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Fuzzy logic based decision support for mass evacuations of cities prone to coastal or river floods

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A B S T R A C T

Facing climate change and more frequent extreme weather conditions, coastal floods and inundations will become more severe. Evacuation can be an efficient solution to secure people's safety in a major disaster. The main difficulty in making an evacuation decision is the imprecise, incomplete and spatially varying nature of the crisis information. In this paper, a fuzzy-logic based method combined with Geographic Information System is proposed to analyze evacuation decision making scenarios. The method can handle qualitative and quantitative data at the same time, avoid sudden changes of decisions affected by uncertainties, and evaluate the spatial necessity to evacuate to support evacuation decision making. The method has been tested at the city of Bordeaux in France. The maps produced representing the need to evacuate can help decision makers better understand evacuation decision situation in terms of local impacts and crisis management anticipation.

1. Introduction

In the context of climate change and urbanization, the increasing risk of river flooding or coastal inundation is already apparent through recent events like the storm Xynthia in 2010, which caused several dozens of deaths in France (Dumas et al., 2013; Lumbroso and Vinet, 2011; Vinet et al., 2012). These catastrophic events, although their extents remain relatively limited, could have justified a preventive evacuation of high-risk areas. However, mass evacuation management is so complex that it requires the coordination of government agencies, local authorities and members of civil society to ensure that clear instructions are given and followed by the population in order to achieve an effective and safe evacuation. In reality, an organized mass evacuation is the ultimate choice when other emergency response processes are not sufficient to protect people's lives. Indeed, it is quite a drastic and risky measure that often affects many people. It can be costly in terms of time, money, and credibility (Kolen et al., 2013; Wolshon et al., 2005). Therefore, the very decision to evacuate by the local or regional authorities remains difficult for technical, political and socio-economical reasons. Numerous and various parameters, sometimes conflicting, have to be considered in the decision process, with some uncertainty inherent in the forecast of the emerging phenomena and its potential impact on the territory and the population.

Based on a multicriteria approach for decision-making, two groups of methods exist in the literature for application in the domain of the threat of a natural disaster: decision based on simple criteria or complex criteria. For simple criteria based methods, an evacuation decision is usually made from assigned threshold values of one or two decision criteria, like the water level forecast or the evacuation time estimation (Frieser, 2004; Baker, 1990). The criteria can be both deterministic (a water level) or/and subjective referring to expert judgments (Bezuyen et al., 1998). Such methods are simple and easy to implement. However, one or two criteria are usually not sufficient to reasonably take a relevant evacuation order that minimizes errors and risks. Moreover, the slight variation of a criterion value around a threshold can greatly affect the final decision. In reality, it is difficult to use a decision support tool in an emergency where a lot of data is uncertain or/and not accurate (Lumbroso and Vinet, 2012).

Previous research studies have already proposed multi-attribute and multi-objective analysis approaches to support the evacuation

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decision process (Kailiponi, 2010; Regnier, 2008). Parts of these multi-criteria methods take into account the notion of uncertainty, generally through a probabilistic approach (Frieser, 2004; Kolen et al., 2013), which is usually to trade off multicriteria between the costs and benefits of evacuation. However, they are not able to integrate subjective variables and expert judgments. On the contrary, in the risk and crisis management field, specialists, stakeholders and even the public usually agree on a framework which provides thresholds and levels of danger like [red, orange, yellow, green] that can be semantically equivalent to [very high, high, moderate, low] in terms of risk. These qualitative levels are derived from physical values and are defined by specialists taking into account their experience of previous events. This is the case in France where climatic or hydrological events are summarized for the decision makers and public by a simple yet easily intuitively understandable colour-coded warning system (Morel et al., 2009).

In order to process and interpret this kind of human-oriented and qualitative information together with quantitative information, we propose to apply a fuzzy logic method to support evacuation decisions. In addition, the fuzzy logic method can adapt human reasoning and thus it is able to integrate expert experience that is important for evacuation decision making.

Before developing the steps of the fuzzy-logic method (§ 3), we first clarify in which cases and under which hypothesis it can apply (§ 2). Then, the results of its application are discussed in the French city of Bordeaux that is prone to coastal flooding resulting from an Atlantic surge in the Gironde Estuary (§ 4).

2. Evacuation decision problem and process

2.1. Context, objectives and hypothesis

The method presented in this article can be applied – or at least adapted – for different urban mass evacuation contexts and types of hazard. Nevertheless, it assumes a set of basic hypotheses and prerequisites that have to be clarified. It mainly concerns an exceptional event (e.g. a storm surge flood hazard) that authorities can forecast several hours in advance, 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 at-risk area (vertical evacuation) (Sorensen et al., 2004). In the context of an alert for a major disaster, the organization of crisis management cannot be improvised, especially in the case of a mass evacuation for which specific plans have to be prepared in advance, outside any crises. These plans can be used as a first level support for decision making, but are not sufficient to take into account real-time and updated data.

Many existing methods and tools for evacuation preparation and management have been designed in different countries for different situations. For example, in the Netherlands and in the UK several evacuation models have been applied for coastal floods situations (Lumbroso and Ballard, 2006), and in the US many evacuation models have been applied relating to areas around nuclear power stations and hurricanes (Lindell and Prater, 2007). Here, we applied a fuzzy-logic based technique to a case study area on the west coast of France, which is affected by both coastal and fluvial floods, aiming at providing a quantitative synthesis visualization to aid the decision making.

2.2. Questions, uncertainty and decision making

When a forecast triggers a flood warning, there are three main questions that authorities have to answer before taking a decision to evacuate:

1 What will be the real level of danger to people's life in at-risk areas and does it justify an evacuation of those areas?
2 Do we have the capacity (in terms of resources and time) to evacuate part or all of the population at risk in the time before the event strikes?
3 Can we achieve this evacuation safely?

Answering these questions depends on many parameters, such as local danger levels and human and material resources etc. It is not possible to simply answer “yes” or “no” to these questions. Some of the parameters can be correctly anticipated (in advance thanks to preparation plans or real time data), but others remain uncertain and vary during the event and the decision making process:

1 The local level of danger for people depends on the forecast and simulation models which is uncertain as an event progresses and is inaccurate due to data acquisition and numerical modelling. In France, the forecast and alert system generally gives a global level of danger by colour codes of red, orange, yellow and green, which facilitate the intuitive awareness of how severe the situation is: red-risk for a major flood, which causes direct threat to the general safety of people and property, orange-risk for a significant level of inundation, which may have a significant impact on community life and on the safety of property and people, yellow-risk for a flood or a rapid rise of water which does not involve significant harm, but requires special vigilance in the case of seasonal and/or outdoor activities (www.vigicrue.fr), but crisis management and intervention need more accurate information based on local water levels and risk mapping.
2 The human and material resources can partly be identified and organized in the preparation phase (Morel and Hissel, 2010a). Nevertheless the actual availability of these resources remains uncertain depending on the time of the event and on the reaction of people to the situation.
3 The implementation of the evacuation conditions on the ground is also subject to unpredictable events like network failures (Morel and Hissel, 2010b), accidents and fuel shortages (Litman, 2006).

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

In our previous work and in the framework of the FP7 EU THESEUS project, an operational methodology was developed to help local authorities to produce evacuation plans in the case of coastal floods in the context of crisis preparation. The project proposed a methodology with six progressive steps to build the plans outside a crisis, plus a seventh one to use and implement these provisional plans during a real event (Morel et al., 2011).

In addition to the process modelling and explanation, the project includes a complete catalogue 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. To move on from crisis preparation to emergency management, we extracted a subset of 21 strategic criteria that decision makers should take into account in the decision process of real-time evacuation, when an alert is triggered. In order to highlight the proposed method, the 21 criteria are condensed into 4 criteria in this paper.

In the next part, we develop the content of the proposed method from the initial process of raw data to the final decision support system. The method handles heterogeneous multiple criteria and can tolerate uncertainties. The results of the fuzzy logic based decision process can be shown on a map using GIS tools (see §4).