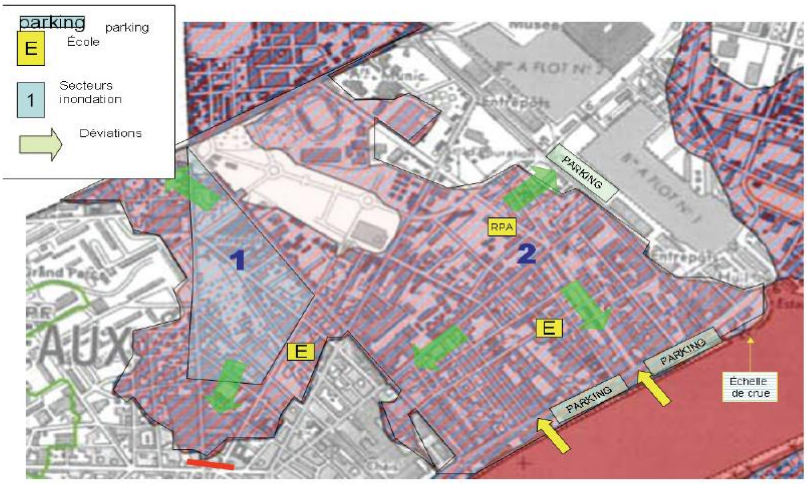


Figure D-15 An example of evacuation sectors at the Bastide (Source: PCS - Bordeaux 2008)



Les Chartrons

Figure D-16 An example of evacuation sectors at the Chartrons (Source: PCS - Bordeaux 2008)

2.4. Crisis management

2.4.1. **The role of local authorities and administration in crisis management**

In France, the administration levels Commune (municipality), Département (department), Région (region) and national level COGIC (Centre Opérationnel de Gestion Interministérielle des Crises) are responsible for the crisis organization, completed by a regional coordinating centre in case of a major disaster. COGIC is the crisis management centre of the French Interior Minister.

When a disaster occurs, the good level(s) which actually intervene(s) depend on the scale level of the event. For the management of all possible kind of risks and crisis such as flooding, the municipality is the primary managerial level since the new law on civil security of 2004. The mayor is in charge of the security of its territory, under the supervision of the Préfet of the department and/or the region. Depending on the magnitude of the event, the mayor should also inform and ask for the intervention of the upper administrative levels: the Préfet of department/region and national services. The Préfet is the coordinator of the national administrations in a department and region. In case of a crisis management which exceeds the territorial limits of a municipality, the Préfet who represents the State is responsible for the supervision of the rescue operations and has the authority over local authorities rescue services. A national disaster is directly managed by the French minister of Interior.

In French crisis management philosophy, evacuation is generally not recommended, but this doctrine is currently evolving with a guide being elaborated by the ministry of Interior.. If an evacuation is necessary and decided by the mayor, it should be validated by the rescue services and the Préfet (PCS-guide pratique d'élaboration 2005).

A general review of the organization of flood emergency management in France is shown in Figure D-17.

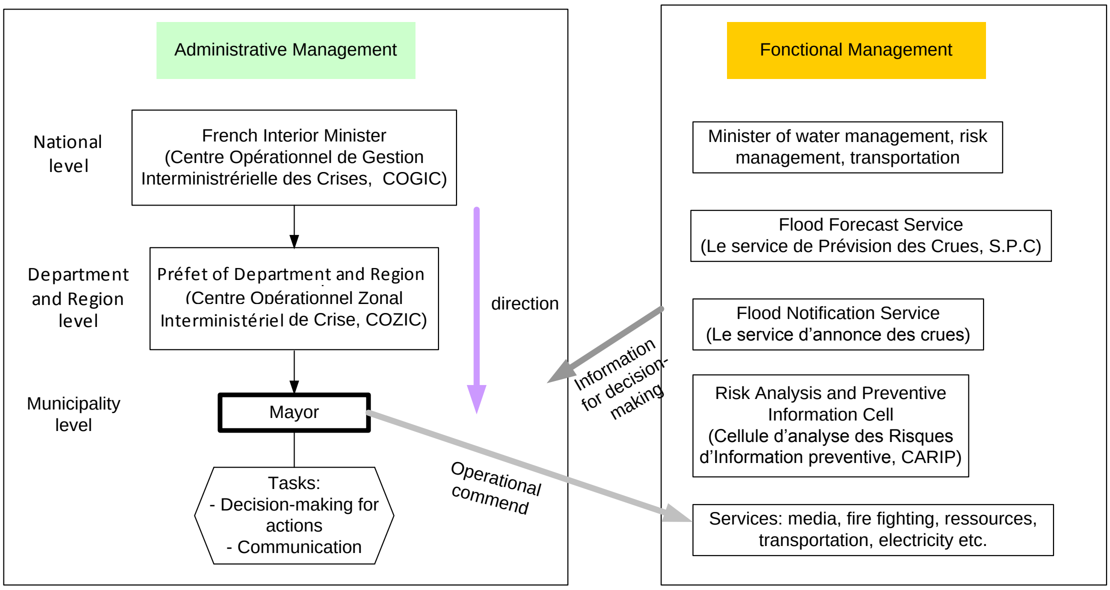


Figure D-17 Overview of administrative and operational responsibility in emergency management in France (PCS-guide pratique d'élaboration, PCS de Bordeaux)

2.4.2. **Forecasting and warning/alert in case of floods and storms**

In France, the "Service Central d'Hydrométéorologie et d'Appui à la Prévision des Inondations" (SCHAPI) is responsible for monitoring river water levels for approximately 1500 measuring stations. They also elaborate and provide a flood forecast and a national alert map for main French rivers, with local levels of alert (and sometimes water levels forecast) for river sections (see Figure D-18 and Figure D-19), distinguishing four threat levels from green (no alert) to red (risk of major floods). This forecast is necessary but not sufficient for local emergency decision since it produces a general forecast (a water level at a reference point or for a river sector) but not detailed local maps of flood risk

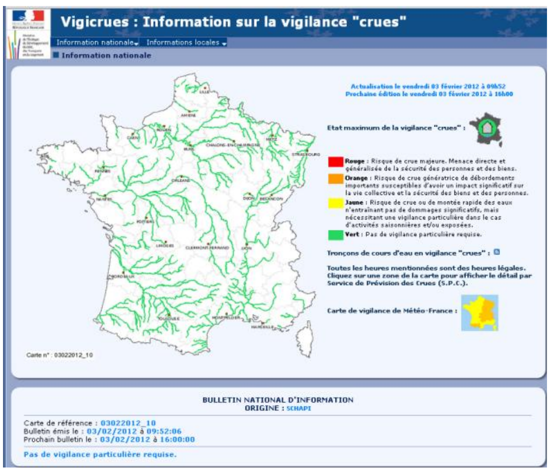


Figure D-18 National flood alerting map (http://www.vigicrues.gouv.fr/)

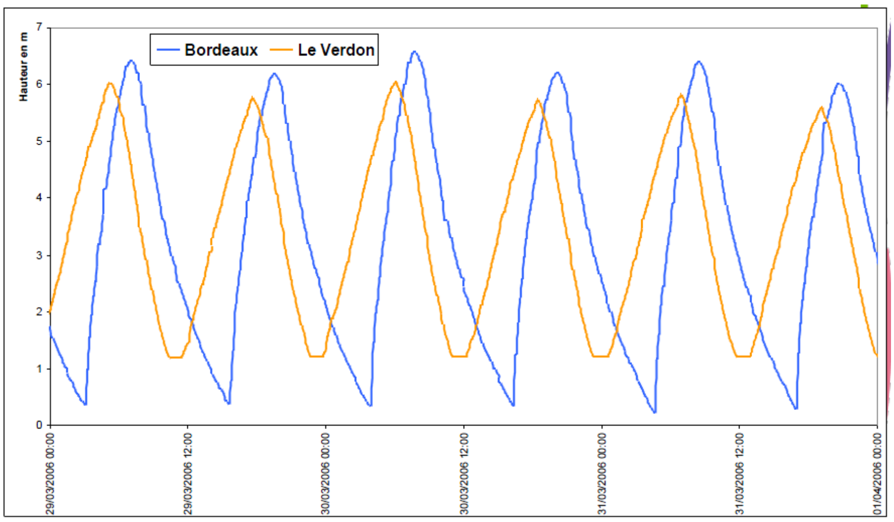


Figure D-19 Example of local water levels data at Bordeaux, with the tide cycle

For coastal floods, the French hydrographical/oceanographical service (SHOM) states water level measuring stations at the French coast. It seems that they currently do not have the ability to read real-time data and that the stations break down too often.

In France, the hazardous events related to dangerous weather conditions are alerted for each department through the 'Vigilance Météo' by Météo-France for the next twenty-four hours. Similar to the flood alert map, four alert levels are distinguished, varying from green (no special alert) to red (absolute alert required). For example, the storm risk map is shown in Figure D-20. In this case, the national bulletin also mentions a risk of maritime submersion on the Atlantic coast. This map is updated twice a day and subsequently spread by the media. The information is also sent to the Préfet who decides whether or not the mayors of the municipalities involved should be warned. In case of an important event, people are warned by the national warning signal.

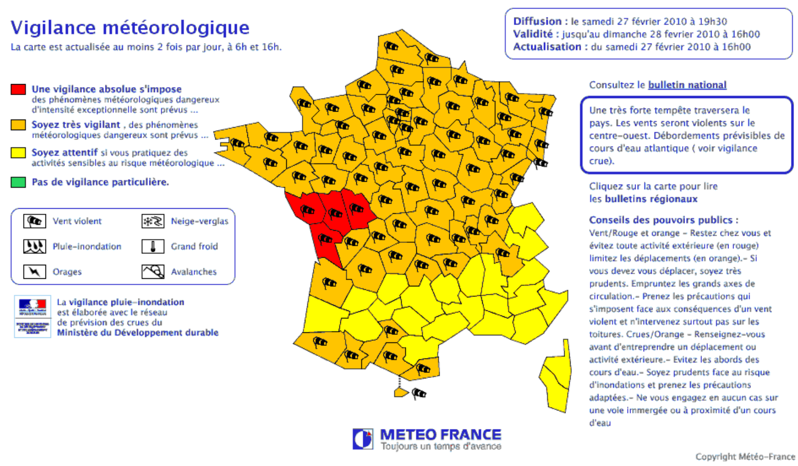


Figure D-20 Storm alert through the Vigilance Météo by Météo-France

From the combination of meteorological forecast and historical events, and thanks to simulation models such as “Pluie-Inondation”, Météo-France provides a flood forecast that can be caused by extreme meteorological phenomena (heavy rainfall, storms, etc.). This forecast and alert gives an overview of the level of the dangerous weather at the regional scale.

Therefore, the forecast services from Météo-France and Vigicrue are very important for local emergency official to get the general information about potential emergency situations. However, these forecasts are not sufficient to give information about the local consequences (e.g. potential damages, elements exposed to flood risk etc.) caused by flooding.

2.4.3. **From alert to risk management: the OSIRIS approach**

OSIRIS (Morel et al. 2009, Morel & Hissel 2010) is a software tool that helps the mayor and its technical services to prepare and manage a flood crisis. In the context of a crisis, it can also helps to make the link between the forecast of local water levels, the corresponding flood maps, the impact on the territory, and finally to produce an optimized action plan to implement before the flood strikes.

OSIRIS, which was initially designed for river flood, has been analyzed to be adapted to the context of the Gironde estuary and the city of Bordeaux, where the physical triggering factors are more complex.

The OSIRIS logic that consists to interpret the PCS with the official real-time forecast and alert could be applied to the issue of an evacuation. But as we seen above, a mass evacuation can’t be triggered only by a water level forecast and that’s why we propose a multicriteria decision method.

2.4.4. **Challenges of evacuation decision before the flood strikes**

As aforementioned, evacuation is considered as a very last resort in France. The PPRI and PCS provide local information about flood scenarios (flood water depths) and evacuation scenarios (zones and direction). Météo-France and Vigicrue provide global information about flood forecast and risk. The OSIRIS tool can be used to interpret this forecast in terms of flood hazard maps and local intervention plans etc. But if OSIRIS can justify triggering simple and local actions depending on water levels, the question remains: to what extent the situation and the forecast could justify a mass evacuation?

Flood forecast translated into flood maps play a very important role in the evacuation decision. For example, in recent event Xynthia, it was reported that there was no evacuation after the warning by Météo-France. Most victims were killed as a result of floods in the coastal areas of the Vendée. The villages of la Faute-sur-Mer and l'Aiguillon-sur-Mer were most severely afflicted by the flood and 29 people were killed.

The interview of Beatrice Lagarde (subprefect of the Vendée) by L'Express indicates the questions of officials about where, when and how to decide an evacuation:

1. "There were no warnings about floods or failing flood defenses. We cannot fantasize about risks and dangers ourselves.
2. And what were we to do at the time that the risk spread over the entire territory of the Vendée – 600,000 persons?
3. Where could we have gone at 22.00 pm to evacuate the 400,000 occupants who were threatened? To the Sahel?"
4. A large-scaled evacuation is complex and normally evacuations are not carried out in case of storms. In case of heavy storms people are advised to stay home since wind gusts, flying debris and falling trees and installations can cause dangerous and traffic-obstructing situations. In this particular event, an evacuation of a few thousand people about 300 to 500 meters from the sea would have saved most people.

As a matter of fact, even though Météo-France had reported the risk of rising water levels, they could not forecast exactly how high the water would rise, which zones could be flooded, if there was a risk of dike breach, and what could be the consequences on the territory and inhabitants. The subsequent conversion into local water levels is explicitly a job for the prefectures and local authorities. The latters claimed that they were not focused on the rising water levels and the flood risk alert, because this information was confused within the usual storm warning and consequent recommendations. Procedures are too limited in this kind of situation to anticipate detailed local impacts and the measures to be taken.

Therefore, the combination of information about storm, flooding and evacuation need challenges local officials to make an evacuation decision. The following aspects need to be improved:

- to make the link between the flood forecast and flood scenarios for a better understanding and awareness about coastal risk;
- to elaborate and provide detailed evacuation scenarios and plans for a better understanding and preparation;
- to make suggestions about evacuation policies (no evacuation, advisory, order etc.) according to the different identified levels and scenarios of risk.

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