Water Utility Journal 3: 37-46, 2012.

Towards human-centred flood evacuation for cities under climate change

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Abstract: Emergency response involving large-scale evacuation of urban population in the event of flood-related events is a serious problem with dire implications that remains largely unsolved. Recent studies and reports conclude that climate change is an undeniable challenge for the current transportation system. The difficulty in responding is not so much in developing response plans, but in implementing them effectively, in a way that they can be understood and accepted by the general public. The time scale for response is also a very important component. In many cases where the flooding is related to hurricanes and other extreme weather effects, a warning may be available several days in advance; in other situations, however, such as dam or levee breaks and tsunamis, the warning might be in the order of a few minutes to an hour (if available at all). In this research, an overall strategy for effective response plan generation with an emphasis in urban areas is presented, comprising components modelling and forecasting both the evolution of the weather phenomena and the condition of the transportation network infrastructure. Specific aspects of generating response plans and modelling the behaviour of evacuees are also discussed. It is concluded that this interdisciplinary problem needs to be addressed carefully in order to result in reduction in the loss of life due to extreme weather conditions, especially in light of increasing urbanization and climate change.

Key words: extreme weather phenomena; floods; transportation infrastructure; evacuation; urban environment; behaviour of evacuees.

1. INTRODUCTION

Emergency response involving large-scale evacuation of population in the event of flood-related events is a serious problem with large implications that remains largely unsolved. Hurricane Katrina left more than 1800 dead in New Orleans in 2005, demonstrating the difficulties of achieving proper evacuations (Kates et al., 2006). While most of the population in this case responded to public calls for evacuation, an estimated one-quarter of the population was either unable or unwilling to leave. When one considers this failure in the US, it is frightening to think how difficult it may be to safely evacuate affected populations when disaster strikes in developing or third world areas, which are ironically often more severely hit by natural disasters. These events appear to be becoming more severe over the past years. The theory of global warming (often debated) has evolved into the concept of climate change, which is a broader and generally better-accepted concept. Such theories are used to explain the occurrence of more frequent and more extreme phenomena, resulting in significant loss of life. What was until very recently considered a once-in-a-century coastal flood in the metropolitan New York City area is projected to occur at least twice as often by mid-century, and 10 times as often by late-century (NECIA, 2007).

Recent studies and reports conclude that climate change is an undeniable challenge for the current transportation system (NRC, 2008; Meyer, 2008; FHWA, 2008). According to the Transportation Research Board Special Report 290 (NRC, 2008), changes in precipitation, sea level, storms and heat waves will have significant impacts on the performance of the transportation and urban system. As a result, it has been proposed that climate change should be taken into consideration in the long-range transportation and land use planning process (NRC, 2008; FHWA, 2008).

The Transportation Research Board (TRB) identifies five climate changes of particular importance to the transportation system in the United States, three of which are rising sea levels, increases in intense precipitation, and increases in hurricane intensity (NRC, 2008). All of these three climate changes can pose flooding risks on the transportation system especially in coastal areas resulting in infrastructure disruption, network interdiction, and serious economic costs.

The transportation network is a critical infrastructure in the event of natural and man-made disasters, when large populations must be expediently evacuated from dense urban areas. Evacuation demand is thus compressed into a relatively short time span, and the available roadway capacity becomes a critical resource that must be judiciously utilized to minimize evacuation time. Recent natural disasters such as Hurricane Katrina and the need for Homeland Security preparedness have mandated that evacuation plans be coordinated across jurisdictions and modes of travel. Such coordination is often lacking, and can result in suboptimal operations during emergency evacuations (Shepherd et al., 2006).

Transportation infrastructure in the coastal areas is especially vulnerable to flood impacts from storm surge, sea level, intense precipitation and other related phenomena (Lu et al., 2013). Developing emergency response plans for such emergencies is not the harder part of the solution. The difficulty is in implementing them effectively, in a way that they can be understood and accepted by the general public. Human beings are notoriously unpredictable under regular conditions; things become much harder under emergency conditions and stress (Prionisti and Antoniou, 2012). Sensitivity analysis has grown from a simple procedure of testing a range of scenarios, to a formalized approach that allows the evaluation of a very large number of scenarios to gain deep insight into the response of a modelled system (Saltelli et al., 2004).

Other technologies that can provide support to the evacuation planning and emergency management include Geographic Information Systems (GIS, e.g. Cova, 1999, Pal et al., 2003, Laefer et al., 2006, Wilmot and Meduri, 2005), decision support systems (e.g. Levy et al., 2007), dynamic traffic assignment (DTA) models (Yan and Han, 2005; Kwon and Pitt, 2005, Balakrishna et al., 2008).

The objective of this research is to provide a review of the problem of emergency response to problems related to the adverse impacts of extreme weather events on transportation infrastructure, and to outline a framework for the human-centred effective generation and implementation of response strategies with the objective of minimizing fatalities. A key factor in this approach is the incorporation of detailed explicit modelling of the behaviour of the evacuees in the process. The remainder of this paper is structured as follows. Section 2 discusses infrastructure-related vulnerabilities, while Section 3 presents some of the parameters related with providing timely and effective response. Section 4 describes the overall strategy for effective response plan generation, while Section 5 focuses on the characteristics of the response plans. One of the key issues is modelling the response and behaviour of evacuees, which is covered in Section 6, which is followed by a concluding section that discusses issues of regulation and further research.

2. INFRASTRUCTURE-RELATED VULNERABILITIES

Transportation infrastructure has a long life span (in the order of at least several decades). Aging of the infrastructure (both due to regular wear and tear, but also non-recurrent events such as earthquakes and floods) leads to the need for considerable maintenance or even replacement. However, this is very costly and often neglected. Several disastrous incidents have taken place recently (including the well publicized collapse of Minneapolis I-35W bridge in Minnesota, which claimed 13 lives) and an assessment of the existing infrastructure in the US has revealed significant problems in a large number of bridges.

A recent study of the structural evaluation of a 326m-long, historic stone arch bridge in Turkey against floods and earthquakes is presented by Turer and Sert (2013). The bridge was originally built in 1292 and repaired in 1875 and early 20th century. The authors' analysis combined field measurements of the structural dimensions of the bridge, truck loading analysis, ambient vibration testing, finite element modelling, 500-year return period flood water dynamic modelling and 475-year return earthquake response spectrum analysis to assess the structural characteristics and response to natural disasters and traffic loads. The findings suggest that the bridge has been overdesigned and that this may be a practical strategy to better optimize resources for sustainable bridges that require lower maintenance and offer longer service life.

Lu et al. (2013) present an accessibility-based criticality prioritization methodology to identify and rank critical transportation infrastructure under flooding risk. In particular, the methodology assesses the network-wide impacts of infrastructure failure to the travel conditions. Based on the findings of the application to the road network of Hillsborough County, Florida, the authors find that while some infrastructure elements may have a larger local impact in the surrounding areas, others may have more long-reaching impacts, thus becoming more important to a much broader region.

3. EFFECTIVE RESPONSE PARAMETERS

The time scale for response is also a very important component. In many cases where the flooding is related to hurricanes and other extreme weather effects, an (at least approximate) warning may be available several days in advance (as was the case, e.g. in hurricane Katrina). Golding (2009) reviews the research on long lead time flood warnings and concludes that emerging forecasting techniques could help support earlier warnings, provided they are casted in probabilistic terms and interpreted appropriately.

In other situations, however, such as tsunamis, the warning might be in the order of a few minutes to an hour (if available at all). Besides the temporal component, however, there are many other complicating factors, such as the different modes. Recently, particular interest has been given to pedestrian traffic. Pedestrians typically move with lower speeds and can cover shorter distances than motor vehicles, but are presumably more flexible in navigating the network and are not limited by traffic bottlenecks. Large-scale traffic simulation models have been adapted to pedestrian simulation (e.g. Lämmel et al., 2010a). Lämmel et al. (2010b) use the agent-based simulation model matsim to evaluate the impacts of the early warning and evacuation information system that is being developed via the "last-mile evacuation" research project. The model is applied in the city of Padang, West Sumatra, Indonesia (for more information and a video of the results, the interested reader is referred to: http://matsim.org/scenario/padang).

Wesselink (2007) discusses how the cultural and social characteristics of different populations can significantly affect the way they decide to protect themselves against the forces of nature. The Netherlands, for example, have long been vulnerable to floods, and in spite of access to technology and financial resources have in general exhibited a lack of risk awareness on this front. New Orleans, on the other hand, may make very different choices, partly due to its circumstances and its much shorter history, taking advantage of an opportunity to deal with flood risk in more creative ways.

The heterogeneity of the population is of paramount importance. An analysis of 829 fatalities from the Katrina hurricane in 2006 (for which age is known) indicates that less than one per cent were children and just over fifteen per cent were under 51 years old (Jonkman, 2007). 85% were older than 51, 70% over 60 and almost half were older than 75 years of age (while only 25% of the population was older than 50 and only 6% was older than 75). Based on the analysis by Jonkman, it was not evident that gender and race were not significant differentiators in the likelihood of a citizen to become a fatality.

4. AN OVERALL STRATEGY FOR EFFECTIVE RESPONSE PLAN GENERATION

Emergency response in the case of extreme weather events is a multidisciplinary activity that requires the synchronization of several different technologies, including data collection, modelling of the phenomenon and modelling of the transportation system (including the behaviour of the evacuees). The overall picture is shown in Figure 1. Data are required from both the side of the weather conditions and considered phenomenon, as well as the state of the transportation networks at any given time. Early warning is therefore a key component. For example, Al-Assadi et al. (2009) present the chip design of a flood prediction system that is based on piezoelectric pressure sensors and can help provide early alerts, potentially even predicting the flood before it actually occurs. Similarly, a large number of conventional and emerging traffic data collection technologies are available to provide information about traffic conditions and the condition of the transportation infrastructure (Antoniou et al., 2011).

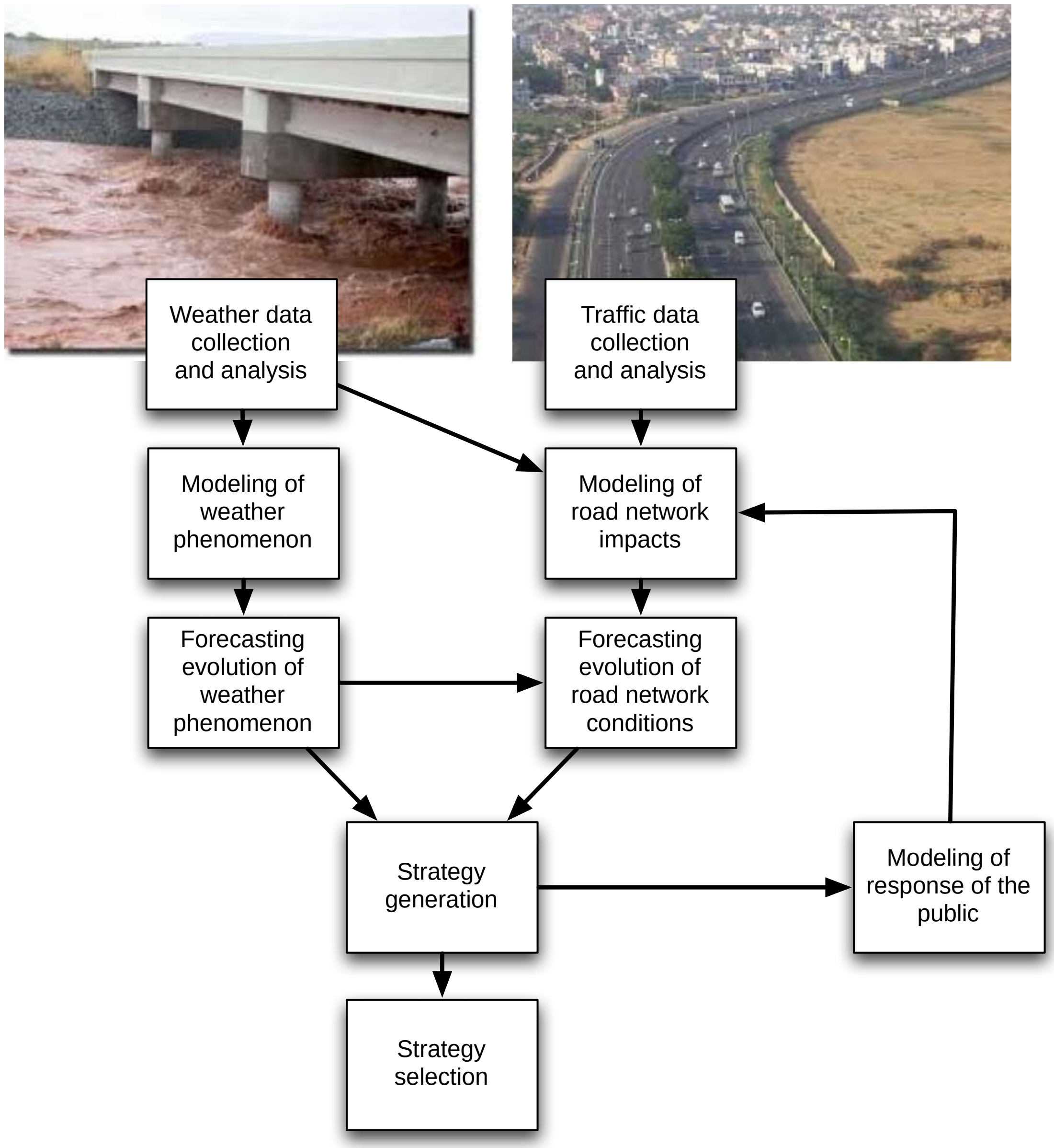

Figure 1. An overall framework for effective response plan generation.

This information is used for the independent modelling of the weather and road network impacts (the latter can take advantage of the data about the weather conditions). For example, a methodological framework for flood risk assessment is provided by Pistrika and Tsakiris (2007) using a three step approach: (a) annualized hazard incorporating probabilities of occurrence and the anticipated potential damages, (b) vulnerability in the flood-prone areas and (c) annualized flood risk. Similarly, a simulation-based framework for transportation network management for emergencies is proposed and demonstrated by Balakrishna et al. (2008).

Forecasting of the evolution of the weather phenomenon and the traffic conditions, as well as their interaction, is of paramount importance for the development of useful plans. Modelling the interaction of the transportation infrastructure network with flooding waters requires sophisticated analysis. For example, Tang et al. (2013) combine the three-dimensional coastal ocean model FVCOM with a two-dimensional shallow water model to simulate hydrodynamic flooding with resolution suitable to modelling the impact to traffic elements such as individual streets with reasonable effort. The affected areas are used to estimate the demand to be evacuated, which is a key component to modelling the problem accurately.

Considering the delay in developing, selecting, disseminating and implementing these plans, any insight into the future of the event is valuable. This information is fused into the generation of alternative response strategies, which are in turn evaluated using behavioural response models to assess the expected behaviour of the potential evacuees. This information is then fed back into the transportation models to obtain consistent estimates and forecasts of the expected conditions. One important observation in this point is that the weather side only feeds information to the transportation side. This is natural, as any information from the transportation side cannot affect the evolution of the weather phenomena, while information about the weather can affect the transportation side (both in terms of limiting its capacity, e.g. by flooding road links or damaging bridges, but also in terms of affecting the willingness of the citizens to travel).

Modelling and simulation are valuable tools in the arsenal of emergency management. Chen and Zhan (2004) investigate the effectiveness of simultaneous and staged evacuation strategies in different road network structures using agent-based simulation, while Liu et al. (2006) propose a cell-based network model to capture critical characteristics associated with the staged evacuation operations. On the other hand, Bronzini and Kicinger (2006) identify the limitations of existing analytical tools for dealing with mass evacuations and propose a conceptual model that combines cellular automata, evolutionary computation and transportation science, along with infrastructure security elements. Chiu et al. (2005) discuss the development of an emergency management scheme that includes a feedback loop using surveillance systems, while Liu et al. (2006) present a model reference adaptive control (MRAC) framework for real time traffic management under emergency evacuation. Jha et al. (2004) use a microscopic simulation model for evaluating emergency evacuation plans. Balakrishna et al. (2008) use a DTA model with detailed behavioural models for a predictive response to the problem of evacuating a large US city.

The question of system optimum versus user optimum optimization for traffic management becomes even more pressing in the case of real-time evacuation planning (Lämmel and Flötteröd, 2009). Travel time is not the only thing that is now at stake; instead lives could be lost if the optimal strategy is not obtained.

5. DEVELOPING EMERGENCY RESPONSE PLANS

An important element to developing an evacuation strategy is knowing where the potential evacuees are located. This can be easier for the night hours, when most people may be presumed to be at their homes, but harder during the days. Naturally, this is varying by time of day and season (since e.g. in the summer months there may be many more tourists in a seaside resort). The next step is knowing where to take the evacuees, i.e. to determine the so-called safe zones and developing the directions to guide people there. Of course, this may not be fixed, but also dynamic, as e.g. weather patterns evolve and a formerly safe location may turn unsafe as well. However, this leads to perhaps the hardest component, which has to do with the behaviour of people under stress. There are two sub-components in this: (i) compliance to the instructions and (ii) characteristics of the actual movement, even if the evacuees decide to follow the instructions.

Alsnih and Stopher (2004) review the procedures associated with the development of emergency evacuation plans. The authors assess the available emergency evacuation models and identify key research directions to investigate the effects of a mass evacuation on current transport networks. Mitchell and Radwan (2006) evaluate various heuristic strategies to improve evacuation of an at-risk region using a representative traffic roadway network. Many researchers treat evacuation planning as an optimization problem (Yuan et al., 2006; Sbayti and Mahmassani, 2006; Liu et al., 2005; Lu et al., 2003).

When evacuation takes place, there often remains a need to provide access for emergency vehicles and personnel to the threatened area creating a conflict between the needs to maximise capacity for evacuation, while continuing to provide access to the threatened area. Relatively little is known about when residents will decide to evacuate. Models of evacuation behaviour may predict the proportions of the population that would leave within certain time periods (Alsnih et al., 2005; Fu and Wilmot, 2007), and may be based or sequential binary logit models (Fu and Wilmot, 2004), evacuation response curves (Fu and Wilmot, 2006), activity-based simulation (Murray-Tuite and Mahmassani, 2003; Murray-Tuite and Mahmassani, 2004; Henson and Goulias, 2006), logistic regression and neural network models (Wilmot and Mei, 2003). Ozbay et al. (2006) conduct a comprehensive and critical review of demand generation and network loading models, while Fu and Wilmot (Fu and Wilmot, 2006) present two hazard-based survival analysis models with time-dependent variables, a Cox proportional hazards model and a piecewise exponential model, to estimate the probability of a household evacuating.

Figure 2 outlines the initial sequence in developing a response plan. The first step is to determine the affected population. Setiadi et al. (2010) propose a conceptual framework and methodology for the estimation of the spatial distribution of exposed social groups, applied to a case of a tsunami in the Indonesian city of Padang. The approach uses heterogeneous information sources, such as census and household survey data with structural information of the urban landscape extracted from remote sensing data. These need to be combined with information on the evolving phenomenon to determine the actually directly affected population and potentially prioritize them.

The next step is to determine where the affected population can be safely moved to, i.e. the so-called “safe zones”. Wilmot and Meduri (2005) present a methodology for the development of hurricane evacuation zones. Evacuation zones and safe zones are then matched, considering the available transportation network, in a way that minimizes the time needed for the evacuation and thus minimizes the chances of fatalities.

Naturally, the biggest challenge is to model the behaviour of the evacuated population. Understanding disaster-warning responses of the general public is a significant social science problem that depends on receiver characteristics, message characteristics and social contexts in disaster warning responses (Drabek, 1999).

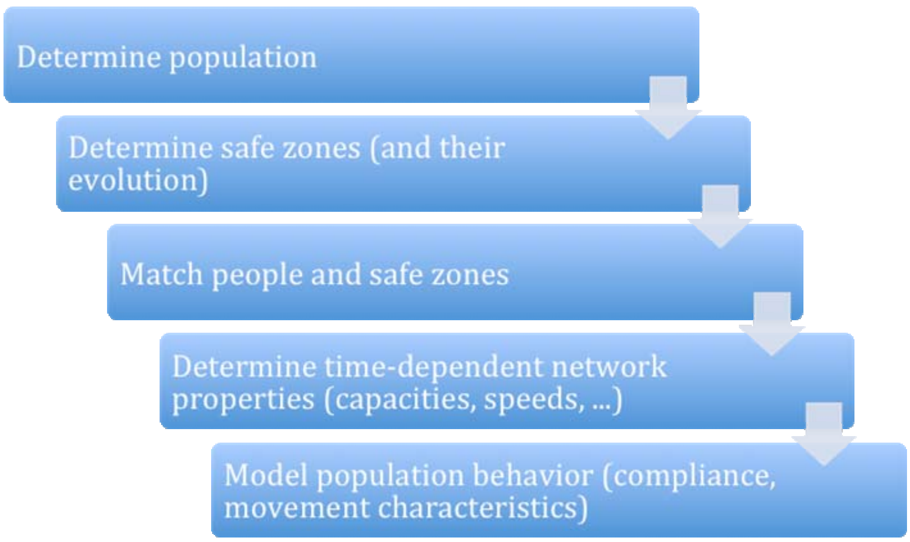

Figure 2. Initial sequence in developing response a plan.

6. MODELING THE RESPONSE OF EVACUEES

The credibility of emergency/evacuation warnings can considerably affect the willingness of the public to collaborate and respond positively. Dow and Cutter (1998) used interesting data from the 1996 hurricane season in South Carolina, to study the evacuation behaviour of the public in the presence of repeated “false alarms”, i.e. evacuations ordered based on expectations of a hurricane landfall that proved to be wrong. One of the main findings of the research was that the unreliability of official warnings led the public to seek alternate information sources.

Parker et al. (2009) explore how people have responded to flood warning information in various areas in Europe and how these responses impact the effectiveness of a flood warning. The authors look at weather the public actually receives the information and then at commonalities of how people respond to these warnings. Finally, the authors identify socio-economic and socio-psychological processes affecting flood warning response and make recommendations on how learning methods could help enhance the response of the public to floor warning information.

Creutin et al. (2009) assess how current techniques for flash flood monitoring and forecasting can meet the needs of the population at risk to evaluate the flood severity and anticipate its danger. One of the main findings was that the accuracy and quality control of real-time radar rainfall data needs to be improved, especially for extreme flash flood-generating storms.

Higgins et al. (2012) performed human factors studies to develop signing strategies for warning motorists of flooding on roadways. Examples of questions tackled by the researchers include: which passive signs are most effective at influencing driver responses, how effective active signs are, whether a stop bar increases the effectiveness of sign messages (such as Do Not Enter, Do Not Cross, or Road Closed), and which signs were considered by the subjects the most helpful in taking decisions about the safety of flooded roads? The findings helped the authors propose uniform signing guidelines for flooding or water crossing situations.

Prionisti and Antoniou (2012) recognize the difficulty of modelling the behaviour of people under distress and propose a different approach. Rather than trying to measure and model the exact behaviour of evacuees, instead they authors develop a sensitivity analysis approach, which provides an envelope of expected conditions. The decision maker can then test the robustness of the proposed plan to the range of plausible scenarios and develop expected ranges of performance for the proposed strategies. Depending on the objective function of the policy maker (e.g. minimize maximum fatalities, maximize saved people, minimize evacuation time, provide unobstructed access to emergency response vehicles, or a combination of the above), expected values of each scenario can be obtained.

Simonovic and Ahmad (2005) also use sensitivity analysis in the context of a computer-based model for flood evacuation emergency planning. In particular, the authors consider factors including uncertainties in the warning consistency, timing of orders, coherence of community and awareness of upstream community flooding and find that the timing of evacuation orders is the most important variable that affected human behaviour during the flood emergency that they studied.

7. DISCUSSION

Climate change is expected to affect many aspects of our lives and –according to many– it may be responsible for some extreme weather phenomena. Civil infrastructure (including transportation infrastructure) will need to adapt to consider this (Keller et al., 2011). Among the general approaches identified by Keller et al. (2011) are ranking of facilities by importance, allowing for flexibility in design, developing alternative scenarios and resources, performing a sensitivity analysis and incorporating risk assessment and management techniques integrated with climate forecasting and infrastructure design. Examples of climate change impacts to transportation infrastructure include temperature change, increased storm intensity or duration and high wind impacts, drought and sea level change.

The challenges associated by this interdisciplinary problem are recognized by several researchers, including Shen and Peng (2011) who develop a methodology that combines forecasts of expected riverine flood area and frequency with methods to identify the estimated flood map and calculate the affected area and infrastructure elements.

Authorities have the ultimate responsibility for evacuation, and one of the main components is flood risk estimation and management. EU Directive 2007/60 is such a document that aims to provide a homogeneous action plan for EU countries. Tsakiris et al. (2009) provide a critical review of the document, highlighting some practical technical issues associated with its application and provide recommendations for its improvement.

Finally, community preparedness is a very important aspect of emergency response. Perry and Lindell (2003) review the concepts of community preparedness and emergency planning and their relationships with training, exercises and the existence of a written plan.

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