1 2 9 0

UNIVERSIDADE D
COIMBRA

Melissa Alexandra Quaresma Gama

FLOOD EMERGENCY LOGISTICS MANAGEMENT

PhD Thesis in Doctoral Program in Transport Systems supervised by Professor Bruno Filipe Santos, Professor Maria Paola Scaparra, and Professor António Pais Antunes, and presented to the Department of Civil Engineering of the Faculty of Sciences and Technology of the University of Coimbra.

June 2022

[Page Intentionally Left Blank]

1 2 9 0

UNIVERSIDADE Ð
COIMBRA

Melissa Alexandra Quaresma Gama

FLOOD EMERGENCY LOGISTICS MANAGEMENT

PhD Thesis in Doctoral Program in Transport Systems supervised by Professor Bruno Filipe Santos, Professor Maria Paola Scaparra, and Professor António Pais Antunes, and presented to the Department of Civil Engineering of the Faculty of Sciences and Technology of the University of Coimbra.

June 2022

[Page Intentionally Left Blank]

FINANCIAL SUPPORT

This research work was financed by “Fundação para a Ciência e a Tecnologia” (FCT, Portugal) through the PhD scholarship with the following reference: SFRH/BD/80533/2011 and was co-financed by the European Social Fund (ESF) within the “Programa Operacional Potencial Humano” (POPH).

[Page Intentionally Left Blank]

AGRADECIMENTOS

Aos orientadores/professores:

Ao Professor Bruno Santos por acreditar em mim, pelo apoio, confiança e disponibilidade, principalmente nesta fase final; ao Professor Pais Antunes por toda a ajuda e confiança; à Professora Paola Scaparra por tudo o que me ensinou; e também um agradecimento ao Professor Nuno Simões pela colaboração e disponibilidade.

À Trenmo Engenharia:

Ao Professor Álvaro Costa e restante equipa que muito contribuíram para que fosse possível terminar este desafio.

Aos amigos:

Um agradecimento especial à Joana Carreira, à Inês Frade, à Diana Jorge, à Anna Beatriz e à Sofia Oliveira que foram um grande apoio nesta fase final do doutoramento; também à Tita, ao Rui Castro, ao Alcides Fonseca e ao Luís Neto pela ajuda e disponibilidade.

À minha família:

Por todo o apoio mesmo que nem sempre tenham compreendido o caminho e as escolhas feitas.

[Page Intentionally Left Blank]

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

Floods are the most common natural disaster worldwide, and their frequency and number of people affected are increasing. Civil protection authorities are in charge of flood emergency management, providing means to help the affected population and ensuring its safety. Shelter location, warning issuing, and evacuation routings are important operations to minimize flooding consequences.

This research presents a four-stage flood planning framework to support civil protection authorities' decisions. In the first stage, all the necessary data – flood map, flood evolution, water level on the road network, affected areas and respective affected population, location of candidate shelters and yards where emergency vehicles are parked, traveling times between affected areas and shelter, etc. – are collected and structured. In the second stage, a multi-period shelter location-allocation model with evacuation orders is developed. Taking into consideration the evolution of the flood, the model minimizes the traveling times between the affected areas and shelters while determining the location of a fixed number of shelters which become available in different time periods, the issuing time of evacuation orders for each demand area, and the allocation of each demand area to a shelter. The solution obtained is the basis for designing the private car evacuation routes between each demand area and the allocated shelter or other final destinations (super nodes), in line with the respective evacuation order issuing. Therefore in the third stage, possible congested zones can be identified and competent entities can be allocated to these zones to ensure public order. The last stage comprises the evacuation process of those who rely on emergency vehicles to reach a shelter. A multi-period vehicle evacuation model is proposed to optimize the evacuation and waiting time of evacuees while determining the emergency vehicles routes and schedules. Both optimization models – the multi-period shelter location-allocation model with evacuation orders and the multi-period vehicle evacuation model – consider that travel times change over time, demand evacuates according to a pattern, and resources are limited and are not readily available. The multi-period shelter location-allocation model with evacuation orders is solved using a simulated annealing heuristic whereas the multi-period vehicle evacuation model is solved using a time-space network and a rolling horizon approach.

Both models and respective solution methodologies are applied to real world-based case studies in the USA and the flood planning framework is applied to a real world-based case study in Portugal. The solutions highlight the importance of using a dynamic approach and of considering the resources availability over time.

RESUMO

As inundações são os desastres naturais mais comuns a nível mundial e a sua frequência e a população afetada estão a aumentar. As Autoridades de Proteção Civil estão a cargo da gestão de inundações, proporcionando os meios e recursos para ajudar a população afetada e garantir a sua segurança e proteção. A localização de abrigos, a emissão de alertas e a definição de rotas de evacuação são operações importantes para minimizar as consequências das inundações.

Este trabalho de investigação apresenta uma metodologia de planeamento de inundações composta por quatro fases, para apoiar as decisões das Autoridades de Proteção Civil. Na primeira fase, todos os dados – mapa de cheia, evolução da inundação, níveis de água na rede viária, áreas afetadas e respetiva população afetada, localização dos possíveis abrigos e terminais onde os veículos de emergência estão estacionados, tempos de viagens entre as áreas afetadas e os abrigos, etc. – são recolhidos e tratados. Na segunda fase, um modelo multi-período para a localização e alocação de abrigos com ordens de evacuação é desenvolvido. Considerando a propagação da cheia, o modelo determina a localização de um número fixo de abrigos que estão disponíveis em diferentes períodos de tempo, o período de tempo em que são emitidas as ordens de evacuação para cada área afetada e aloca cada uma destas áreas a um abrigo, enquanto minimiza os tempos de viagem entre as áreas afetadas e os abrigos. A solução obtida serve de base para a definição das rotas de evacuação em veículos privados entre as áreas afetadas e os respetivos abrigos, de acordo com emissão das ordens de evacuação. Assim, na terceira fase é possível identificar as áreas congestionadas e consequentemente alocar as entidades competentes a estas zonas para garantir a manutenção da ordem pública. A última fase inclui o processo de evacuação para a população que não tem meios próprios para chegar até um abrigo. Um modelo multi-período de evacuação é proposto para determinar as rotas e horários dos veículos de emergência enquanto os tempos de evacuação e de espera são minimizados. Ambos os modelos de otimização consideram que os tempos de viagens variam ao longo do tempo, que a população afetada evacua de acordo com

um padrão e que os recursos, para além de limitados, não estão prontamente disponíveis. O modelo multi-período de localização e alocação com ordens de evacuação é solucionado através da heurística *simulated anneling*. Para o modelo multi-período de evacuação é proposta uma rede espaço-tempo e é solucionado através de uma abordagem *rolling horizon*.

Ambos os modelos são aplicados a estudos de caso nos EUA e a estrutura de planeamento de inundações é aplicada a um estudo de caso em Portugal. As soluções destacam a importância de considerar abordagens dinâmicas e de considerar a disponibilidade dos recursos existentes.

1. INTRODUCTION

1.1. Background

The effect of natural disasters, such as earthquakes, hurricanes, or floods is tremendous and devastating. Among all natural disasters, floods are a significant threat for many countries and, as demonstrated by recent events (e.g., the 2021 summer floods in the United Kingdom, western Germany, Netherlands, Belgium, Luxembourg, and France), they can cause enormous life, property, and economic losses. The consequences from floods are often heavy and can lead to human losses; evacuation and displacement of people; isolation of villages; public or private damaged property; submerged or damaged roads other infrastructures and facilities; interruption of the supply of goods and basic services (e.g., potable water, electricity, telecommunication, and fuel); loss of activity production; and socio and economic activities affected for a long period. According to CRED & UNDRR (2021), in 2020 there were 33.2 million people injured or affected by floods, the number of flood deaths increased 18 % when compared to 2000-2019 annual average of 5,233 deaths, and the economic losses were 51,3 billion US dollars which represent an increase of approximately 55 % from 2000-2019 annual average of 33.2 billion US dollars. In the future, it is expected that the number of population exposed to this type of disasters will increase. Due to the increase of urban population, the lack of long-term planning in some urban areas, and the climate change, flood prone areas are being developed. In fact, according to OECD (2019) 20 % of the population will be at risk from flood, in 2050.

In most countries, the civil protection authorities are in charge of flood events planning and management. When compared with earthquakes, rain flood disasters are more easily predicted but yet they can still be as devastating as unpredicted earthquakes. Despite the devastation, the planning of these events is usually done based on rain-drainage models. With the technological advances of the last decades, these models have improved significantly and they are already capable of providing the information on the magnitude and evolution of different rain scenarios, for given return-periods (Leandro & Shucksmith, 2021). However, given the degree of uncertainty associated with rain-flood events, it is still difficult to precisely predict in advance the magnitude of the flood, its evolution in time, the roads and facility that will be damaged, and the population affected by the flood. Consequently, not all relevant information is available. Thus, in terms of planning, what civil protection authorities usually have are flood emergency plans which comprise the identification of all agencies involved and the lines of action, the definition of the management disaster structure, flood risk maps, and in some cases evacuation maps.

In terms of management of flood reactions, when facing a real flood situation, the flood emergency plans do not define exact response actions, being the decisions left for real judgments based on i) the experience of the entity responsible for the protection; ii) previous emergency studies; and iii) a set of standard procedures. In addition, the uncertainty of these events, in time and space, is rarely dealt within those plans.

The current planning and management approach, followed by most civil protection authorities in the world, is more rule based, e.g., the response operations depend on the level of alert which is defined in relation to the precipitation and flow measurements. However flood variations or resources availability are not taken into account within the flood emergency plans, resulting in normally effective but probably few efficient and highly costly flood disaster responses. Existing flood management practice will certainly need to evolve in the future in order to cope with the complexity of disasters management and to increase its efficiency.

1.2. Motivation

Disaster management is defined as a set of sequential stages which aim to decrease human, physical, and economic losses, to reduce personal suffering, and to recover quickly (Rawls & Turnquist, 2012). The typical disaster management cycle, represented in Figure 1.1, is composed by four phases: mitigation (before the disaster), preparedness (to early signals), response (during the disaster), and recovery (after the disaster) – Janssen et al., 2009; Thévenaz & Resodihardjo, 2010; Simonovic, 2011; Galindo & Batta (2013); Esposito Amideo et al. (2019). Each phase is described as following:

– The mitigation phase occurs before the disaster and, in the years before, the objective is to prevent the beginning of the disaster or moderate its consequences;
– The preparedness phase occurs moments before the disaster and consists in preparing the necessary resources and in establishing a disaster response plan;
– The response phase, comprising the reaction and intervention phases, takes place during the disaster event;
– The recovery phase consists in stabilizing the community and restoring the normalcy in the months and years after the disaster.

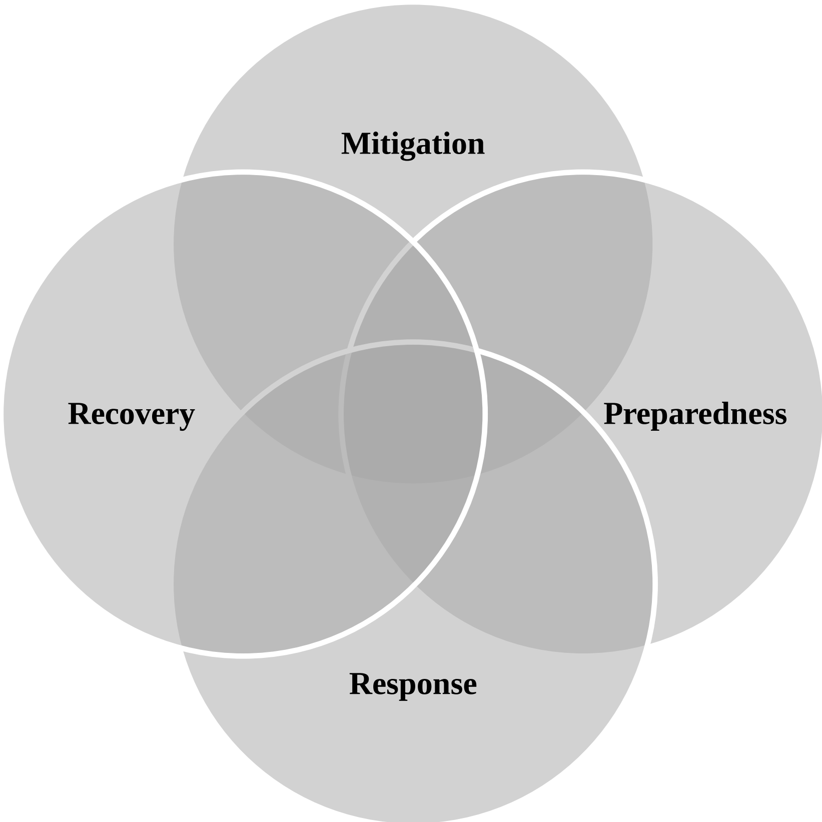


Figure 1.1 – Diagram of integrated disaster management (Simonovic, 2011).

Even so, from the existing literature on this topic, most papers focus on a single stage of the disaster cycle. According to Galindo & Batta (2013), there are few works in the literature where disaster management is seen in an integrated way, dealing with two or more phases. There is the need to adopt more integrated approaches and develop consistent analytical models (Simonovic, 2011; Caunhye et al., 2012; Bayram, 2016).

Flood emergency logistics operations are challenging. Operations are divided into different areas of intervention, such as means and resources management, logistical support, communication and information management, evacuation procedures, maintenance of public order, medical services and casualty transportation, and these operations are performed by different actors, institutions, and entities (Divisão de Planeamento de Proteção Civil, 2017).

In the past, government agencies tended not to invest in disaster management actions and consequently, the response to flood events was a late, low-efficient and highly costly reaction. Nowadays, the importance of disaster management has increased and the governments invest more. For instance, the European Union had showed that concern, forcing their member states to develop planning and management approaches which are more comprehensive and detailed (Directive 2007/60/EC of the European Council and European Parliament of 23 October, 2007).

1.3. Objectives

This research tackles the problem of flood disaster management and it mainly focus on the preparedness and the response to a flood disaster when the emergency response operations need to be prepared and then put into practice.

The aim of the research proposed is to develop a planning framework that could be used by civil protection authorities to support flood emergency operations decisions. The planning framework assume a dynamic approach that given the flooded demand areas, the amount of demand in each one, the transportation network and the road network conditions for different periods, identifies the location of shelters, the time for issuing evacuation orders, the allocation of the affected population to the shelters, the evacuation routes, and the emergency vehicles evacuation schedule.

In particular, the work developed had the following objectives:

- to understand the existing disaster management challenges;
- to understand flood emergency plans and the respective operations during a flood emergency;
- to overview the existing literature in terms of disaster management focusing on shelter location and evacuation routing;
- to develop multi-period models to handle one of the most important components of disaster management: time;
- to integrate shelter location, evacuation routing, and evacuation order issuing in order to model the impact of evacuation orders on the evacuation process;
- to integrate emergency vehicles availability and evacuation routing decisions;
- to develop a planning framework which copes with flood propagation, resources availability and limitations, and evacuee behavior to determine shelters location and opening times, evacuation orders issuing, evacuation routes and schedules for car-based evacuation and for emergency vehicles-based evacuation.
- to apply the planning framework in a real case study to demonstrate the practicability of the framework.

1.4. Innovation

This thesis adds to the existing literature by proposing a dynamic approach to cope with the challenges of a flood emergency problem. For instance, it is considered that road conditions vary over time, demand behavior follow a pattern over time and resources availability also vary over time.

In addition, different emergency operations are combined, such as shelter location, evacuation order issuing, and emergency vehicles routing and scheduling while considering resources limitations. The coordination of different entities, such as security forces to ensure public order, it is also considered.

Finally, this research promotes the interdisciplinary research by using appropriate flood models to predict flood propagation.

1.5. Outline

This thesis comprises six chapters. Chapter 1 and Chapter 6 correspond to the thesis introduction and conclusion respectively. Chapter 2 presents an overview of the disaster management field within the scientific literature and in practice. The remaining three chapters, Chapter 3 to Chapter 5, are written in the format of a scientific paper which means that can be read one after another or independently.

Chapter 3 is a transcription, following the formatting rules of the thesis, of the paper published in 2016, in the EURO Journal on Computational Optimization, volume 4, pages 299-323, entitled "*A multi-period shelter location-allocation model with evacuation orders for flood disasters*" (DOI: 10.1007/s13675-015-0058-3). In this chapter, the multi-period shelter location-allocation model with evacuation orders is presented. Taking into account the propagation of the flood, the model minimizes the traveling times between the affected areas and shelters while determining the location of a fixed number of shelters which become available in different time periods, the issuing time of evacuation orders for each demand area, and the allocation of each demand area to a shelter. The model is applied to the Wake County (USA) case study.

Chapter 4 focusses on the evacuation of those who rely on authorities to reach a shelter. Thus, the multi-period emergency vehicle evacuation model is proposed to determine the vehicles routes and schedules. The model aims at optimizing the evacuation and waiting time of evacuees while considering a limited fleet of emergency vehicles with capacity constraints and which become available in different time periods. As in Chapter 3, the model is applied to the Wake County (USA) case study.

Chapter 5 presents the planning framework developed to support civil protection authorities during flood emergencies. This framework comprises four stages and starts with data collection and processing. The model presented in Chapter 3 is applied to determine shelters location and opening times, to issue evacuation orders, and to assign evacuees to shelters. These operation decisions are complemented with a traffic congestion analysis which identifies the critical areas and, consequently, the allocation of security forces to these areas. The model presented in Chapter 5 is also applied to evacuate the population from the affected areas to the shelters and to determine the routes and schedules of the emergency vehicles. The planning framework is applied to a more complex case study in Coimbra (Portugal).

1.6. Publications and Presentations

The work included in this thesis had already been published or presented in several occasions. The research presented in Chapter 3 was published in the EURO Journal on Computational Optimization, volume 4, pages 299-323, entitled "*A multi-period shelter location-allocation model with evacuation orders for flood disasters*", in 2016 (Gama et al., 2016). Other research developed had been presented and discussed in several international and national conferences between 2013 and 2018:

- Gama, M., Santos, B.F. (2018),"*The dynamic bus evacuation problem for a flood disaster using a time-space network*". 15º Encontro Anual do Grupo de Estudos em Transportes, Fátima, Portugal, February 19-20, 2018.

- Gama, M., Santos, B.F., Scaparra, M. P. (2016), "*A Multi-Period Shelter Location-Allocation Model with Evacuation Orders for the Flood Emergency Evacuation Problem*". 13º Encontro Anual do Grupo de Estudos em Transportes, Figueira da Foz, Portugal, January 4-5, 2016.

- Gama, M., Scaparra, M. P., Santos, B.F. (2015), "*Simulation Annealing Algorithm Applied to the Flood Emergency Evacuation Problem*". 18th Euro Working Group on Transportation, Delft, The Netherlands, July 14-16, 2015.

- Gama, M., Santos, B.F., Scaparra, M. P. (2014), "*A dynamic allocation-location model for emergency logistics - the case of Wake County (USA)*". 11º Encontro Anual do Grupo de Estudos em Transportes, Unhais da Serra, Portugal, January 6-7, 2014.

- Gama, M., Scaparra, M. P., Santos, B.F (2013), "*Optimal location of shelters for mitigating urban floods*". 16th Euro Working Group on Transportation, Oporto, Portugal, September 4-6, 2013.

- Gama, M., Scaparra, M. P., Santos, B.F (2013), "*A shelter location model for flood emergencies*". 26th European Conference on Operational Research, Rome, Italy, July 1-4, 2013.

- Gama, M., Santos, B.F., Scaparra, M. P. (2013), "*Flood emergency logistics management*", 10º Encontro Anual do Grupo de Estudos em Transportes, Alcobaça, Portugal, January 3-4, 2013.

2. RESEARCH BACKGROUND

2.1. State of the Art

Several authors have provided reviews on disaster management. For instance, Altay & Green (2006) focused on the application of operation research (OR) to disaster management from 1982 to 2004. Galindo & Batta (2013) continued this review for researches from 2005 to 2010. Both authors highlighted that mathematical programming and model development were predominant methodologies and research contributions, respectively. In the first period (1982-2004), most of the researches fall within the mitigation phase while, in the second period (2005-2010), response phase followed by preparedness phase have received more attention. Simpson & Hancock (2009) provided an overview on OR researches applied to emergency response, from 1965 to 2007, according to four focus groups: i) urban services, such as fire, police, patrol, or ambulance services; ii) disaster services, such as evacuation or rescue; iii) hazard specific, such as flood, hurricane, terrorism, or pandemic; and iv) general emergency. Similar to Altay & Green (2006), mathematical programming was the most common methodology with exception for the hazard specific group where probability and statistical methods were the most common. Later, Caunhye et al. (2012) have reviewed optimization studies within the emergency logistics topic according to the main pre and post-disaster operations (e.g., facility location, relief distribution, and casualty transportation). The author concluded that most of the studies did not combine different operations, were single objective and the most common objective was minimizing response times or distance costs and unmet demand over time. Murray-Tuite & Wolshon (2013) evaluated the highway-based evacuation modeling covering different areas such as warning and information, demand forecast and consecutively trip generation and distribution and mode of transportation assignment, and emergency strategies to minimize evacuation time. Anaya-Arenas et al. (2014) provided an overview on relief distribution networks in response to disasters focusing on the optimization of location and network design problems and of transportation and routing problems. The authors highlighted that most of the modelling approaches on location problems considered a single period planning horizon and ignored resources availability. On the transportation problems, the authors found that most of the researches considered a heterogeneous fleet and a multi-depot network. Özdamar & Ertem (2015) presented an overview on logistic models for the response phase, including relief delivery, casualty transportation, and evacuation models, and for the recovery phase which includes road and infrastructure restoration and debris management models. The authors also evaluated the use of information systems to facilitate the use of the mathematical models. Bayram (2016) has reviewed the network-based large scale emergency evacuation optimization model which included traffic assignment and traffic flow models and evacuation demand estimation. The author highlighted that most of the researches focused on evacuation with private vehicles as well as did not considered shelter location decisions, which are crucial for a safe and timely evacuation. In addition, most of the approaches were deterministic and the modeling was static preventing the models to cope with the uncertainties and dynamic of the evacuations. More recently, Esposito Amideo et al. (2019) have reviewed nine optimization studies that combine shelter location and evacuation routing problems for the response phase of a disaster. The review highlighted that most of the studies did not have the involvement of stakeholders, did not include evacuee behavior or infrastructure disruption. On the other hand, most of the researches incorporated somehow congestion issues. Regarding shelters, all of the studies considered capacity, budget or staff constraints, but most of them did not include shelters availability. Regarding evacuees, most of the studies focused on self-evacuation to shelters and none of the studies combined the three categories of evacuation: i) self-evacuation to shelters; ii) self-evacuation to other destinations; and iii) supported-evacuation to shelters.

Each of these reviews identified challenges and future work direction within disaster management. In order to have more realistic models and consequently more application-oriented, it was proposed interdisciplinary research (Murray-Tuite & Wolshon, 2013; Özdamar & Ertem, 2015; Esposito Amideo et al., 2019); a better coordination among disaster management entities (Galindo & Batta, 2013), for example the inclusion of volunteer coordination (Simpson & Hancock, 2009); and the integration of different disaster operations (Caunhye et al., 2012; Özdamar & Ertem, 2015; Bayram, 2016). For more realistic models, it was also proposed a better modeling of human behavior (Bayram, 2016) including issues such as vehicle procurement, time of the day, route diversion, evacuee demographics, route preferences, and warning signals (Esposito Amideo et al., 2019); more focus on special-needs population, on mass-transit-based (Bayram, 2016) and multi-modal evacuation (Bayram, 2016; Esposito Amideo et al., 2019); the combination of different evacuee categories (Esposito Amideo et al., 2019); and integration of infrastructure disruption (Esposito Amideo et al., 2019), and congestion (Murray-Tuite & Wolshon, 2013; Esposito Amideo et al., 2019). Regarding modeling techniques and solution methodologies, it was proposed multi-objective approaches (Altay & Green, 2006; Caunhye et al., 2012; Esposito Amideo et al., 2019); stochastic and dynamic models (Anaya-Arenas et al., 2014; Bayram, 2016; Esposito Amideo et al., 2019); new methods and technologies, such as soft OR approaches (Altay & Green, 2006; Simpson & Hancock, 2009; Galindo & Batta, 2013; Esposito Amideo et al., 2019), sensing algorithms (Altay & Green, 2006), advanced algorithms (Galindo & Batta, 2013; Özdamar & Ertem, 2015), statistical analysis (Galindo & Batta, 2013); and GIS-based interfaces (Galindo & Batta, 2013; Esposito Amideo et al., 2019); information and decision support systems (Simpson & Hancock, 2009; Anaya-Arenas et al., 2014; Esposito Amideo et al., 2019); and real-time information (Murray-Tuite & Wolshon, 2013).

2.2. State of the Practice

Rain-floods are temporary and extreme natural phenomena, caused by moderate and permanent rainfalls or by sudden rainfalls with high intensity. Floods can lead to loss of lives and property and have a negative impact on the economy and the environment. Therefore, the reaction planning and management of these disasters are of extreme importance.

Many countries had already taken flood protection measures, adding considerable value and improvement on the flood risk management. In this chapter, a general overview on the practices adopted by the different countries is presented, starting with the measures taken by the European Union (EU) and the proceeding with evacuation maps. Then, a detailed description of the Portuguese legislation and practices is presented.

2.2.1. The EU context

Between 1998 and 2002, Europe suffered more than one hundred floods with severe consequences. After these damaging events, there were communications and directives on flood protection, prevention, and mitigation where, in order to assess and manage the flood, flood maps were required. The regulatory framework is primarily presented and the flood and evacuation maps are presented next.

2.2.1.1. Regulatory framework

In the Communication on Flood risk management - Flood prevention, protection and mitigation (COM, 2004), the development and implementation of an EU Action Program on flood risk management was proposed. In order to develop and implement a coordinated flood prevention, protection, and mitigation action program, it was determined that the Member States and the European Commission should work together. The COM (2004) also referred an effective method to reduce the probability and/or the impact of flood events. This method consists on the development of flood risk management programs including the following elements: i) prevention; ii) protection; iii) preparedness; iv) emergency response; and v) recovery and lessons learned. “The prevention consists on preventing damage caused by floods by avoiding construction of houses and industries in present and future flood-prone areas; by adapting future developments to the risk of flooding; and by promoting appropriate land-use, agricultural and forestry practices. The protection consists on taking measures, both structural and non-structural, to reduce the likelihood of floods and/or the impact of floods in a specific location. The preparedness consists on informing the population about flood risks and what to do in the event of a flood. The emergency response is the development of emergency plans in the case of a flood. And the recovery and lessons learned consist on returning to normal conditions as soon as possible and mitigating both the social and economic impacts on the affected population” (COM, 2004).

The European Commission, in order to reduce and manage the risks caused by floods on human health, the environment, the cultural heritage, and the economic activity, proposed the Directive 2007/60/EC of the European Council and European Parliament of 23 October

(2007) – Duty to preliminary assessment of flood risk. The Directive requires Member States to undertake an assessment of flood risk, to map flood hazard and risk, and to take adequate measures to reduce the risk of floods. This Directive promotes the public access to all information and the public opinion in the planning process.

The information exchange carried out in the context of the Floods Action Program and the Working Group on Floods has led to the development of the *Handbook of Good Practices in Flood Mapping* (EXCIMAP, 2007). This document describes the current practices across the EU. It should be said that the document is not meant to express the views of the European Commission or correspond to the requirements of Directive 2007/60/EC. In the handbook there are references to the types of floods which might occur in member state's territories, the flood maps primarily uses, the type and contents of the flood hazard maps, the flood risk maps, the production of these maps, and for the flood maps dissemination.

2.2.1.2. Flood maps

Flood maps are primarily used for emergency planning and management. For this purpose, the flood maps can be developed at two different levels: national or regional, and local. According to the *Handbook of Good Practices in Flood Mapping* (EXCIMAP, 2007), at the national/regional level, the flood maps are used for major emergencies that may need national or regional intervention. These maps must contain flood extent, flood risk indicators such as number of people potentially affected, utility infrastructures affected, and road/rail or other communication infrastructure affected. The maps should also contain other relevant data, such as summary of vulnerability or risk data, and information of the disruption of infrastructures, or utilities with a national/regional impact. At the local level, the flood maps are used for localized emergency response planning, like evacuation and access routes, road closures, etc. These maps must contain flood extent and depth for different return periods, and other relevant flood parameters, such as vulnerability and risk. The maps should also contain real time information such as extent, remotely sensed, which is useful where or when available.

In the Directive 2007/60/EC, flood mapping is considered a crucial element of flood risk management. The assessment and management of flood risks will require Member States to prepare two types of maps by 2013 (article 6): flood hazard maps and flood risk maps.

Flood hazard maps are maps that show the extent and expected water depths/levels of an area flooded in three scenarios: i) a low probability scenario relative to extreme events; ii) a medium probability scenario (at least with a return period of 100 years); and if appropriate iii) a high probability scenario. There are several examples of flood hazard maps, some indicating the location where the combination of current velocity and water depth may be dangerous (e.g., in England and Wales), others including the more or less comparable drag force parameters (e.g., in Austria), and others relating the combination velocity-depth with frequency (e.g., in Germany and in Switzerland).

For the flooded areas under the scenarios referred above, potential population, economic activities and the environment at potential risk from flooding, among other things, are represented in flood risk maps. There are also many examples of flood risk maps. Germany has the only official maps indicating potential damages. In Italy, Spain and Switzerland the flood risk maps are risk zone maps which are based on the combination probability of flooding – use sensitivity/vulnerability to flooding. Moreover, in Italy and Switzerland the risk zonation is also related with spatial planning regulation and construction requirements. Other type of risk maps are the vulnerability maps, regarding social vulnerability of the population (e.g., in England and Wales) or vulnerable services (e.g., in Germany).

In the handbook there is also reference to other types of maps that can be developed as a complement to the flood maps. One of these maps is the emergency map that includes important information, such as number of people to plan the scale of response and resources needed, evacuation route, safe refuge centers, hospital response plans, facilities at risk, transportation disruption, locations where operational flood response is required, areas where evacuation is required, evacuation routes and shelter areas. These emergency maps are essential for crisis management and rescue services and may be used by emergency response authorities or for public information.

2.2.1.3. Evacuation maps

A special group of flood prevention maps are the evacuation maps, which concentrate on how to act when a flooding disaster becomes evident, indicating evacuation routes, location of shelters, etc. These maps can also include other information, such as potential flooding depths. There are very few examples of this type of maps in practice. However, the development of these maps is a necessary trend in most countries in the EU and there are already some examples (EXCIMAP, 2007).

Hamburg, in Germany, is a good example of a well-planned information package for urban population in a large city (EXCIMAP, 2007). The citizens have available on the internet information related to the activities that are being implemented for the objective of flood protection. This information is easily accessible and well-presented. The evacuations maps, indicating the evacuation zones corresponding to different water levels, the location of evacuation locations, emergency residences, bus stops from where evacuation busses will depart are available for different parts of the city. The maps also contain an extensive description of the expected situation in case of flooding and detailed advice to the general public on how to act in such event.

In the Netherlands, the evacuation maps indicate the mandatory evacuation routes, the one-way converted road, and the closed entrances and exits (EXCIMAP, 2007). These maps are easily interpreted by the general public. There are also decision-support maps in which different zones are represented: i) areas that will remain dry; ii) areas that will reach a water level that leaves the first floor of dwellings dry; and iii) areas that will reach such water depths that evacuation will be required. These maps can also indicate the arrival time of different inundation depths, in order to take decisions on the best evacuation routes.

Outside of the EU, Japan and USA are great examples in the development of flood prevention maps (EXCIMAP, 2007).

In Japan, flood maps are elaborated in two steps. In the first step, the Minister of Land, Infrastructure and Transport, and the prefecture determine the flood-prone areas. And in the second step, the municipalities produce the Flood Hazard Maps. The municipalities are obliged to inform their inhabitants on the flood risk and to distribute flood risk and inundation maps freely, increasing the flood-preparedness and contributing to the spatial planning within the municipality. The evacuation maps indicate the location of shelters and temporary shelters, evacuation routes, boundaries of evacuation areas, the location of flood warning speakers, and the roads that should not be used for evacuation. A negative aspect of these maps is the topographical layout which is not sufficiently clear to be used in practical situation, but may be used in simulation of flood situations.

In the USA, the maps make reference to the contraflow principle. This principle was created to increase road capacity, reversing the normal traffic flow direction, changing two-direction roads into one-direction (evacuation) roads. For each road crossing of New Orleans city, a detailed map is available, indicating the contraflow plan and the instructions for the evacuation by car. For the County of Sacramento in California, the flood depth map is combined with the rescue-evacuation map. The flood depth maps indicate inundation levels and the time that water will take to rise in affected neighborhoods, whereas the rescue and evacuation route maps identify rescue areas, evacuation areas, and potential evacuation routes.

2.2.2. The Portuguese Context

In Portugal, there is specific legislation related with the civil protection activity and with the emergency planning. Beyond this, there is legislation of various kinds that indirectly affect the activity of civil protection. The legislation that regulates the activity of civil protection in the national territory is primarily presented and the legislation related with flood situation is presented next. Finally, a reference is made to a simulation exercise which took place on February 16th 2012, in the district of Coimbra.

2.2.2.1. Civil Protection

Civil protection is the activity developed by the State, Autonomous Regions, Local Government, citizens and all public and private entities (Autoridade Nacional de Protecção Civil, 2016). The objective is to prevent risks inherent to an event of serious accidents, disasters or calamities of natural or technological origin, to mitigate their effects, and to protect and rescue people and property in danger, when those critical situations occur.

The Civil Protection Framework Law is approved by *Lei n.º 27/2006, de 3 de julho, da Assembleia da República (2006),* as subsequently amended by *Lei Orgânica n.º 1/2011, de 30 de novembro, da Assembleia da República (2011)* and *Lei n.º 80/2015 de 3 de agosto, da Assembleia da República (2015).* This law clarifies civil protection policy and operations framework, establishes the coordination bodies, and considers the National Civil Protection Authority (ANPC – *Autoridade Nacional de Proteção Civil*) and the civil protection agents as enforcement bodies.

Decreto-Lei n.º 134/2006, de 25 de julho, do Ministério da Administração Interna (2006), as subsequently amended by *Decreto-Lei n.º 114/2011, de 30 de novembro, do Ministério da Administração Interna (2011)* and *Decreto-Lei n.º 72/2013, de 31 de maio, do Ministério da Administração Interna (2013),* implements the Integrated Protection and Relief Operations System (SIOPS – *Sistema Integrado de Operações de Protecção e Socorro*), defining the structures, rules and procedures that ensure that all civil protection agents act, at the operational level. The SIOPS sets the operation management system which represents the form of operational organization that develops in a modular fashion in accordance with the size and type of event. The SIOPS also defines the meaning of special alert, which has four levels (blue, yellow, orange and red), activated progressively, depending on the seriousness of the situation and the degree of readiness that it requires. The coordination of institutional SIOPS is ensured, at national and district levels, by the Operational Coordination Centers (CCO – *Centros de Coordenação Operacional*), comprising representatives of the entities whose intervention is justified on the basis of each occurrence. The CCO is responsible for managing the operational participation of each force or service in the relief operations.

Decreto-Lei nº 203/2006, de 27 de outubro, do Ministério da Administração Interna (2006) merged the National Fire Service and the Civil Protection, forming the . *Decreto-Lei n.º 75/2007, de 29 de março, do Ministério da Administração Interna (2007)* gives to the ANPC the legal and organic instruments necessary to ensure the population security and the safeguarding of assets, in order to prevent the occurrence of major accidents and catastrophes, to ensure the management of claims and collateral damage, and to support the restoration of the functions that lead to normality in the affected areas. It came to provide the ANPC with a new model of organization that ensures an efficient and timely exercise of the functions in the context of forecasting and risk management, protection and rescue activities, the activities of firefighters, and matters of emergency planning. More recently, the National Emergency and Civil Protection Authority (ANEPC – *Autoridade Nacional de Emergência e Protecção Civil*) succeeds the ANPC and its regulation is approved by *Decreto-Lei n.º 45/2019, de 1 de abril, do Ministério da Administração Interna (2019).*

The special alert state for the organizations integrated in the SIOPS is described in the *Declaração (extracto) n.º 97/2007, de 16 de maio, do Serviço de Estrangeiros e Fronteiras (2007)*. According to the degree of probability and the severity of the emergency event, the level of special alert to be triggered and its correlation with the level of mobilization and the readiness of the civil protection agents are defined. The relationship between the severity of the negative consequences and the probability of occurrences reflects, in general, the typical degree of risk. The matrix of risks is presented in Table 2.1.

Table 2.1 – Matrix of risks (*Declaração (extracto) n.º 97/2007, de 16 de maio, do Serviço de Estrangeiros e Fronteiras, 2007*).

Probability / Frequency	Severity / Intensity				
	Residual	Reduced	Moderated	Accentuated	Critical
Confirmed	Low	Moderated	High	Extreme	Extreme
High	Low	Moderated	High	Extreme	Extreme
Medium-High	Low	Moderated	Moderated	High	High
Medium	Low	Low	Low	Moderated	Moderated
Medium-Low	Low	Low	Low	Low	Low
Low	Low	Low	Low	Low	Low

The table of degree of severity, which is typified by the intensity scale of the negative consequences of the events, and the table of degree of probability are presented in APPENDIX A.

The special alert levels for the SIOPS consider, generally, the degree of risk which is transcribed in Table 2.2.

Table 2.2 – Matrix of special alert levels 'vs' degree of risk (*Declaração (extracto) n.º 97/2007, de 16 de maio, do Serviço de Estrangeiros e Fronteiras, 2007*).

Level	Degree of Risk
Red	Extreme
Orange	High
Yellow	Moderated, moderated severity and medium probability
Blue	Moderated

The operating rules of the National Civil Protection Commission are defined by ordinance of the member of the Government responsible for the Civil Protection, as referred in the *Decreto-Lei n.º 56/2008, de 26 de março, do Ministério da Administração Interna (2008)*. At the municipal level, the institutional and operational framework of the Civil Protection is defined by *Lei n.º 65/2007, de 12 de novembro, da Assemblea da República (2007),* as subsequently amended by *Decreto-Lei n.º 114/2011, de 30 de novembro, do Ministério da Administração Interna (2011)* and *Decreto-Lei n.º 44/2019, de 1 de abril, da Presidência do Conselho de Ministros (2019),* where the organization of the Municipal Civil Protection Services (SMPC – *Serviços Municipais de Protecção Civil*) is established and the role of the local operational commander is also determined.

2.2.2.2. Emergency plans

The preparation of emergency plans for civil protection is regulated by the *Resolução n.º 30/2015, de 7 de Maio, Da Comissão Nacional de Proteção Civil (2015)* which normalizes the structure and contents of emergency plans, streamlines the process of drafting, review, and approval, and introduces mechanisms for periodic verification of their effectiveness. The emergency plans establish the classification of risk, the preventive measures to be taken, the identification of means and resources needed in situations of serious accident or disaster, the mobilization criteria and the coordination of mechanisms of usable means and resources, public or private, the operational structure that will guarantee the unity of the direction and the constant monitoring of the situation, and finally the definition of the responsibilities inherent to public or private organizations, services, and facilities connected with civil protection activity.

The emergency plans for civil protection are formal documents in which the civil protection authorities define the guidelines for the mode of action of the various agencies, services and facilities to engage in civil protection operations that are essential to the response and restoration of normalcy, in order to minimize the effects of a serious accident or disaster on the lives, economy, heritage, and environment. Thus, these documents are developed in order to organize, guide, facilitate, streamline and standardize the actions needed to answer. The resolution demands emergency plans that should be simple, flexible, dynamic, accurate and suitable to local conditions. They should also allow the anticipation of scenarios which might trigger a major accident or disaster, defining the organizational structure and procedures for preparing and increased response to emergency.

These emergency plans can be classified according to the purpose and the scope. Regarding the purpose, the emergency plans can be general or special. If they are prepared to face the generality of the emergencies that are allowed in each territorial and administrative scope, the emergency plans are called general. They are special, if the emergency plans are prepared with the purpose of being applied when there are specific serious accidents and catastrophes whose nature requires an appropriate scientific or technical methodology, and whose occurrence in time and space is predicted with high probability, or even with low probability, but with unacceptable consequences. Regarding scope, the plans are national, regional, district, or municipal, depending on the territorial extension of the emergency situation. Considering a disaster in a municipality, the civil protection at the municipal level is more suitable to intervene, due to the proximity of the means of assistance, the ability for a quick analysis of the situation, and the knowledge of local reality. The district structure should only intervene when the emergency situation overflows the boundaries of the municipality or local means are insufficient to combat it, always requesting the mayor of the municipal council. The national level intervention will be activated following a similar logic. If a special plan involves more than one municipality of the same district, it is considered a supra-municipal plan and if it involves more than one district, the special plan is considered supra-district.

2.2.2.3. Flood Specific Legislation

The protection measures against floods can be found in the Water Law (Lei n.º 58/2005, de 29 de dezembro, da Assembleia da República, 2005), as subsequently amended by Lei n.º 44/2017, de 19 de junho, da Assembleia da República (2017). The article 40 refers that the flooded zones or the zones threatened by floods should be subject to special prevention and protection measures. The areas where the edification is prohibited or conditioned should be defined. The creation of an alert system for the safeguarding of people and goods is the responsibility of the Institute of Water in conjunction with the ANPC and the Hydrographic Region Administration.

Resolução n.º 15/2008, de 21 de abril, da Assembleia da República (2008) with respect to risk of flooding recommends to the government the adoption of all available laws, regulations and administrative provisions necessary to transpose the Directive 2007/60/EC of the European Council and European Parliament of 23 October (2007), until November 26, 2009.

2.2.2.4. Simulation Exercise

On February 16th 2012, the ANPC conducted a simulation exercise which aims at testing the Special Operations Plan for Floods in the Coimbra District and highlighting the training of operational response entities that have responsibilities and duty to cooperate in case of serious accident or disaster-related occurrences in flood basin Mondego.

The reference flood scenario for this simulacrum was the flood event of January 2001, which flooded most of the agriculture areas and small urban areas in Baixo Mondego region. With the deployment of the event in the municipality and given the occurrence of various emergency situations, the Municipal Civil Protection Commission (CMPC – *Comissão Municipal de Protecção Civil*) got together in an emergency room at the municipal fire-station in Coimbra. The CMPC is composed by the Director of Civil Protection Service of Coimbra, the Municipal Operational Commander, the Fire Brigade Commanders of Coimbra and Brasfemes, the representative of the Republican National Guard of Coimbra, and the representative of the public security police of Coimbra. The chair of this commission is the Mayor of Coimbra.

In this simulation exercise, several tasks were developed, such as triggering the warning to populations at risk, coordination of assistance means, communication through the Media of advices and attitudes to be adopted by the population, maintenance of law and order, ensuring movement on access roads needed for rescue and evacuation, evacuation of wounded and sick people, and availability of transport, accommodation, food and warm clothing to the population. After a request for help, the appropriate means are assigned, since each entity involved has their own mission in an emergency situation. The entity responsible for the response takes into account the means that are still available. Regarding the evacuation, the preferable temporary or permanent shelters are opened spaces, such as soccer fields, or closed and wide spaces, such as schools, churches, and the buildings of cultural and sporting associations. Shelters choices are made based on personal knowledge about the existing buildings near to the evacuation zone. The capacity and the risk of inundation are some of the characteristics taken into account when choosing a location to evacuate people at risk. The definition of the routes being used by the Civil Protection vehicles were based on the information of the road infrastructure damages occurred and the self-experience of the drivers.

3. A MULTI-PERIOD SHELTER LOCATION-ALLOCATION MODEL WITH EVACUATION ORDERS FOR FLOOD DISASTERS

3.1. Introduction

Floods are a significant threat for any countries and, as demonstrated by recent events (e.g., the 2014 United Kingdom winter floods, the 2013 Central Europe floods, the 2013 North India floods, and the 2010–2011 Philippine floods among others), they can cause enormous life, property, and economic losses. In the future, it is expected that the number of people exposed to this type of disaster will increase. According to the Organisation for Economic Co-operation and Development (OECD, 2012) 20 % of the world's population will be exposed to flood events by 2050. More recently, the World Resources Institute (WRI, 2015) affirmed that on average 21 million people per year are affected by river floods and 2 million more people could be affected by this type of floods by 2030.

In most countries worldwide, civil protection authorities are in charge of flood response operations planning and management. Due to the lack of relevant information available, in most cases the emergency flood plans developed by the civil protection authorities only comprise the identification of all entities involved and the lines of action for each entity, the definition of the management disaster structure, flood risk maps, and in some cases evacuation maps. Thus, when facing a real flood situation, the decisions are left for real judgments based on the experience of the entity responsible for the protection, previous emergency studies, and a set of standard procedures. In recent years, disaster management has gained increasing attention from researchers and government agencies. Significant investments have been made in developing disaster risk reduction, preparedness and response strategies. For instance, the European Union is forcing their member states to develop planning and management approaches in order to cope with the complexity of flood disaster management and to increase its efficiency (COM, 2004). Still the current approaches followed during flood emergency situations usually results in reasonably effective flood disaster response, but with low efficiency and high costs (Simonovic, 2011).

In order to help civil protection authorities' decisions in flood situations, a novel multi-period optimization model approach for flood disasters is presented. The model approach comprises a mixed-integer linear programming optimization model and a solution framework involving a simulated annealing (SA) heuristic. According to the authors' knowledge, this is the first emergency logistics optimization model approach that combines decisions about the location of shelters, the allocation of evacuees to shelters and the issuing time of evacuation orders to the areas affected by the disaster.

The optimization model can be casted as a multi-period location-allocation model with shelters capacity restrictions. Shelters are facilities in which evacuees can find health assistance, food, and safety. Public facilities, such as schools, day care centers, or sports halls, can be used as potential shelters. The location of the shelters depends on the road network, the evolution of the flood (water depths and speeds), and the location of the rescues. The model optimizes the total travel times between the affected population and the shelters while determining the location of a fixed number of shelters to be opened in each time period, the issuing time of evacuation orders in each demand area, and the allocation of each demand area to shelters.

The proposed model is able to cope with some of the practical challenges characterizing flood emergency logistics operations and introduces several innovative aspects. First, in disaster management, time is a crucial component and its inclusion in a mathematical model is essential for a reliable representation of real situations (Galindo & Batta, 2013). As a consequence of floods propagation, road conditions and demand for shelters vary over time. Increasing water levels on the road network, in fact, may reduce the traveling speed on some roads or even render them completely unusable in some time periods. In addition, floods propagate in different areas at different times. Consequently, populations do not react to a flood at the same time and the demand for shelters evolves over time during the event. Our model captures all these dynamic aspects. We use a dynamic rain-flood model, such as the models discussed in the review paper from (Hénonin et al., 2013) to predict the magnitude and the evolution of the flood over time and space. The information generated by the rain-flood model is coupled with our emergency logistics model according to the methodology proposed by Melo et al. (2015). A second issue that must be taken into account when modeling rescue operations is that evacuation support resources (e.g., shelters, volunteers, medical teams, and relief supplies) are not all readily available at the onset of a disaster. To model this aspect, we assume that shelter facilities (including staff and equipment) become gradually available in different time periods. Finally, given the dynamic evolution of the flood and of the shelters availability, it is essential to coordinate and optimize the timing for issuing evacuation orders for the different affected areas so as to streamline the coordination of evacuation procedures. After receiving an evacuation order, people start evacuating to the designated shelter. In this work, we assume that people evacuate according to a standard pattern, such as an S-shaped curve, as proposed in many studies in the literature (Sherali et al., 1991; Rawls & Turnquist, 2012; Murray-Tuite & Wolshon, 2013; Li et al., 2013).

The organization of the paper is as follows. In subchapter 3.2, an overview of disaster management studies proposed in the literature is presented. Subchapter 3.3 introduces the notation and mathematical formulation of the problem. The SA heuristic to solve the optimization model is introduced in subchapter 3.4. In subchapter 3.5, we present some computational results on a set of randomly generated problems to demonstrate the efficiency of the SA heuristic proposed. A practical application of the modeling approach and the importance of adopting a dynamic model are discussed in subchapter 3.6 using a real world based case study. In the last section, some final concluding remarks and possible future research lines are presented.

3.2. Disaster Management Literature Overview

Disaster management is defined as a set of sequential stages which aim to decrease human, physical, and economic losses, to reduce personal suffering, and to recover quickly (Rawls & Turnquist, 2012). The typical disaster management cycle is composed of four phases: mitigation (before the disaster), preparedness (up to the early signals), response (during the disaster), and recovery (after the disaster) (Janssen et al., 2009; Thévenaz & Resodihardjo, 2010; Simonovic, 2011; Berkoune et al., 2012). For a comprehensive literature review of optimization models in the area of disaster management, the reader is referred to Altay & Green (2006), Caunhye et al. (2012), Galindo & Batta (2013).

The disaster management phase in which the location of shelters is decided varies from study to study. Some authors consider the identification of the best shelter locations as a pre-disaster operation (i.e., mitigation and preparedness phases). That is the case in Sherali et al. (1991), which presented one of the first emergency location works. The authors developed a single-period location-allocation model for a region threatened by a hurricane. The model determines the optimal shelter location while minimizing the total evacuation time. A heuristic and an exact implicit enumeration algorithm based on the generalized Bender's decomposition approach were developed. Kongsomsaksakul et al. (2005) developed a location-allocation model for flood evacuation planning with shelter capacity constraints. The model identifies, for the pre-disaster phase, the number and the location of shelters so as to minimize the total travel time between evacuees and shelters. The influence of the flood on the travel times was not discussed. A genetic algorithm was used to solve the bi-level programming problem. Park et al. (2012) presented a methodology to locate tsunami vertical evacuation shelters for people evacuating by foot. The authors used a genetic algorithm to solve the resulting problem. For supporting decisions in the preparedness phase of a hurricane disaster, Li et al. (2012) developed a location-allocation model which minimizes the expected unmet shelter demand and the expected total network travel time. A heuristic based on Lagrangian relaxation and scenario decomposition was developed to solve the problem. More recently, Rodríguez-Espíndola & Gaytán (2015) presented a tool for flood disaster preparedness combining the use of GIS and an optimization model. The model identifies the location of shelters and distribution centers, the allocation of prepositioned goods, and the distribution decisions to satisfy flood victims, while the costs (acquisitions, shipping, and facility preparation) and the total distance traveled by goods and people are minimized. The bi-objective model was solved using a weighted-sum method and the epsilon-constraint method.

Other authors consider the location of shelters as a post-disaster operation during the disaster phase. This was in fact suggested by Altay & Green (2006). According to the authors, the opening of shelters and the evacuation of threatened populations are part of the response phase. Chanta & Sangsawang (2012) proposed an optimization model integrated with GIS to find the optimal shelter location during a flood disaster. The model maximizes the number of flood victims that can be covered or can reach a shelter within a fixed walking distance and minimizes the total distance of all flood victims to their closest shelters. The bi-objective problem was solved using the epsilon-constraint method. Taking into account that refugees' needs vary over time, Chen et al. (2013) proposed a hierarchical model that locates earthquake shelters during three evacuation periods. The model minimizes the total population-weighted travel distance during the evacuation period, in an attempt at increasing the overall efficiency of the evacuation.

Considering pre- and post-disaster operations, Li et al. (2011) developed a two-stage model addressing both sheltering network planning and management for hurricanes. Locations, capacities, and resources of new permanent shelters are identified in the preparedness phase (first stage) while in the response phase (second stage), evacuees and resources are allocated to shelters. The objective is to minimize the costs related to shelters and resources. The L-shaped algorithm was used to solve the two-stage stochastic problem.

The majority of shelter location models existing in the literature take into account capacity restrictions and the approaches are in most of the cases static—i.e., parameters such as demand, travel times, and costs are not time dependent. According to Galindo & Batta (2013) it is unrealistic to consider these parameters as static, since they change as disasters evolve. From the above works, only Li et al. (2012) and Chen et al. (2013) took into account the fact that travel times change over time. However, in the field of disaster management, other authors considered time-dependent demand (e.g., Chiu et al., 2007; Bretschneider & Kimms, 2011, 2012; Bish & Sherali, 2013) or even time-dependent demand and supply (e.g., (Özdamar et al., 2004; Yi & Özdamar, 2007). Lim et al. (2012) capture the dynamic of the evacuation network over time by extending the original (static) network to a time-expanded (dynamic) network. More recently, Huang et al. (2015) used a time space network to take into account the information and decisions updates in a rolling horizon approach. Simulating the real-time effect of a disaster propagation, Yuan & Wang (2009) model the travel speed on the network as a continuously decreasing function of time for path selection in emergency logistics management.

None of the above-mentioned works addresses the problem of optimizing the issuing of evacuation orders while taking into account shelters availability and disasters propagation. In this paper, we adopt an innovative modeling approach which optimizes short-term response operations. Specifically, we propose a multi-period flood responsive location-allocation model that places shelters in reaction to the flood evolution and determines the optimal time to start evacuating the affected areas. Another innovative feature accounted for in the model is that travel times are dependent on the level of water on the road network and, therefore, change over time.

3.3. Model Formulation

In this section, we present a multi-period location-allocation model with capacity restrictions to optimize evacuation decisions at the onset of a flood disaster. The assumptions of our multi-period shelter location problem (MPSLP) are as follows:

1. Road conditions and, hence, traveling times between demand nodes and candidate shelter locations are time dependent.
2. Shelters become available in different time periods, with only a few of them available at the onset of the disaster.
3. After receiving an evacuation order, people evacuate in the following time periods and the percentage of people evacuating in each time period is described by an S-shaped curve. Based on Sherali et al. (1991) work, we assumed that the initial reaction of people to evacuation orders is slow. Gradually the percentage of people evacuating increases in the following time periods. At the end of the evacuation process there are few evacuees left and the percentage of people evacuation decreases again.
4. Only a small percentage of the population affected by the flood evacuates to a shelter, while the remaining affected population seeks refuge in different places. In our model

we consider the demand of each demand node to be the population that needs to go to a shelter.

5. People from the same area evacuate to the same shelter using their own vehicles. People without private vehicles will rely on a variety of alternatives including: riding with friends, neighbors, family, or civil protection help.
6. Shelters have a limited capacity for accommodating the demand assigned to them.

The model uses the following notation.

Sets:

I set of demand nodes ($i = 1, ..., |I|$)

J set of potential shelter sites ($j = 1, ..., |J|$)

T set of periods in the time horizon ($t = 1, ..., |T|$)

S set of periods in the S-shaped curve ($s = 1, ..., |S|$)

Parameters:

H_i expected demand of node i

Z_j capacity of shelter at site j

P_t maximum number of shelters that can be opened up to period t (where $P_{|T|}$ corresponds to the maximum number of shelters to be opened at the end of the time horizon)

K_s percentage of people evacuating s periods after the evacuation order according to the S-shaped curve

D_{ijt} traveling time from node i to site j in period t

Decision variables:

w_{ijt} number of people evacuating from node i to shelter j in time period t

x_{ij} 1 if people from node i are assigned to shelter j ; 0, otherwise

y_{jt} 1 if a shelter at j is open in time period t; 0, otherwise

c_{it} 1 if the evacuation order at node i is issued in time period t; 0, otherwise

The MPSLP can be formulated as follows:

$$\min C = \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} D_{ijt} \cdot w_{ijt} \tag{3.1}$$

subject to

$$\sum_{j = J} y_{jt} \leq P_t, \forall t \in T, \tag{3.2}$$

$$\sum_{j \in J} x_{ij} \leq 1, \forall i \in I, \tag{3.3}$$

$$\sum_{i \in I} \sum_{t \in T} w_{ijt} \leq Z_j, \forall j \in J, \tag{3.4}$$

$$\sum_{j \in J} \sum_{t \in T} w_{ijt} = H_i, \forall i \in I, \tag{3.5}$$

$$\sum_{j \in J} w_{ijt} = H_i \cdot \sum_{s=1}^{\min\{|s|, t\}} K_s \cdot c_{i(t-s+1)}, \forall i \in I, t \in T, \tag{3.6}$$

$$w_{ijt} \leq x_{ij} \cdot H_i, \forall i \in I, j \in J, t \in T, \tag{3.7}$$

$$w_{ijt} \leq y_{jt} \cdot H_i, \forall i \in I, j \in J, t \in T, \tag{3.8}$$

$$y_{jt} \geq y_{j,t-1}, \forall j \in J, t \in T, \tag{3.9}$$

$$w_{ijt} \in \Re^+, \forall i \in I, j \in J, t \in T, \tag{3.10}$$

$$x_{ij} \in \{0, 1\}, \forall i \in I, j \in J, \tag{3.11}$$

$$y_{jt} \in \{0, 1\}, \forall j \in J, t \in T, \tag{3.12}$$

$$c_{it} \in \{0, 1\}, \forall i \in I, t \in T, \tag{3.13}$$

The objective function (3.1) minimizes the total traveling time between demand nodes and shelters over the planning horizon. Constraints (3.2) ensure that no more than P_t shelters are located by the end of time period t. Constraints (3.3) state that all the demand from each node i is allocated to one and only one shelter. Constraints (3.4) ensure that the capacity of each shelter is not exceeded. Constraints (3.5) guarantee that all the demand of node i evacuates to some shelter. Constraints (3.6) compute the number of people evacuating from node i at time t based on the S-shaped curve used to model the evacuee behavior. Namely, people at i evacuate at time t only if they have received an evacuation order in any of the previous $|S|$ time periods (in which case $c_{i(t-s+1)} = 1$). The exact number of people evacuating at time t depends on the parameter K_s defined by the S-shaped curve. Constraints (3.7) ensure that people from node i can be assigned to shelter j in any time t, only if node i is assigned to shelter j. Constraints (3.8) guarantee that demand can only be assigned to sites where shelters are located. Constraints (3.9) ensure that once opened, a shelter must remain opened. Finally, constraints (3.10)–(3.13) represent the binary and continuous restrictions on the decision variables.

3.4. Solution Methodology

Model (3.1)–(3.13) is a mixed-integer programming model that can be solved by general-purpose optimization solver packages. However, given the number of decision variables and constraints, finding optimal solutions to problems of realistic size may take several hours of computing time. Given that the model aims at supporting civil protection authorities' decision-making in response to flood emergencies, obtaining a good fast solution is deemed more important than obtaining the optimal solution in several hours. Thus, we propose a simulated annealing heuristic to solve the MPSLP. SA is based on the process of annealing where material is first melted at a high temperature and then slowly cooled to reach a thermodynamic equilibrium. First proposed by Kirkpatrick et al. (1983) and widely used in combinatorial optimization problems (e.g., Murray & Church, 1996; Antunes & Peeters, 2001; Antunes et al., 2003; Doostparast et al., 2015), the SA is a local search approach which generates and evaluates a solution at each iteration. The annealing process is used to escape local optimality by accepting non-improving solutions with a given acceptance probability. This probability depends on the cooling temperature and the quality of the newly generated solution. The main issues to be addressed in the design of an SA algorithm are: (1) the generation of a new solution through the exploration of the neighboring solution-space of the current solution; (2) the cooling scheme used to reduce the temperature during the annealing process.

The SA heuristic used in this study is described in Figure 3.1.

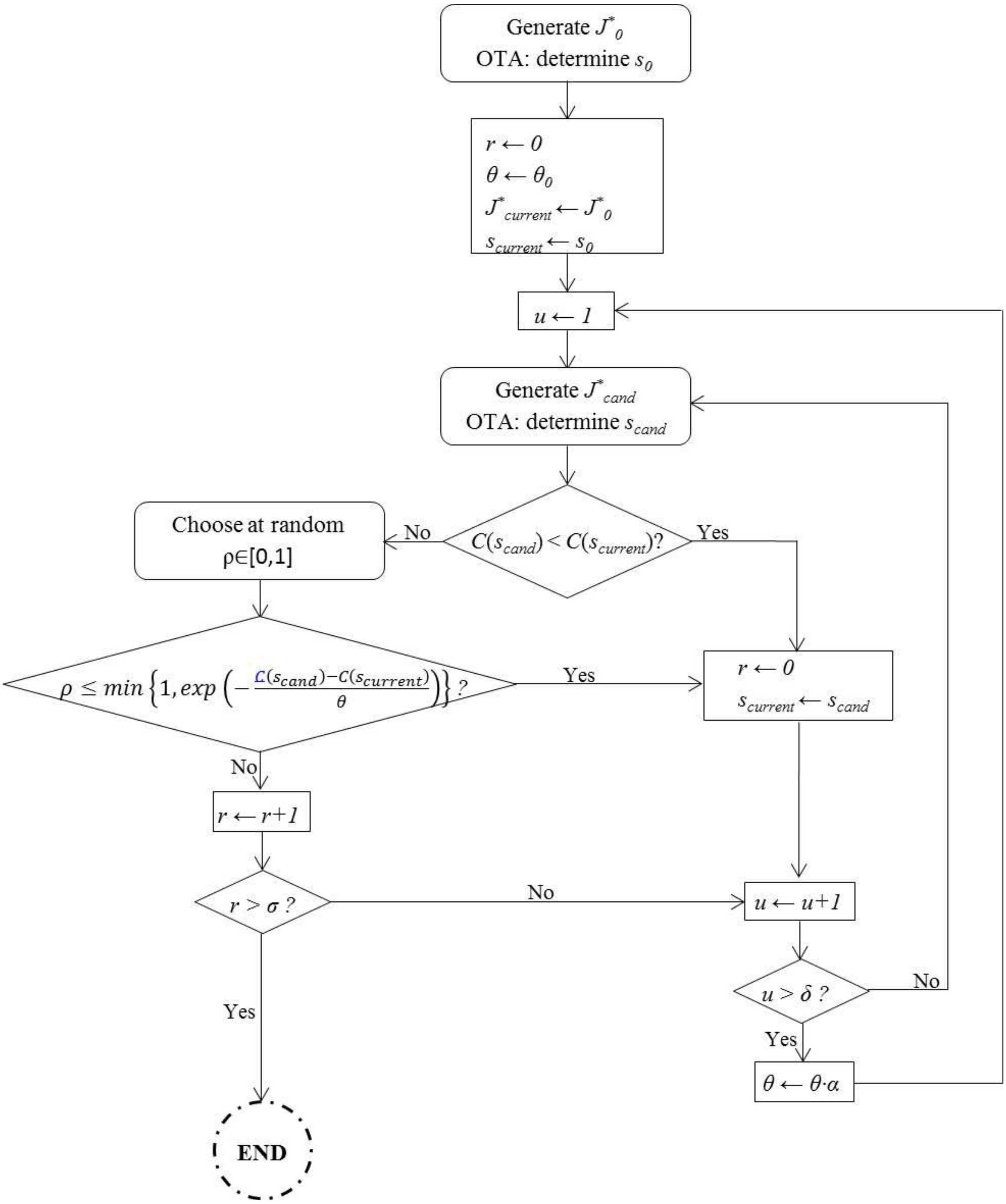


Figure 3.1 – SA heuristic.

The first step of the heuristic consists of a construction phase where an initial solution (s_0) is generated. In the construction phase, a set of shelters to open is first selected. This is done by considering the travel times in the first time period and allocating each demand node to its closest potential shelter. The $P_{|T|}$ shelters with the largest demand allocated to them are then selected. Once the set of opened shelters, J_0^*, has been determined, the shelters' opening times and the allocation of demand nodes to the shelters are computed using the procedure below.

Opening Time and Allocation algorithm – OTA(J^*)

Step 1 Set initial values: $iter \leftarrow 0$; $s^{iter} \leftarrow \{\}$; $C(s^{iter}) \leftarrow \infty$;
Step 2 Determine initial allocation matrix (x_{ij}^{iter});
repeat
    Step 3 $iter \leftarrow iter + 1$;
    Step 4 Determine opening times matrix (y_{jt}^{iter});
    Step 5 Update allocation matrix (x_{ij}^{iter});
    Step 6 Restore shelters' capacity restrictions if violated;
    Step 7 Determine the objective function value $C(s^{iter})$ and $\Delta C = C(s^{iter}) - C(s^{iter-1})$;
until $\Delta C = 0$
Step 8 **return** $s = s^{iter}$ as the best solution (y_{jt}, x_{ij}) for the set of selected shelters J^*.

The OTA procedure takes a set of open shelters, J^*, as an input and returns a solution $s = (y_{jt}, x_{ij})$, which specifies when each shelter is opened (y_{jt}) and which demand nodes evacuate to each shelter (x_{ij}). Note that in this procedure we assume that an evacuation order (c_{it}) is issued to a demand node as soon as the shelter to which the node is assigned becomes available.

Details of the individual steps of the OTA procedure are as follows:

- In Step 1, the iteration counter (*iter*), the initial solution and its cost are initialized.
- In Step 2, an initial allocation of demand nodes to the open shelters is determined by assuming that all the shelters in J^* are opened in the first time period and that all demand nodes start evacuating at the beginning of the planning horizon. Namely, the travel times between each demand node and each selected shelter are determined according to:

$$\overline{D}_{ij1} = \sum_{s=1}^{|S|} H_i \cdot K_s \cdot D_{ijs}, \forall i \in I,\ j \in J^* \tag{3.14}$$

Then each demand node is allocated to the closest selected shelter.

- In Step 3, the iteration counter is simply incremented.
- In Step 4, the opening times for each selected shelter are determined. To do this, we use an iterative process which, in each time period *t*, determines the deterioration of the objective function value caused by opening a shelter one time period later. Namely, at each iteration *t*, the objective function deterioration due to opening shelter j in the next time period is computed as $\Delta OF_{jt} = OF_{jt+1} - OF_{jt}$, where

$$OF_{jt} = \sum_{i=1}^{I} \sum_{s=t}^{t+|s|-1} x_{ji}^{iter-1} \cdot H_i \cdot K_{s-t+1} \cdot D_{ijs}, \forall j \in J^*, t = 1,...,T - |S| \tag{3.15}$$

Starting from period 1, ΔOF_{j1} is computed for each $j \in J^*$ and the P_1 shelters with the highest ΔOF_j values are opened at $t = 1$. In time period two ($t = 2$), ΔOF_{j2} is computed for each remaining shelter and the ($P_2 - P_1$) shelters with the highest loss values are opened. The process is repeated for the remaining time periods until all the $P_{|T|}$ shelters are opened.

- Steps 5 and 6 involve the multi-period allocation of demand nodes to shelters and the restoration of the capacity constraint at each shelter. The allocation is simply done by allocating each demand node to its closest selected shelter, taking into account the shelter opening time and the road conditions in each time period (Step 5). The total demand allocated to each shelter is then computed. If the capacity of a shelter is exceeded, we identify the demand nodes whose travel time increases the least when reallocated to another selected shelter with some spare capacity. We denote by t_j the opening time of shelter j and by $J^{'}$ the set of shelters with exceeded capacity. Let $j^{'}$ be a shelter in $J^{'}$ and $I_{j^{'}}$ the set of demand nodes allocated to it. For each demand node $i \in I_{j^{'}}$ and shelter $j \in J^{*} \setminus \{J^{'}\}$, the travel time increase for reassigning i to j is computed as:

$$\sum_{s=t_j}^{t_j+|S|-1} H_j \cdot K_{s-t_j+1} \cdot D_{ijs} - \sum_{s=t_{j^{'}}}^{t_{j^{'}}+|S|-1} H_j \cdot K_{s-t_{j^{'}}+1} \cdot D_{ij^{'}s}, \forall i \in I_{j^{'}}, j \in J^{*} \setminus \{J^{'}\} \quad (3.16)$$

For each shelter $j^{'}$ in $J^{'}$ the customers in $I_{j^{'}}$ are processed in ascending order of travel time increase and reallocated to their closest shelter with spare capacity until the capacity restriction of $j^{'}$ is no longer violated. The allocation matrix is then updated. This step (Step 6) ends when all the selected shelters verify the capacity constraints.

- In Step 7, the objective function value of the new solution is evaluated. If this is different from the objective function value of the solution found at the previous iteration, the process is iterated; otherwise, the OTA procedure ends, returning the opening time matrix and the allocation matrix for the set of shelters J^{*}.

The solution generated during the construction phase is then used in the SA heuristic to initialize the current set of selected shelters ($J^{*}_{current}$) and the current solution ($s_{current}$). The initial temperature of the cooling schedule (θ), the counter r and the iteration counter (u) are also initialized.

The next phase of the heuristic is the local search phase. At each iteration, the current set of shelters ($J^{*}_{current}$) is perturbed by a random swap of a selected shelter with a non-selected shelter. Thus, a new candidate set of shelters (J^{*}_{cand}) is generated. The corresponding solution value (s_{cand}) is determined by using the OTA procedure previously described for the construction phase.

The SA heuristic proceeds by checking if the objective function value of the candidate solution is lower than the value for the current solution. If it is, the current solution is replaced by the candidate solution and the counter r is reset to zero; otherwise, the candidate solution is accepted with a given probability. This probability is defined according to the Metropolis criterion. This is the most commonly criterion used in the literature in the implementation of SA heuristics (Johnson et al., 1989). According to this criterion, the acceptance probability ρ is given by:

$$\rho = \exp\left(- \frac{C(S_{cand}) - C(S_{current})}{\theta} \right) \tag{3.17}$$

That is, the probability of accepting a non-improving solution is larger at the beginning of the process, when the temperature θ is still high. If a non-improving solution is accepted, the counter r is reset to zero; otherwise, it is increased by one. Every time a new solution is generated (whether accepted or not), the iteration counter (u) is increased by one. After testing δ candidate solutions (where δ is the temperature length), the temperature is reduced by α (the cooling rate) and the iteration counter (u) is reset to one. The SA heuristic terminates when the counter r exceeds a predefined stopping number (σ), meaning that σ consecutive non-improving solutions have been generated and not accepted.

3.5. Computational Results

In this section, we use some randomly generated problems to evaluate the SA heuristic efficiency. Ten random instances are generated for four different size problems (10, 20, 30 and 40 demand nodes and shelters). We start by explaining how these random instances are generated, followed by the analysis of the SA heuristic efficiency.

3.5.1. Random Instances

The random instances were generated assuming that the study area has a square shape with 100 × 100 square length-units and that the flood propagates from a coordinate (0;0) to a coordinate (100;100) (Figure 3.2). The territory was divided in one central area where the expected impact of the flood is high (darker area), two areas adjacent to the central area where the expected impact is medium, and two areas further away from the diagonal line where the expected impact of the flood was assumed to be minor (lighter areas).

The deterministic parameters (e.g., the number of periods, the maximum number of shelters to open in each time period and the parameters of the S-shaped curve) are presented in Table 3.1. It was assumed that after receiving an evacuation order, the evacuation from each demand area follows the three-segment S-shaped curve displayed in Figure 3.3 (based on Sherali et al., 1991). Based on this curve, the percentage of population evacuating in each of the three time periods is equal to 15, 75, and 10 %, respectively.

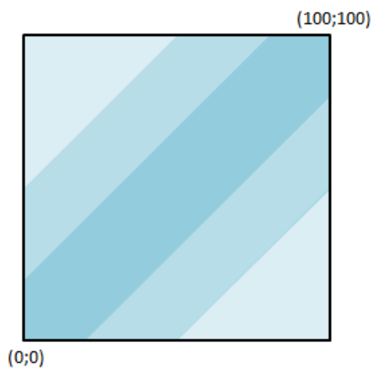


Figure 3.2 – Flood propagation.

Table 3.1 – Deterministic elements of the random problems for four different size problems.

$\lvert I \rvert \times \lvert J \rvert$	P_t	$\lvert T \rvert$	$\lvert S \rvert$	K_s
10 × 10	[1,2,2,3,3,4,4,4]	8	3	[0.15,0.75,0.10]
20 × 20	[1,3,3,5,5,7,7,7]			
30 × 30	[2,4,5,6,8,10,10,10]			
40 × 40	[3,6,8,10,12,14,14,14]			

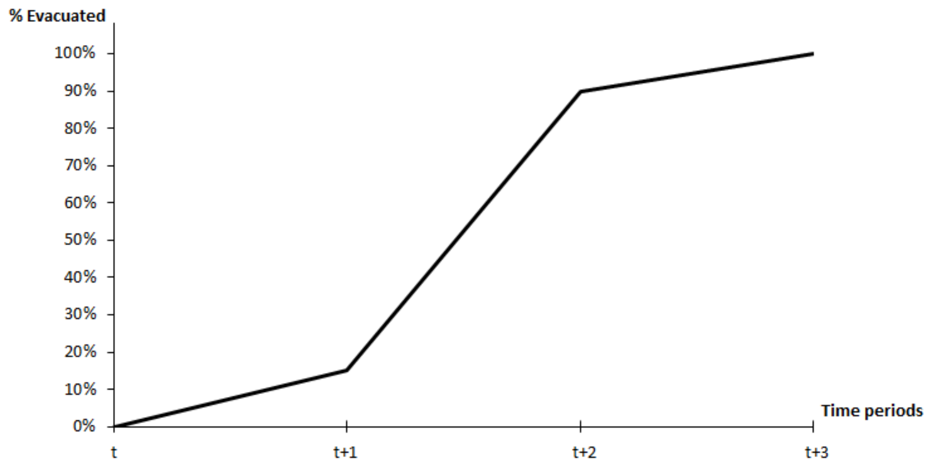


Figure 3.3 – Three-segment S-shaped curve representing the percentage of people evacuating in three time periods after receiving an evacuation order at time *t* (based on Sherali et al., 1991).

The stochastic part of the generation of these instances includes the coordinates of the demand nodes and of the shelter sites, the evolution of the travel times through time, the demand of each node, and the capacity of each shelter site. The coordinates of demand nodes and shelter sites were assumed to be random integers uniformly distributed between 0 and 100. To determine the initial travel times between each demand node and each shelter site, the Euclidean distance between each demand node and each shelter site was computed and a standard speed of 50 length-units/h was assumed. With the evolution of the flood, the speeds may decrease and consequently the travel times may increase in each time period. We assumed that in each time period the travel times could either stay the same (with a probability of 50 %) or increase (with a probability of 50 %). The increase of the travel times depends on the evolution of the flood and the location. Therefore, if the travel time would increase in a given time period, it would increase by 30 % in the central area, by 10 % in the two middle areas, and by 5 % in the further away areas. The demand at each node was assumed to be a random integer uniformly distributed between 50 and 550. All shelters sites have the same capacity, which was estimated as follows:

$$Z_j = \frac{\sum_{i \in I} H_i}{P_{|T|} \cdot \beta}, \tag{3.18}$$

where β is set equal to 0.8 (Lorena & Senne, 2004)

3.5.2. Solutions Techniques Comparison

The ten random instances generated for each problem size were used to evaluate the efficiency of the SA heuristic when compared with a commercial optimization solver. The Model (3.1)–(3.13) was implemented using IBM ILOG OPL modeling language and solved with the optimization solver CPLEX 12.5. For the SA heuristic, and after some trial and error calibration, we have assumed the following parameters:

- $\theta_0 = 0.13 \cdot C(s_0)$: this means that solutions 30 % higher than the initial solution will be accepted with a probability of approximately 10 %;
- $\delta = P_{|T|}$: where $P_{|T|}$ is the maximum number of shelters to be opened;
- $\alpha = 0.2$;
- $\sigma = 100 + 25 \cdot P_{|T|}$: this means that the stop criterion for the heuristic has a fix component (regardless of the problem size) and a variable component dependable on the maximum number of shelters to be open. The SA heuristic stops after $100 + 25 \cdot P_{|T|}$ consecutive non-improving solutions have been generated and not accepted.

Both solution techniques were implemented on an Intel Core 2 Quad CPU 2.50GHz PC running Windows 7 64-bits.

The SA heuristic and CPLEX (CPX) were compared in terms of the gap between the objective function values of the solutions and the computation times. The gap was determined according to:

$$GAP(\%) = \frac{C(S_{SA}) - C(S_{CPX})}{C(S_{CPX})}, \tag{3.19}$$

where $C(S_{SA})$ and $C(S_{CPX})$ are the objective function values of the solutions determined by the SA heuristic and by CPLEX, respectively. The comparison between both techniques for the smaller size problems is shown in Table 3.2.

For small problems, the SA heuristic found optimal solutions or solutions which were very close to the optimal. The average gap was never larger than 1.3 % and for 65 % of the instances the SA heuristic found the optimal solution. The computation time differences between the two solutions techniques were larger for the 20 × 20 problems than for the 10 × 10 problems - on average, the SA heuristic found the solution in 6.25 and 2.6 % of the time needed by CPLEX, for the two data sets, respectively.

For larger size problems (i.e., 30×30 and 40×40), CPLEX can take a significant amount of computing time to converge to optimality. Thus, for these problems the CPLEX execution was stopped after 15 minutes. Since we are dealing with an emergency situation, it is critical to have fast solutions, and waiting more than 15 minutes to obtain a solution may be impractical. For these problems, the gap between the objective function values and the computing times for both techniques are presented in Table 3.3. The negative gaps (bold in Table 3.3) mean that the SA heuristic determines a better solution than CPLEX after 15 minutes of computing time.

For both problem sizes, the SA heuristic could determine solutions that are better than the ones found by CPLEX (after 15 minutes) in at least half of the cases. Analyzing the ten 30×30 instances in more detail, there were two instances where CPLEX found the optimal solution within 15 minutes. In one of these instances, the SA heuristic found the same optimal solution in less than 17 seconds, while the exact algorithm took more than 4 minutes. For the other instances, the SA never used more than 24 seconds to find solutions that were, on average, only 0.1 % worse than the solutions found by CPLEX. For five of the ten instances the solution found by SA was even better than the solution provided by CPLEX after 15 minutes.

Table 3.2 – Objective function value gap and computing time for CPX and SA for small problems.

Problem	OF value (in minutes)						Computing time (seconds)			
	10 ×10			20 ×20			10 ×10		20 ×20	
	CPX	SA	Gap (%)	CPX	SA	Gap (%)	CPX	SA	CPX	SA
1	82,519	82,519	0.0	160,143	160,206	0.0	2.4	0.2	186.5	3.0
2	111,594	111,594	0.0	97,405	97,405	0.0	2.5	0.2	30.7	3.4
3	72,539	73,105	0.8	156,477	156,477	0.0	2.9	0.2	453.9	5.4
4	93,812	94,232	0.4	149,652	151,607	1.3	3.3	0.2	146.0	2.9
5	83,907	83,907	0.0	153,520	154,854	0.9	2.2	0.3	66.2	3.7
6	55,369	55,424	0.1	115,021	115,021	0.0	3.9	0.2	14.9	2.5
7	131,912	131,912	0.0	105,050	105,516	0.4	3.2	0.2	50.9	4.6
8	82,519	82,519	0.0	160,143	160,206	0.0	6.9	0.2	207.7	2.9
9	86,896	86,896	0.0	137,588	137,588	0.0	1.6	0.3	80.3	3.0
10	87,824	87,824	0.0	147,985	148,282	0.2	3.4	0.2	114.9	3.6
Average			0.1			0.3	3.2	0.2	135.2	3.5

Table 3.3 – Objective function value gap and computing time for CPX and SA for large problems.

Problem	OF value (in minutes)						Computing time (seconds)			
	30 × 30			40 × 40			30 × 30		40 × 40	
	CPX	SA	Gap (%)	CPX	SA	Gap(%)	CPX	SA	CPX	SA
1	211,892[a]	208,411	**-1.6**	205,687[a]	195,817	**-4.8**	900.0	21.6	900.0	62.4
2	159,374	159,374	0.0	173,463[a]	143,585	**-17.2**	283.5	16.6	900.0	54.9
3	191,772	194,940	1.7	167,157[a]	147,816	**-11.6**	775.1	19.1	900.0	75.6
4	122,864[a]	126,617	3.1	174,978[a]	162,812	**-7.0**	900.0	15.9	900.0	59.1
5	227,303[a]	223,358	**-1.7**	218,399[a]	217,331	**-0.5**	900.0	14.7	900.0	91.2
6	148,015[a]	147,383	**-0.4**	167,990[a]	162,097	**-3.5**	900.0	9.8	900.0	101.7
7	175,070[a]	175,912	0.5	198,930[a]	189,591	**-4.7**	900.0	23.9	900.0	112.5
8	211,892[a]	208,411	**-1.6**	205,687[a]	195,817	**-4.8**	900.0	21.7	900.0	61.7
9	171,922[a]	177,217	3.1%	174,260[a]	145,336	**-16.6**	900.0	14.3	900.0	78.6
10	175,603[a]	175,337	**-0.2**	179,651[a]	181,594	1.1	900.0	13.8	900.0	110.6
Average			0.3			**-7.0**	825.9	17.1	900.0	80.8

[a]OF value of the solution found after 15 minutes (i.e., this is not the global optimal solution)

With regard to the 40 × 40 problems, for nine of the ten instances the SA found better solutions than CPLEX after 15 minutes. In fact, for one of the ten instances the SA heuristic could find a solution with an objective function value 17.2 % lower than the value of the solution found by CPLEX. Not only the final solution was better but also the computing time was significantly lower (54 seconds versus 15 minutes).

From these results, it can then be concluded that the proposed SA algorithm is an efficient heuristic for the problem under analysis, capable of finding optimal solutions or close to optimal solutions for most of the instances tested. For large-scale problems, the SA heuristic is a very good option to find high-quality solutions in a short amount of time.

3.6. Case Study

In this section, we use a real world-based case study to demonstrate the applicability of the modeling approach proposed. In addition, we illustrate the impact of using a dynamic approach to model the emergency evacuation process, as compared with a traditional static approach.

The case study is located in the Wake County in the US state of North Carolina. As of the 2010 census, this county's population is 900,993 inhabitants. For the case study, we considered the flood plain map and geo-information provided by the North Carolina State University Libraries. The evolution of the flood was simulated based on the flood map and on the orography of the region.

The region was divided in 59 demand areas, which represent the zones affected by the flood. The demand at each area represents the population that is affected by the flood. The total population affected by the flood was estimated to be 300,975 inhabitants (around one-third of the total population of the county). Figure 3.4 displays the region under study, the affected areas, the population per affected area, the potential shelter locations, and the capacity of the shelters. The most highly populated areas in the region are in the central part, in particular in the northwest–southeast axis that passes in the center of the region.

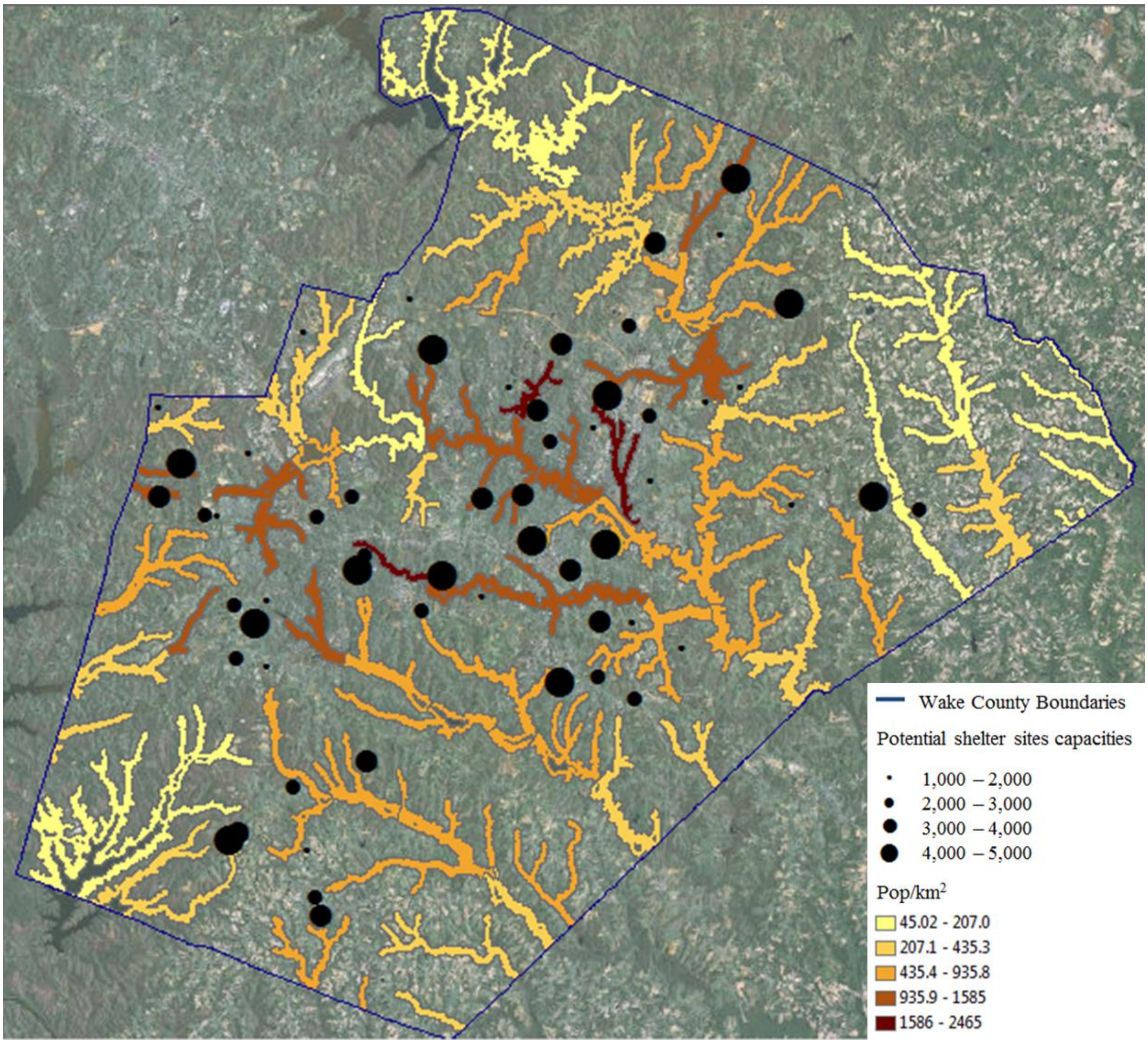


Figure 3.4 – Wake County boundaries, affected areas, population per area and potential shelter locations.

The evacuation process over time was assumed to be the same as the one considered in the previous section—i.e., after receiving an evacuation order, the evacuees evacuate according to a three time periods S-shaped curve where 15 % of the people evacuate in the time period the evacuation order is emitted, 75 % evacuate in the following time period, and 10 % evacuate two time periods after the evacuation order. In practice, it is known that only a small percentage of the population affected by a flood seeks refuge in a shelter, while the remaining affected population evacuates to different destinations. This is also suggested in the literature. For instance, Li et al. (2012) consider that, for a hurricane scenario, only 8–16 % of the evacuation demand looks for a shelter. Therefore, for this case study we assumed that 9 % of the total affected population looks for assistance in shelters, which resulted in an overall demand of 27,062 evacuees.

We considered a planning horizon of 4 hours and simulated the evolution of the flood by dividing the 4 hours in eight time periods, each with a fixed length of 30 minutes. The water levels on the road network were generated for each time period. It was assumed that in every period the water levels were equal or higher than in the previous period and that some roads were already flooded in the first time period. In the last period, there were some zones where, due to the orography and the land use, the water level exceeds 0.5 meters, thus precluding the use of the road network. Since the water level on the road affects the maximum speed a car can travel, it was necessary to determine the maximum speed for each arc of the road network in each time period based on the water depth. Based on Nayak & Zlatanova (2008), the maximum speeds for five different types of roads are shown in Table 3.4.

Table 3.4 – Maximum speeds (km/h) for different free-flow speed roads according to water depth (based on Nayak & Zlatanova, 2008).

Type of road	Water depth in the road (m)					
	0	]0, 0.1]	]0.1, 0.2]	]0.2, 0.3]	]0.3, 0.5]	> 0.5
Type 1	40	16	8	4	1	0
Type 2	55	23	11	5	1	0
Type 3	70	28	14	7	1	0
Type 4	80	32	18	9	1	0
Type 5	105	42	21	10	1	0

Given the length of each network arc and the maximum speed a car can travel along it, the travel time was determined for each arc and for each time period. For each demand area, the population was considered to be concentrated in a single demand node located in the centroid of the demand area. Using Network Analyst, an ArcGIS extension, the shortest paths (in terms of time) between each demand node and each shelter site were computed for the eight time periods.

A total of 60 sites across Wake County were used as potential shelter locations. These shelters are existing public schools, such as elementary, middle, and high schools in the Wake County that are located outside of the affected area. These schools are spread out across the entire territory, with a higher concentration in the most densely populated areas in the center of the region. The capacity of the shelters was computed based on the size of the schools and on a standard evacuation criterion according to which each person assisted in a shelter needs an average space of 1.86 m2 (American Red Cross, 2002). It was considered that only one-third of the area of the school is effectively available to receive the evacuees. The rest of the area was considered to be for support of the assistance service provided to the evacuees or area not suitable to accommodate and assist people. This resulted in shelter with capacity varying from around 1100 to 5000 people. We considered that a maximum of 20 shelters could be opened. In the first time period a maximum of six shelters could be opened. In the following four time periods, it would be possible to open up to a maximum of 9, 12, 16, and 18 shelters, respectively. We assumed that no shelters could be opened after period 6, so that the evacuation can be completed by time period 8 according to the S-Shape curve.

To use the SA heuristic we have assumed the same heuristic parameters used in the Computational Results section. The CPLEX solution was not considered in this case study given the complexity of the problem. After a computing time of 3 hours the solution gap (i.e., the difference between the incumbent solution at that time and the lower bound estimation of the solution) presented by CPLEX was still 3.0 %.

3.6.1. Analysis, Results and Discussion

The solution for this case study was obtained after 124.6 seconds (approx. 2 minutes) and resulted in an objective function value of 193,006 minutes (i.e., total traveling time between demand nodes and shelters over the planning horizon). The number of shelters opened in each time period, the number of demand areas receiving an evacuation order in each time period, the population evacuating in each time period, and the overall travel time (OF) are displayed in Table 3.5(a). The location of the selected shelters is shown in Figure 3.5.

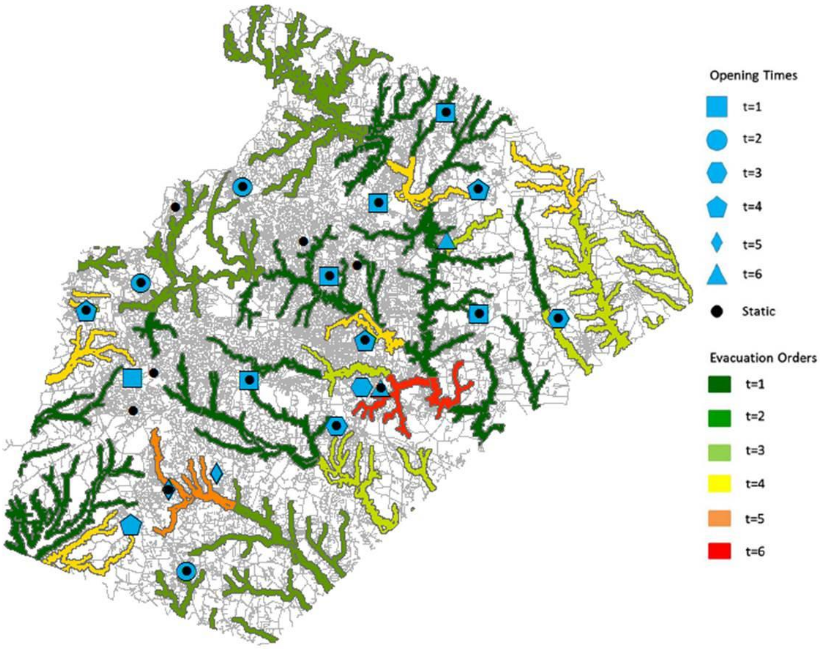


Figure 3.5 – Selected shelters location for dynamic and static approach and delivery times of evacuation orders for the dynamic approach.

It can be observed that most of the demand evacuates in the initial time periods, especially in the second and third period. The demand in these initial time periods has origin in the areas most affected by the flood in the initial stage of the disaster. In terms of the geographic location of the shelters, the shelters were evenly spread over the territory. The initial shelters were located near to the most densely populated areas affected by the flood, followed by shelters located in more peripheral areas of the region in order to cover the demand that was far away from the shelters opened in the first time period. The shelters to be opened in the last time periods were, in general, located in such a way that they complement the coverage of shelters previously opened and that were already serving a high evacuees' demand. The demand areas less affected by the flood received the evacuation orders in the last time period and were allocated to the shelters opened at the end of the planning horizon.

To investigate the impact of the dynamic aspects of a flood disaster on the selection of shelters location and on the evacuation orders decisions, we compared our dynamic solution with a static solution.

Table 3.5 – Results: (a)-Dynamic solution; (b)-Static solution; (c)-Static solution adopted in the dynamic approach.

Time periods	# Opened shelter	(a) Dynamic solution		(b) Static solution		(c) Static solution adopted in the dynamic approach	
		# evacuation orders	# evacuees	# evacuation orders	# evacuees	# evacuation orders	# evacuees
1	6	26	2,100	Na	Na	21	1,731
2	9	14	11,324	Na	Na	14	9,414
3	12	9	5,901	Na	Na	10	5,476
4	16	6	2,946	Na	Na	6	3,584
5	18	2	2,619	Na	Na	5	2,964
6	20	2	1,182	Na	Na	3	2,114
7	20	0	885	Na	Na	0	1,593
8	20	0	105	Na	Na	0	185
OF (min)		193,006		169,187		201,094	

The static solution simulates the standard approach commonly used in the literature. It assumes a single-period model and the dynamic evolution of the flood is not taken into account. Thus, shelters location decisions were based on the road conditions at the onset of the flooding event and all the demand was assumed to evacuate at the same time. The results for the static approach were also obtained through a SA heuristic similar to the one presented in this paper but which did not consider the time dimension of the problem. Additionally, the OTA algorithm was adapted to only determine the allocation of demand nodes to shelter. Evacuation order times and demand's split over three time periods was not considered. The results of the static approach are presented in Table 3.5(b) and the location of the selected shelters is displayed in Figure 3.5 (black dots). In this static solution, the opened shelters were more concentrated in the central area of the region. In addition, the objective function value was clearly an underestimate of the true values obtained when the actual road conditions were taken into account. In fact, it can be concluded that the solution obtained with a static model can be misleading and may be highly suboptimal when applied in reality. In some cases, the evacuees' allocation identified by the model may even be infeasible if some road segments become unusable due to the water level.

This direct comparison between the dynamic solution and the static solution can be unfair. In practice the implementation of the static solution necessarily follows a dynamic process. The resource limitations over time force this dynamic implementation of the static solution. Thus, we opted to also compare the dynamic solution with a solution obtained by taking the static solution as an input to our dynamic model. Namely, we run the dynamic model imposing that the 20 shelters selected at the end of the planning horizon corresponded to the 20 shelters identified by the static model. Given these 20 shelters, the dynamic model determined when to open them, when to send the evacuation orders and the best allocation of demand nodes to the shelters. The results of this experiment are presented in Table 3.5(c).

By comparing the dynamic solution with the static solution adopted in the dynamic approach, we observe that the fully dynamic approach provided a solution that is 4.2 % better. This means that the consideration of the flood dynamics in the process of deciding the shelter location improved the solution by 4.2 %. Another relevant observation is the fact that the number of evacuees in the last time periods was higher for the static solution than for the fully dynamic solution. This reflects the fact that the flood does not affect all demand nodes at the same time. While in the dynamic solution prioritization was given to the demand nodes affected by the flood in the initial time periods, in order to evacuate these nodes before the road conditions degrade too much, in the static solution this was not totally possible. The location of the shelters was already defined without considering these dynamics. Thus location decisions limited the capacity available in the initial periods and forced evacuation orders to be postponed for some demand nodes.

These results show what could happen when the location of shelters is determined without taking into consideration the dynamic propagation of a disaster. The estimation of a flood evolution can provide a better overview of the evacuation needs and help to evaluate how these needs will evolve over time. A solution approach including these dynamic aspects provides more effective solutions, which explicitly address real emergency requirements.

3.7. Conclusions

This chapter presents a multi-period capacitated location-allocation model for optimizing evacuation operations by civil protection authorities during flood disasters.

To take into account the consequences of floods evolution over time, several time dependent components are incorporated into the proposed modeling approach. The main rationale underlying the model is that floods are dynamic events, which evolve over time. Consequently, a realistic optimization model should capture the dynamic aspects associated with such events. These include changes to road conditions, the increasing availability of shelter facilities over time, and the necessity of issuing evacuation orders to the affected populations in different time periods. Also, it is crucial that a model is able to emulate the evacuees' behavior in response to a flood evacuation order. In real situations, in fact, people do not evacuate immediately after receiving an evacuation order. Instead, evacuation takes place in a phased manner over time. Our model incorporates all of these issues and determines the optimal location of a fixed number of shelters in each time period, the best time to issue evacuation orders in each affected area, and the demand that is assigned to each shelter. The model objective is to maximize the accessibility to shelters by minimizing the overall travel time of the evacuees. To the best of our knowledge, this is one of the first studies dealing with a dynamic approach to tackle the problem of optimizing shelter locations and evacuation orders in flood emergency scenarios. Since the main purpose of the proposed model is to support civil protection authorities' decision-making in response to flood emergencies, it is crucial that good solutions to the model can be quickly identified.

To this end, we develop a simulated annealing heuristic. Experiments carried out on a set of randomly generated problems demonstrate the efficiency of the proposed SA heuristic in finding high-quality solutions in modest computing time.

The applicability of our model is illustrated with a real world-based case study. The analysis of the results for this case study highlights the importance of using a dynamic approach when dealing with flood disasters in practice.

To further increase the applicability and accuracy of our model, several different extensions can be considered in the future. As an example, different scenarios should be included in the analysis to tackle the uncertainty characterizing flood events. Routing decisions and road traffic conditions are also an important component in emergency planning and should be integrated into the model. Finally, the distribution of emergency supplies to the open shelters should also be optimized into a model which combines shelter location, supply distribution and evacuation decisions. The model should be tested on other more complex case studies to derive additional insights.

[Page Intentionally Left Blank]

4. THE MULTI-PERIOD VEHICLE EVACUATION PROBLEM FOR FLOOD DISASTERS USING A TIME-SPACE NETWORK

4.1. Introduction

Floods are the most common natural disaster worldwide, and their frequency and number of people affected are increasing (OECD, 2019). In 2020, there were 23% more floods than the average from the previous two decades and the consequences were devastating – 33.2 million people were affected by floods and 6,171 deaths (CRED & UNDRR, 2021). According to the Water Resource Institute (Kuzma & Luo, 2020), 132 million people will be affected by river floods in 2030.

Civil protection authorities are in charge of flood response operations planning and management in most countries worldwide. The emergency flood plans developed by the civil protection authorities foresee the availability of transportation for the population who may not own a private vehicle to evacuate. These plans also comprise the identification of all entities involved and the lines of action for each entity, the definition of the management disaster structure, the identification of all resources available, flood risk maps, and in some cases, evacuation maps. Thus, when facing a real flood situation, the decisions are left for real judgments based on the experience of the entity responsible for the protection, previous emergency studies, and a set of standard procedures.

Evacuation is the most crucial disaster management operation to reduce the number of fatalities (Caunhye et al., 2012; Bayram, 2016). Regarding the destination of the evacuation, for some evacuees the safe place outside the flooded area is the home of relatives or friends or even a hotel. However, for other evacuees the safe pace is at a designated shelter (e.g., schools, sports halls, warehouses) (Mileti et al., 1992). When evacuating, a significant part of evacuees cannot use private vehicles to evacuate and therefore depend on other means to evacuate, such as transit services (Bayram, 2016) or civil protection authorities.

In order to help civil protection authorities' evacuation operations in flood situations, a multi-period vehicle evacuation model is proposed. The aim is to manage the allocation of a fleet of vehicles made available to civil protection authorities' to transport evacuees between their location during the flood and their pre-assigned shelter. The model approach comprises a mixed-integer linear programming optimization model and a solution technique involving a time-space network of this dynamic problem. A fleet of evacuation vehicles with a limited capacity is available at multiple yards. It is assumed that demand nodes have a known number of evacuees ready to be evacuated to a predefined shelter after receiving an evacuation order at a specific moment in the planning horizon. The objective is to evacuate all the affected population dependable on civil protection transport while minimizing the travel time and the waiting time experienced by the evacuees. Therefore, the proposed model determines the schedule and the route of each evacuation vehicle, i.e., for each time period in the planning horizon, the model identifies the location of each vehicle, the number of evacuees in each vehicle, and the number of evacuees waiting at each demand node.

As Gama et al. (2016) demonstrated it is essential to include the time component in a mathematical model for a more accurate representation of the real situation of disaster management. As a consequence of floods propagation, road conditions and demand for shelter vary over time. Travel times are affected by the rise of water levels on the road network as traveling speed may be reduced on some roads or even crossing may become impossible in some time periods. Flooding affects different areas at different times and, consequently, evacuees do not react at the same time to the disaster and demand for shelters evolves over time. These dynamic aspects are modeled by assuming that travel times vary over time and evacuation orders are issued at different time periods. Moreover, we assume that after receiving an evacuation order, the population evacuates according to a standard pattern, such as an S-shaped curve, as proposed in many studies in the literature (Sherali et al., 1991; Rawls & Turnquist, 2012; Murray-Tuite & Wolshon, 2013; Li et al., 2013). Another issue to consider when modeling emergency operations is that evacuation transportation resources (e.g., vehicles and drivers) are not readily available at the onset of a disaster. Civil protection authorities can use emergency vehicles from entities identified in the flood emergency plans and from private companies, however it is necessary to request them. For this reason, evacuation vehicles may not be available before the flood starts. Thus to incorporate this aspect in our model, we assume that vehicles become gradually available in different time periods. The work developed by Gama et al. (2016) is used to generate the location and the opening times of shelters, the assignment of demand to these shelters, and the optimal time to issue evacuation orders.

This work is the first to incorporate different logistic operations for flood emergency evacuation such as flood dynamics and evacuation resources availability. Also, to the best of our knowledge, this is the first work to manage civil protection authorities' emergency vehicles.

The organization of the chapter is as follows. Subchapter 4.2 presents an overview of carless evacuation works in the literature. In subchapter 4.3, the time-space network is defined, and the model formulation of the problem and the rolling horizon approach are introduced. The modeling approach is applied to a real world-based case study in subchapter 4.4. Subchapter 4.5 presents some final comments on the work developed and on the future work.

4.2. Carless Evacuation Literature Overview

Evacuation - the movement of people from an affected area to a safer place outside the threatened area (Stepanov & Smith, 2009; Dhamala & Adhikari, 2018) - is an essential emergency logistics operation to protect the population from the consequences of disasters (Caunhye et al., 2012; Bayram, 2016). Evacuation planning is a complex process (Stepanov & Smith, 2009) and can be studied from different perspectives: i) type of disaster, i.e., notice or short-notice evacuation, associated with natural disasters which can be somewhat predicted in advance, and no-notice evacuation, associated to man-made disasters which happen with no warning (Abdelgawad & Abdulhai, 2012); ii) moment of evacuation, i.e., evacuation can be carried out before a disaster strikes as a way preparedness, or after the occurrence of a disaster as a response to disaster impacts (Caunhye et al., 2012); iii) evacuees mode of transportation, i.e., some evacuees use their private vehicles to reach a safe place (car-based evacuation) while other evacuees are carless, i.e., people without a private car, elderly or people with special needs therefore depend on other transportation modes to reach a safe place (carless evacuation) (Dhamala & Adhikari, 2018).

This overview focus on carless evacuation studies for both types of disasters and both moments of evacuation. Table 4.1 summarizes the studies under analysis.

Table 4.1 – Carless evacuation studies in the literature.

Study	Type of disaster	Moment of evacuation	Objective	Main Features	Solution Technique
Sayyady & Eksioglu (2010)	Man-made (no-notice evacuation)	Post-disaster evacuation	Total evacuation time and casualties minimization	Incorporation of traffic flow dynamics (traffic congestions)	Time-space network and tabu search
Bish (2011)	Hurricanes (notice evacuation)	Pre-disaster evacuation	Duration of evacuation minimization	VRP variant	Heuristic algorithms
Abdelgawad & Abdulhai (2012)	Man-made (no-notice evacuation)	Post-disaster evacuation	Overall travel and waiting time minimization	VRP variant; subway and bus networks	Constraint programming and local search
Goerigk & Grün (2014)	Man-made (no-notice evacuation)	Post-disaster evacuation	Overall travel and waiting time minimization	Demand uncertainty	Branch and Bound framework
Deghdak et al. (2015)	unspecified	Post-disaster evacuation	Duration of the schedule minimization	Travel times vary over time	Time-indexed formulation and heuristic algorithms
Dikas & Minis (2016)	unspecified	Post-disaster evacuation	Total time required to transport casualties minimization	Casualties evolve over time	Hybrid solution framework

Study	Type of disaster	Moment of evacuation	Objective	Main Features	Solution Technique
Qazi et al. (2016)	Flood (short-notice evacuation)	Pre-disaster evacuation	Number of evacuees maximization	Demand arrival following a pattern; multiple bus trips	Time-space network
Swamy et al. (2017)	Hurricanes (notice evacuation)	Pre-disaster evacuation	Total distance minimization	Improvement of route design by using simulation	Sequence of sub-problems and a heuristic neighborhood search
Qazi et al. (2017)	Flood (short-notice evacuation)	Post-disaster evacuation	Number of evacuees maximization	Gradual flooding of pickup points; Effect of congestion on travel times	Time-space network
Zhao et al. (2020)	Notice evacuation	unspecified	Overall travel and waiting time minimization	Round-trip; Unfixed routes	Two-layer algorithm
Lu et al. (2021)	Hurricane or Flood prone (notice evacuation)	Pre-disaster evacuation	Evacuation duration time minimization	Pedestrian and bus networks	Optimal

The Bus Evacuation Problem (BEP) was introduced by Bish (2011) for emergency preparedness. It is presented as a unique variant of the Vehicle Routing Problem (VRP) in which routes are determined and assigned to multiple vehicles, and for each route a shelter is selected. The model minimizes the duration of the evacuation while considering bus and shelter capacity constraints. The author also proposed a heuristic that solves the problem by separating the route construction from the route assignment. Goerigk & Grün (2014) considered a simplified version for the BEP and assumed that the number of evacuees is not known in advance. The problem is applied to a man-caused disaster, and it is solved heuristically. Dikas & Minis (2016) proposed a new formulation of the BEP for transporting casualties after a disaster strikes. The objective is to minimize the total time required to transport casualties to medical facilities, assuming that casualties increase over time and vehicles availability is limited. The authors also proposed a hybrid solution framework to solve the problem. For the evacuation after a major disaster, Deghdak et al. (2015) proposed a time-index formulation for the BEP, which considers that travel times vary over time. These variations represent events that change the state of the transportation network, such as earthquake aftershocks, road repairs, or roads congestion. The problem is solved heuristically. Abdelgawad & Abdulhai (2012) also presented a new variant of the VRP to model public vehicles (buses and subway trains) routing and scheduling in a no-notice emergency evacuation. The objective is to minimize the overall travel and waiting time while being subjected to time and capacity constraints. The problem is solved using a constrained programming approach and a local search framework. Swamy et al. (2017) provided an evacuation strategy using public transportation before a hurricane strikes. The planning framework is multi-stage - 1) definition of the pickup locations; 2) assignment of evacuees to shelters; 3) generation of bus routes and bus dispatching sequence – and includes a simulation tool to improve the performance of the overall system. Sayyady & Eksioglu (2010) proposed a methodology to design plans for transit-based evacuation, which is applied to a no-notice event. The objective is to minimize the number of casualties and the total evacuation time. The model considers bus capacity limitations and incorporates traffic flow dynamics, such as traffic congestion. A time-space network is presented to reduce the size of the problem, while a tabu search algorithm is used to solve the problem. For Qazi et al. (2016), the study from Sayyady & Eksioglu (2010) presented several limitations. Thus, the authors presented what they called the short-notice bus-based evacuation under dynamic demand (SBED) model based on a time-space network. The model assumes that demand follows a specific pattern when arriving at pickup points and considers bus routes to be flexible. The SBED model is then used to investigate the impact of demand variation and evacuation route flexibility on evacuation planning and, according to Qazi, Nara, et al. (2017), route flexibility reduces resources. Later, Qazi et al. (2017) applied the SBED approach but took flood propagation and congestion into account. Considering that buses do not need to pick up evacuees until a full load as well as can serve different pick-up points and shelters, Zhao et al. (2020) developed a round-trip bus evacuation model which determines the bus routes and each bus arrival and departure time while minimizing the evacuees evacuation time and waiting time. This model is applied to notice events, and it is solved with a two-layer algorithm. More recently, Lu et al. (2021) combined pedestrian and bus networks to design evacuation routes for emergency preparedness. The optimization model determines the location of pickup nodes, where evacuees assemble using the existing pedestrian network and assigns available buses to move the evacuees from pickup nodes to safe areas while minimizing the evacuation duration time.

We consider flood evacuation as a disaster response operation and, therefore, the proposed multi-period vehicle evacuation model falls within the post-disaster category. To the best of our knowledge, none of those mentioned above works addresses the problem of route design and scheduling while taking into account emergency vehicles availability and disaster propagation. Thus, we present a multi-period vehicle evacuation model that takes into account not only the consequences of a flood propagation – travel times vary over time, and evacuees start evacuating at different time periods and according to a pattern – but also considers that resources (e.g., vehicles and drives) are not immediately available. To solve this problem, a rolling horizon technique is adopted. This optimization technique not only has been applied to many different fields in the literature but is also well suited for emergency situations. With a rolling horizon approach, initial solutions are obtained in a short time allowing them to be implemented by civil protection authorities while solving the evacuation problem for later time periods.

4.3. Methodology

This section presents a multi-period vehicle evacuation model to optimize emergency vehicle schedules and routes at the onset of a flood disaster.

4.3.1. Problem Description

A set of emergency vehicles are available at different yards to evacuate the population from demand areas affected by a flood to shelters outside of the affected area. The assumptions of the multi-period vehicle evacuation problem are as follows:

1. Road conditions and, hence, traveling times between yard nodes and demand nodes, demand nodes and shelter sites, and between demand nodes are time-dependent.

2. The evacuation order of each demand node and its respective shelter are known in advance.
3. Vehicles become available only at the yard nodes and in different time periods, with only a few of them available at the onset of the disaster.
4. Vehicles have a limited capacity for evacuating the demand.
5. Evacuees wait for vehicles at demand nodes.
6. Evacuees evacuate according to an S-shaped curve after receiving an evacuation order. Based on Sherali et al. (1991) work, evacuees react slowly after receiving the evacuation order, i.e., a small percentage of evacuees starts evacuating after the evacuation order is issued. In the following periods, the number of evacuees responding to the evacuation order issue gradually increases. By the end of the evacuation process, only a few evacuees are left and the percentage of evacuees is smaller again.

4.3.2. Time-Space Network

The time-space network enables entities to move both in time and space dimensions (Chen & Chao, 2004). The time-space network comprises nodes and arcs, both defined according to time and space attributes.

Three sets of nodes are considered in this time-space network: i) *yard nodes* which represent the initial location of vehicles; ii) *demand nodes* which represent the location of evacuees, i.e., where evacuees wait for the vehicles; iii) *shelter sites* which represent the final destination for both evacuees and vehicles. The arcs of the time-space network represent the movements of vehicles and evacuees. The evacuation vehicles move from yard nodes to demand nodes where evacuees are collected. These vehicles can then move towards another demand node or a shelter site where evacuees are sheltered. Once at a shelter site, the vehicles can either move towards demand nodes to collect more evacuees, wait to move later, or end service. Evacuees wait at demand nodes to be collected by vehicles. Once collected, the evacuees follow the evacuation vehicle route until they are left at their designated shelter.

Therefore, two sets of arcs are considered in the time-space network: movement arcs and waiting arcs. Movement arcs comprise *yard nodes – demand nodes arcs, shelter sites – demand nodes arcs, demand nodes – demand nodes arcs,* and *demand nodes – shelter sites arcs*. It is assumed that the movement of evacuees is restricted to the last two types of movement arcs. Waiting arcs comprise the waiting arcs for evacuees at demand nodes (*evacuee waiting arcs*) and the waiting arcs for vehicles at yard nodes or shelter sites (*vehicle waiting arcs*). An illustrative representation of the described time-space network concept is shown in Figure 4.1.

The construction of the time-space network follows these important assumptions:

1. Vehicles can wait at yard nodes or shelter sites but cannot wait at demand nodes. Thus, emergency vehicles can not arrive at a demand node before the evacuation order is issued.
2. The movement of emergency vehicles between demand nodes is restricted to demand nodes assigned to the same shelter.
3. Vehicles can move to a demand node if, from that demand node and from that time period, it is possible to arrive to the assigned shelter within the planning horizon. If it is not possible, it is assumed that demand node is flooded.
4. There are evacuee waiting arcs from the beginning of evacuation until the last time period when it is possible to arrive to the assigned shelter.
5. There are vehicle waiting arcs at yard nodes from the moment a yard has vehicles available until the end of the planning horizon.
6. There are vehicle waiting arcs at shelter sites from the moment a vehicle arrives at a shelter until the end of the planning horizon.

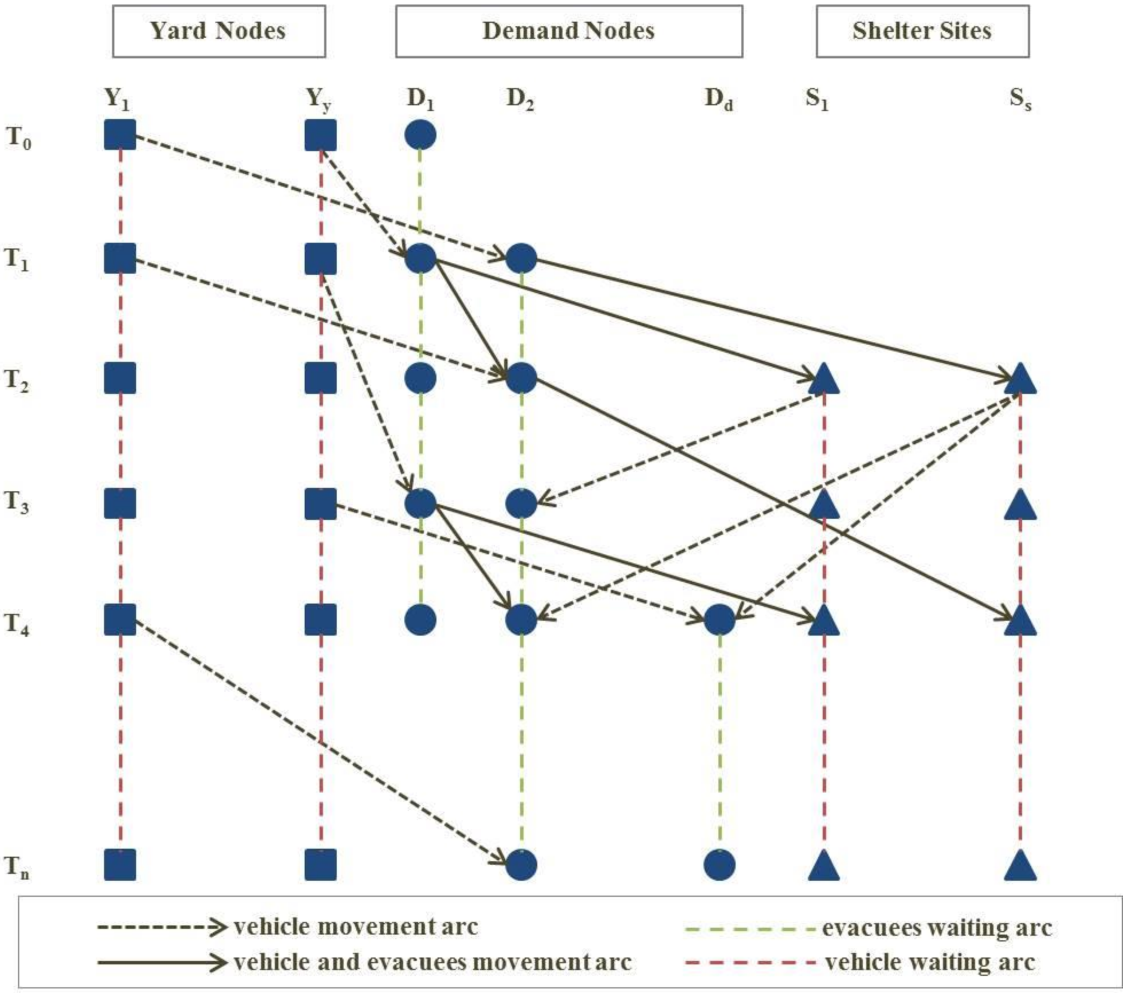


Figure 4.1 – Time-space network representation.

4.3.3. Model Formulation

The formulation of the mathematical model uses the following notation:

Sets:

Y^{TSN}	set of time-space network yard nodes
D^{TSN}	set of time-space network demand nodes
S^{TSN}	set of time-space network shelter sites
V	set of vehicles movement and waiting arcs
E	set of evacuee movement arcs

W	set of evacuee waiting arcs
$DOut_i$,	set of vehicles and evacuee movement arcs getting out time-space network demand node i
DIn_i	set of vehicles and evacuee movement arcs getting in time-space network demand node i
$DWOut_i$	set of evacuee waiting arcs getting out time-space network demand node i
$DWIn_i$	set of evacuee waiting arcs getting in time-space network demand node i
$SOut_i$	set of vehicles movement arcs getting out time-space network shelter site i
SIn_i	set of vehicles movement arcs getting in time-space network shelter site i
$SWOut_i$	set of vehicles waiting arcs getting out time-space network shelter site i
$SWIn_i$,	set of vehicles waiting arcs getting in time-space network shelter site i
$YOut_i$	set of vehicles movement arcs getting out time-space network yard node i
YIn_i	set of vehicles movement arcs getting in time-space network yard node i
$YWOut_i$	set of vehicles waiting arcs getting out time-space network yard node i
$YWIn_y$	set of vehicles waiting arcs getting in time-space network yard node i
K	set of type of vehicles

Parameters:

H_i	demand at time-space network demand node i
B_{ik}	number of vehicles of type k added to the time-space network at yard node i
Q_k	capacity of vehicle type k
$Time_m$	time spent by vehicles and evacuees when moving or waiting at arc m

Decision variables:

y_{mk} flow of vehicles of type k traveling in arc m belonging to set of vehicles movement and waiting arcs V

x_m flow of evacuees in arc m belonging to the set of evacuee moving arcs E

w_m flow of evacuee waiting at arc m belonging to the set of evacuee waiting arcs W

The multi-period vehicle evacuation problem can be formulated as follows:

$$\min C = \sum_{m \in E} x_m \cdot Time_m + \sum_{m \in W} w_m \cdot Time_m \,, \tag{4.1}$$

subject to

$$x_m \le \sum_{k \in K} Q_k \cdot y_{mk} \,, \forall\, m \in E \,, \tag{4.2}$$

$$\sum_{m \in DWOut_i} w_m + \sum_{m \in DOut_i} x_m - \sum_{m \in DWIn_i} w_m - \sum_{m \in DIn_i} x_m = H_i \,, \forall\, i \in D^{TSN} \,, \tag{4.3}$$

$$\sum_{m \in DOut_i} y_{mk} - \sum_{m \in DIn_i} y_{mk} = 0, \forall\, i \in D^{TSN} \,, k \in K \,, \tag{4.4}$$

$$\sum_{m \in SOut_i} y_{mk} + \sum_{m \in SWOut_i} y_{mk} - \sum_{m \in SIn_i} y_{mk} - \sum_{m \in SWIn_i} y_{mk} = 0, \forall\, i \in S^{TSN} \,, k \in K \,, \tag{4.5}$$

$$\sum_{m \in YOut_i} y_{mk} + \sum_{m \in YWOut_i} y_{mk} - \sum_{m \in YIn_i} y_{mk} - \sum_{m \in YWIn_i} y_{mk} = B_{ik} \,, \forall\, i \in Y^{TSN} \,, k \in K \,, \tag{4.6}$$

$$y_{mk,} \in Z^+ , \forall\, m \in V, k \in K \,, \tag{4.7}$$

$$x_m \in \Re^+ , \forall\, m \in E \,, \tag{4.8}$$

$$w_m \in \Re^+ , \forall\, m \in W \,, \tag{4.9}$$

The objective function (4.1) minimizes the total evacuee traveling and waiting time. Constraints (4.2) ensure that vehicles capacity is not exceeded at any vehicle movement arc. Constraints (4.3) state the flow conservation for evacuees at each demand node. Constraints (4.4) - (4.6) are the flow conservation constraints for vehicles at demand nodes [(4.4)], shelter sites [(4.5)], and yard nodes [(4.6)]. Finally, constraints (4.7) - (4.9) represent the continuous restrictions on the decision variables. Variable decisions x and w represent the flow of evacuees and thereby they represent integer values. However solving a discrete problem is harder than solving a continuous problem due to the large increase of possible combinations. For this reason, these variables are considered continuous variables instead of integer.

4.3.4. Solution Methodology

Model (4.1) - (4.9) is a mixed-integer programming model that general-purpose optimization solver packages can solve. However, optimally solving realistic size problems may take several hours of computing time. Since the main goal is to assist civil protection authorities during a flood emergency evacuation, time is crucial and a fast solution is essential. Thus, we decided to adopt a rolling horizon approach to solve the multi-period vehicle evacuation problem. The rolling horizon approach had been applied to solve the multi-period problem in many different fields, as mentioned in Glomb et al. (2021). This technique divides the planning horizon into several time windows solved sequentially. Each time window is a smaller problem that can be solved much faster, computing solutions in a short computing time. More importantly, a solution for the initial time windows can be computed in a matter of seconds. This way, if needed, the civil protection authorities can immediately start implementing the emergency plan while the solutions for later time windows are still being computed.

The application of the rolling horizon approach is explained in Figure 4.2. The multi-period vehicle evacuation problem is initially solved for a smaller time window (*Time Window 1*), obtaining an optimal solution to solve the problem only related to decisions in this first time window. Part of this solution is then considered (shaded part of Figure 4.2-*B*) when solving the multi-period vehicle evacuation problem for the following time window (*Time Window 2*). This procedure is repeated until a solution is obtained for the planning horizon.

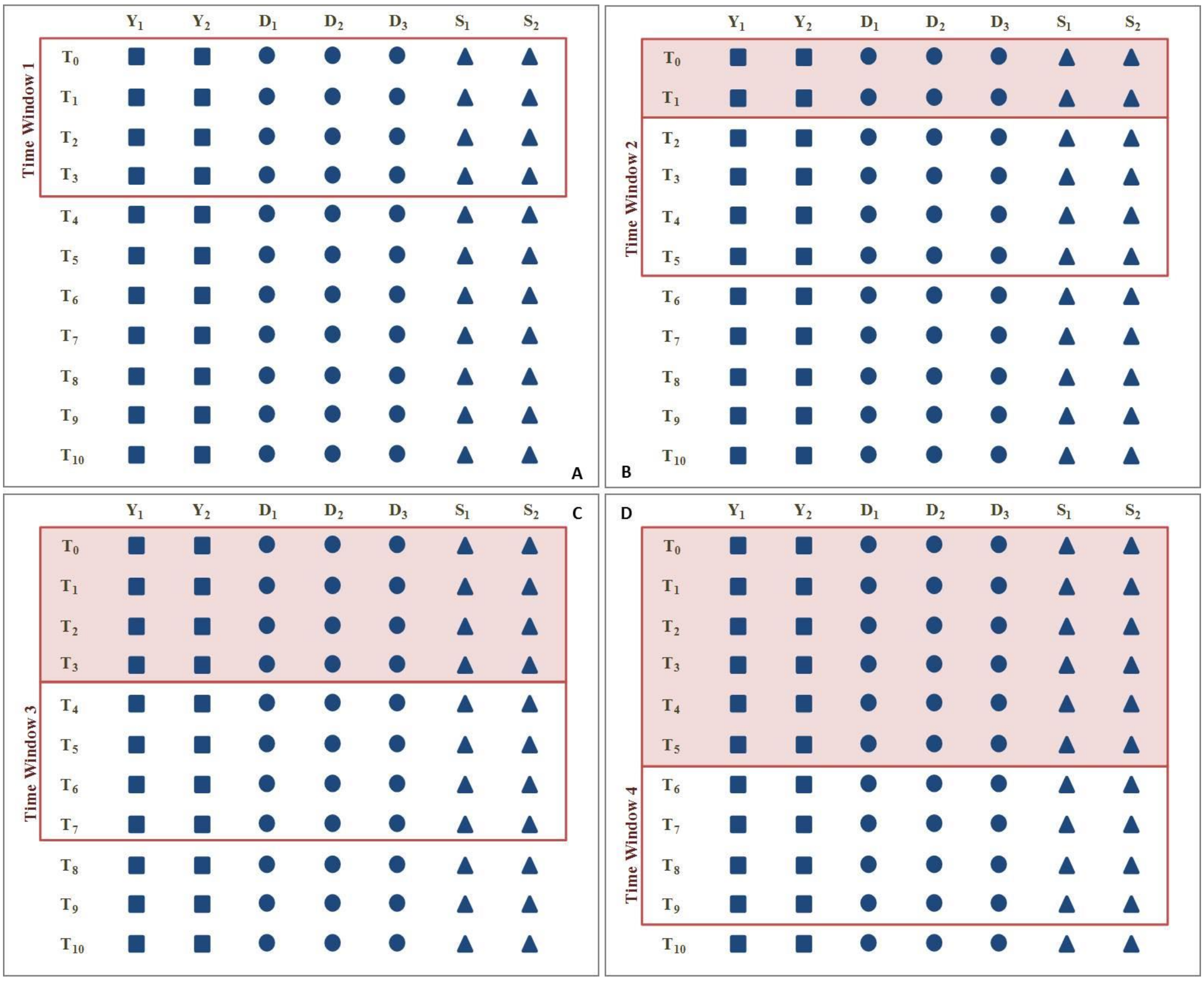


Figure 4.2 – Rolling horizon approach applied to a time-space network (sequence of time windows: A, B, C, and D).

4.4. Case Study

In this section, we use a real world-based case study to demonstrate the applicability of the modeling approach proposed.

The case study is located in the Wake County in the US state of North Carolina, introduced and also used in Chapter 3. The North Carolina State University Libraries provided the flood plain map and geo-information. The evolution of the flood was simulated based on the flood map and the orography of the region.

As of the 2010 census, this county's population is 900,993 inhabitants. The region was divided into 59 demand areas, which represent the zones affected by the flood. The demand at each area represents the population that is affected by the flood. The total population affected by the flood was estimated to be 300,975 inhabitants (around one-third of the county's total population). Figure 4.3 displays the region under study, the affected areas, the population per affected area, and the locations of yards and shelters.

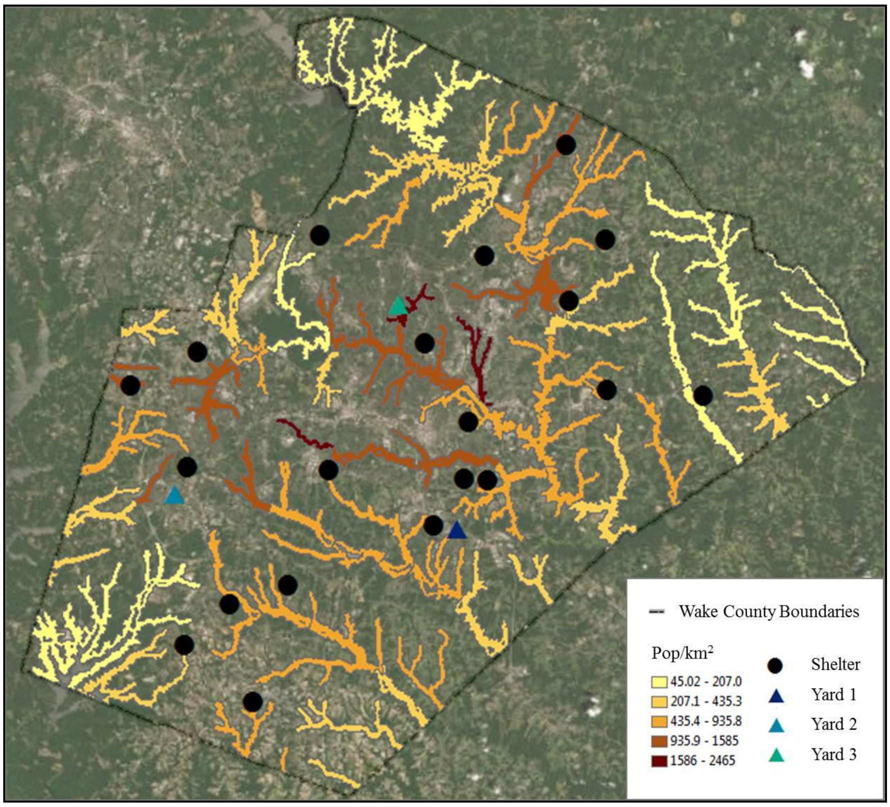


Figure 4.3 – Wake County boundaries, affected areas, population per area and yard and shelter locations.

In practice, it is known that only a small percentage of the population affected by a flood seeks refuge in a shelter. In contrast, the remaining affected population evacuates to different destinations outside the affected areas. Li et al. (2012) consider that, for a hurricane scenario, only 8–16 % of the evacuation demand looks for a shelter. Therefore, in this study, we also assumed that 9 % of the total affected population looks for assistance in shelters, resulting in 27,062 evacuees. Regarding the mode of transportation to reach a shelter, Renne (2018) asserts that 20-30 % of households are carless. Therefore, for this case study, 30 % of the population evacuating to a shelter seeks help to reach the shelter and it was assumed that approximately 50 % of these evacuates with assistance from the civil protection authorities, which resulted in overall demand of 4,170 evacuees. These percentages can be adjusted to each specific case, considering the socio-demographics of the region and the civil protection knowledge about the demand expected.

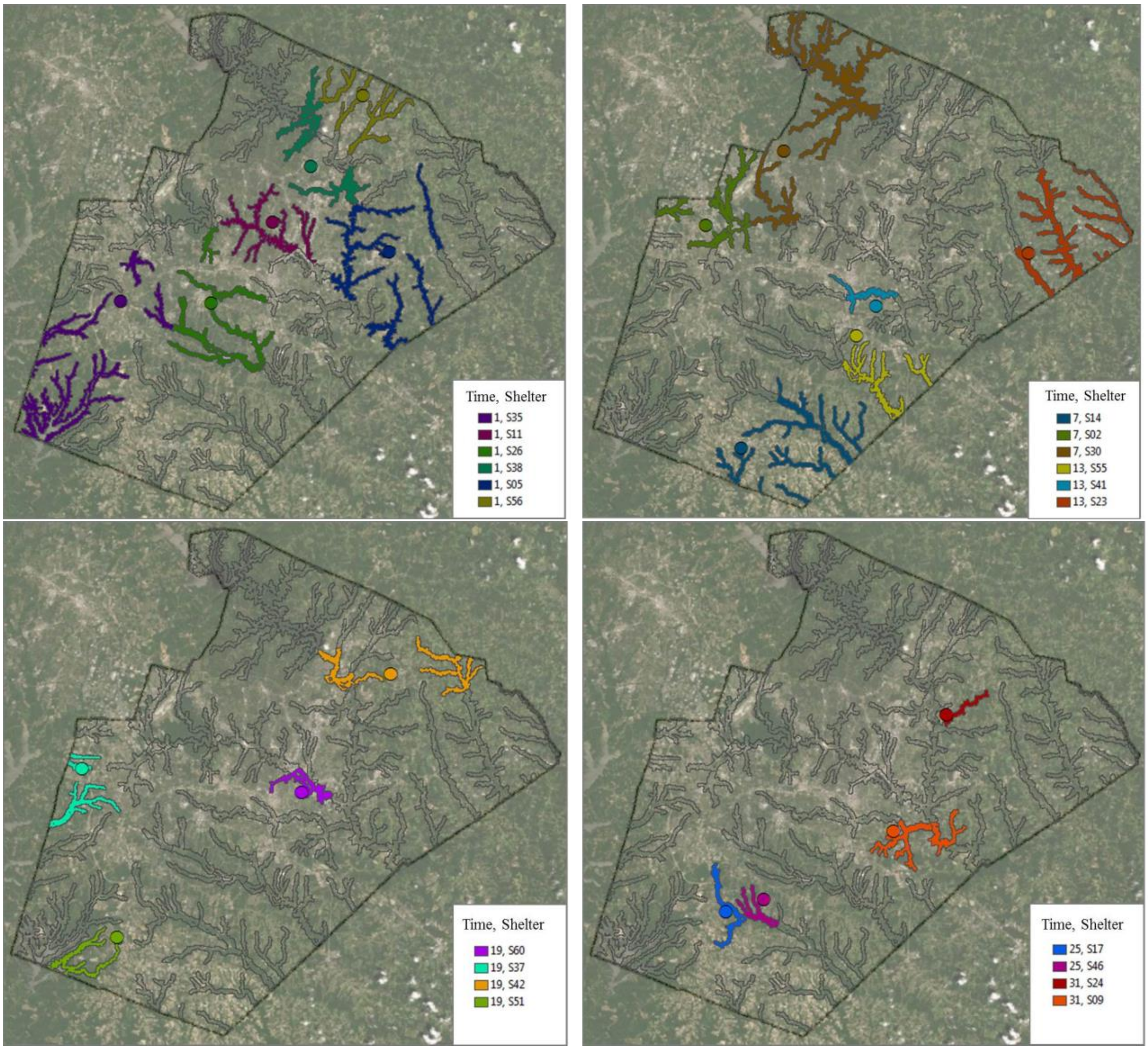


Figure 4.4 – Opening time of each shelter, period of time when evacuees receive the evacuation order and the selected shelter.

To solve the vehicle evacuation problem, it was assumed that the location and opening times of shelters, the moment when evacuation orders are issued for each demand area and the corresponding allocation of these areas to shelters was pre-computed following the methodology proposed in Gama et al. (2016) (see Chapter 3). Hence, the solution shown in Figure 4.4 was considered for this case study. In total, 59 demand areas and 20 shelters were considered. We considered a planning horizon of 4.5 hours and simulated the evolution of the flood by dividing the planning horizon into fifty-four time periods, each with a fixed length of 5 minutes. Time Period 1 presented the highest number of evacuation orders issued (26) while in Time Period 7, fourteen evacuation orders were issued. Time Period 13 presented nine evacuation orders issued while in Time Period 19, six evacuation orders were issued. Time Periods 25 and 31 presented the same number of evacuation orders issues (2).

The evacuation process was assumed to follow an eighteen time period S-shaped curve, represented in Figure 4.5. It was assumed that the first evacuees start their evacuation two periods after an evacuation order is issued, representing the time they need to be prepared for an evacuation following the order received. Following the S-shaped curve, the first 15 % of the population is evacuated in the following three time periods. Another six time periods later, 75 % of the population is evacuated. The remaining 10 % of the population evacuates in the final six time periods.

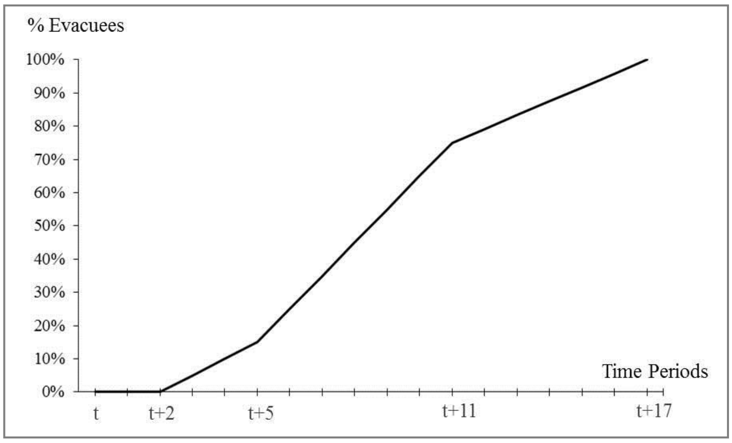


Figure 4.5 – Eighteen-segment S-shaped curve representing the percentage of people evacuating in eighteen time periods after receiving an evacuation order at time t [based on Sherali et al. (1991)].

According to the evacuation order issuing, at time periods 7 to 12 a higher number of evacuees is ready to evacuate (Table 4.2), corresponding to 75 % of demand receiving an evacuation order at Time Period 1 and 15 % of demand receiving an evacuation order at Time Period 7.

Table 4.2 – Number of evacuees ready to evacuate per each time period intervals.

Time Periods							
1 – 6	7 - 12	13 – 18	19 – 24	25 – 30	31 - 36	37 – 42	43 - 48
330	1,716	912	450	420	192	132	18

For this case study, it was assumed that some roads were already flooded in the first time period. The flood propagation results in an increase of water levels in the first 4 hours of the planning horizon and in a decrease of water levels in the last 0.5 hour of the planning horizon. Due to the orography and the land use, some areas, at some moment of the planning horizon, experience water levels higher than 0.5 meter, preventing the use of the road network. The water depths directly impact the maximum speed on the road network. Therefore, it was necessary to determine the maximum speed on each arc of the road network for each time period based on the water level. The maximum speeds were defined based on Nayak & Zlatanova (2008) and in a similar way to Gama et al. (2016) (see Chapter 3). Considering the maximum speed of each arc of the road network and its length, it was possible to determine each arc's traveling time and time period. The shortest paths, in terms of time, between demand nodes and shelter site or yard nodes were then computed for the fifty-four time periods using Network Analyst, an ArcGIS extension.

Regarding the available evacuation vehicles, we considered that these would be located at three yards across the Wake County (Figure 4.3). In total, it was assumed that 45 vehicles would become available between the initial time period and Time Period 13, fifteen per yard. In the first time period, each yard had five available vehicles for the rest of the planning horizon. At Time Period 7, another five vehicles per yard were considered, and the remaining five vehicles per yard became available at Time Period 13. It was assumed that each vehicle could carry a maximum of 84 passengers (seated or standing).

The time-space network created for the problem described above comprised a total of 3,109 nodes, 34,684 movement arcs, and 3,027 waiting arcs.

4.4.1. Analysis, Results and Discussion

The solution for this case study was obtained by applying the rolling horizon approach for the time windows described in Table 4.3. The time interval with a fixed solution, i.e., an optimal solution determined in previous time windows, and the computing times for solving the multi-period vehicle evacuation model are also presented. For each time window, the (4.1) - (4.9) model was implemented using FICO Xpress Mosel modeling language and solved with the optimization solver FICO Xpress 8.5 on an Intel Core i7-2670QM CPU 2.50GHz PC running Windows 7 64-bits. The time windows do not present the same amount of time periods. This happens to make sure that the consequences of the propagation of the flood, such as demand nodes that are flooded and evacuation cannot be carried on, are taken into account.

Table 4.3 – Rolling Horizon time windows and computing times.

Time Window	Time Interval with a fixed solution	Computing Times (s)
1 - 13	-	13.1
8 - 19	1 - 7	293.7
14 - 25	1 - 13	134.5
20 - 37	1 - 19	252
26 - 43	1 - 25	1.5
32 - 49	1 - 31	0.6
38 - 54	1 - 37	0.3

The optimization of this problem resulted in an objective function value of 66,630 minutes. This represents the total evacuation time over the planning horizon, including the total traveling time between demand nodes and shelters (41,240 minutes) and the total waiting time (25,390 minutes). The first evacuations took place at Time Period 4 where twenty two evacuees are picked up and the last evacuations occurred at Time Period 48 with three evacuees arriving at the respective shelters in the next time period. The average evacuation time, i.e., the time between evacuees are picked up and arriving at the respective shelter was 9.9 minutes – the minimum evacuation time was 5 minutes and the maximum evacuation time was 30 minutes – and the average vehicle capacity was 13.3 evacuees – the minimum capacity was 1 evacuee and the maximum capacity was 66 evacuees. Regarding demand nodes, the average demand evacuation time, i.e., the time between a demand node can start evacuating and evacuation of the last evacuees, was 80.5 minutes – the minimum demand evacuation time was 70 minutes and the maximum evacuation time was 145 minutes.

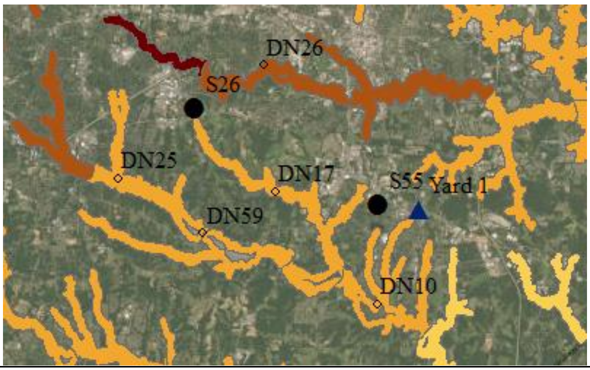
The 45 vehicles considered were all used in the evacuation process. However, as shown in Table 4.4, not all vehicles left the yards immediately. From the five vehicles available at yard 1 at Time Period 1, three left the yard at Time Period 1 while two waited at the yard until Time Period 2 and Time Period 4. At Time Period 7, five more vehicles were available at each yard and, as observed, most of all left the yards in that time period with exception of one vehicle that waited at yard 2. It is important to recall that in time periods 7 to 12, 41 % of the total demand was ready to evacuate since this time interval includes 75 % of evacuees that received an evacuation order at Time Period 1 and 15 % of evacuees that received the evacuation order at Time Period 7.

Table 4.4 – Number of vehicles available (I), waiting (W), and leaving (O) each yard at each time period.

Time Period	Yard 1			Yard 2			Yard 3		
	I	W	O	I	W	O	I	W	O
1	5	2	3	5	1	4	5	3	2
2	2	1	1	1		1	3	2	1
3	1	1					2		2
4	1		1						
5									
6									
7	5		5	5	1	4	5		5
8				1		1			
9 - 12									
13	5	4	1	5		5	5	1	4
14	4	2	2				1		1
15	2	1	1						
16	1		1						
17 - 54									

As an example of a route and schedule of the vehicles, we present in Table 4.5 the sequence of nodes followed by a vehicle available at Yard 1 at Time Period 1. Although it was available since the beginning of the planning horizon, this vehicle only left the yard at Time Period 4. As defined before (see subchapter 4.3) the evacuation vehicles cannot wait at demand nodes. Five different demand nodes were visited by this vehicle which revisited two of the demand nodes (DN59 and DN26) and also visited two different shelters. This vehicle was operational for 160 minutes whereas the total evacuation time was 70 minutes.

Table 4.5 – Vehicle route and schedule.



Departure Time Period	Departure Node	Arrival Node	Arrival Time Period	# evacuees
1	Yard1	Yard1	2	-
2	Yard1	Yard1	3	-
3	Yard1	Yard1	4	-
4	Yard1	DN59	7	-
7	DN59	DN17	8	12
8	DN17	S26	10	36
10	S26	DN25	12	-
12	DN25	S26	14	44
14	S26	DN26	16	-
16	DN26	S26	18	4
18	S26	DN59	20	-
20	DN59	S26	22	5
22	S26	DN26	24	-
24	DN26	S26	26	2
26	S26	DN10	30	-
30	DN10	S55	33	6
33	S55	S55	34	-
34	S55	S55	35	-
		(…)		
53	S55	S55	54	-

Figure 4.6 represents the number of evacuees ready to evacuate (blue), according with the S-shaped curve and designated as evacuees arriving, the number of evacuees waiting at the demand node (red), and the number of evacuees that leave the demand node (green) for each time period for demand node 17 (DN17) and demand node 10 (DN10). DN17 had a total of 78 evacuees and received an evacuation order at Time Period 1. Evacuees were ready to evacuate at Time Period 4 and the pattern of evacuation is shown by the blue line. DN17 was visited five times by evacuation vehicles (see the green bars). The waiting time for evacuees was, on weighted average, 6.6 minutes. DN10 had a total of 108 evacuees and received an evacuation order at Time Period 13. Evacuees were ready to evacuate at Time Period 16 and the pattern of evacuation is shown by the blue line. This demand node was visited seven times (see the green bars). The waiting time for evacuees was, on weighted average, 2.3 minutes.

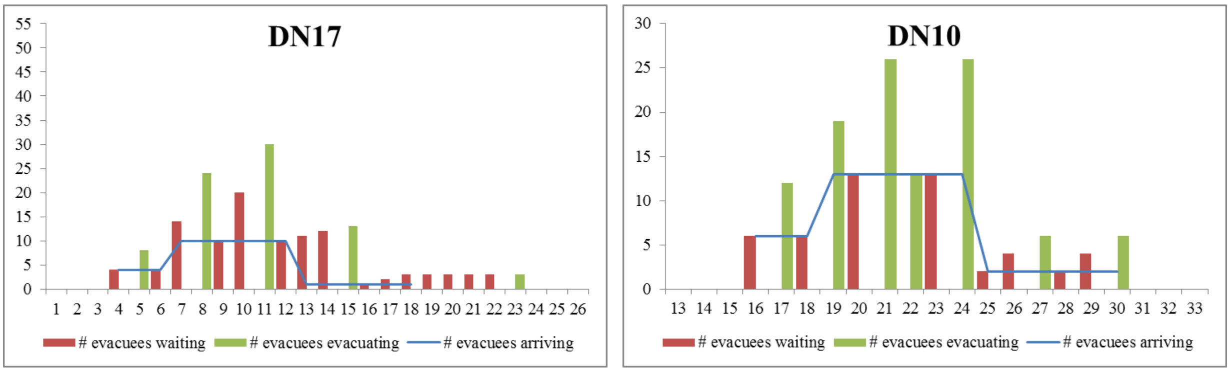


Figure 4.6 – Number of evacuees ready to evacuate, waiting, and evacuating at each time period for Demand Node 17 (DN17) and Demand Node 10 (DN10).

4.4.2. Sensitivity Analysis

Regarding the available evacuation vehicles, it was considered two different types of vehicles: type 1 with a maximum capacity of 84 passengers (seated or standing) and type 2 with a maximum capacity of 21 passengers (seated or standing). The yards location, the total number of vehicles and the availability remained the same, but each yard present two vehicles of type 1 and three vehicles of type 2.

The rolling horizon approach applied to the previous problem was also considered to solve this problem. The increase of complexity of the problem was verified in the increase of the computing times as shown in Table 4.6. The total evacuation time over the planning horizon increased approximately 6 %, to a total of 70,710 minutes, which includes the total traveling time between demand nodes and shelters (41,885 minutes) and the total waiting time (28,825 minutes).

Table 4.6 – Rolling Horizon time windows and computing times for the problem with two types of vehicles.

Time Window	Time Interval with a fixed solution	Computing Times (s)
1 - 13	-	89.5
8 - 19	1 - 7	249.1
14 - 25	1 - 13	115.6
20 - 37	1 - 19	491.9
26 - 43	1 - 25	4.6
32 - 49	1 - 31	0.8
38 - 54	1 - 37	0.4

The first and last evacuations occurred in the same time periods as in the previous problem, but twenty five evacuees were evacuated in Time Period 4 and three evacuees were evacuated in Time Period 48. The average evacuation time, i.e., the time between evacuees are picked up and arriving at the respective shelter was 9.9 minutes – the minimum evacuation time was 5 minutes and the maximum evacuation time was 35 minutes – and the average vehicle capacity was 13.5 evacuees – the minimum capacity was 1 evacuee and the maximum capacity was 78 evacuees. Regarding the demand nodes, the average demand evacuation time, i.e., the time between a demand node can start evacuating and evacuation of the last evacuees, was 76.6 minutes – the minimum demand evacuation time was 70 minutes and the maximum evacuation time was 130 minutes.

The 45 vehicles were all used in the evacuation process and, when compared with the previous problem, the vehicles left earlier the yards as observed in Table 4.7. As expected, almost all available vehicles at Time Period 7 left the yards in that period of time and the same happened in Time Period 13.

Table 4.7 – Number of vehicles of type 1 and 2 available (I), waiting (W), and leaving (O) each yard at each time period.

Time Period	Type 1									Type 2								
	Yard 1			Yard 2			Yard 3			Yard 1			Yard 2			Yard 3		
	I	W	O	I	W	O	I	W	O	I	W	O	I	W	O	I	W	O
1	2		2	2	1	1	2	2		3		3	3	2	1	3	1	2
2				1		1	2	1	1				2	1	1	1		1
3							1		1				1		1			
4 - 6																		
7	2		2	2		2	2		2	3		3	3	1	2	3		3
8													1		1			
9 - 12																		
13	2	1	1	2		2	2		2	3	1	2	3		3	3		3
14	1	1								1	1							
15	1		1							1		1						
16 - 54																		

Regarding the demand node analysis, DN17 was visited four times (see green bars). Although the evacuation time of this demand node had decreased – last evacuees evacuated at Time Period 18 instead of Time Period 23 – the weighted average waiting time for evacuees increased to 9 minutes. This happened because not only the demand node was visited less often, when compared with the previous solution, but also some vehicles had a lower capacity. Let us have a look to Time Period 14: in this time period, twenty two evacuees were ready to evacuate however only twenty one (the maximum capacity of type 2 vehicles) were evacuated. The last evacuee ready to evacuate was only evacuated at Time Period 18. Similar to the previous solution DN10 was visited seven times (see green bars) and the weighted average waiting time for evacuees slightly increased to 2.6 minutes.

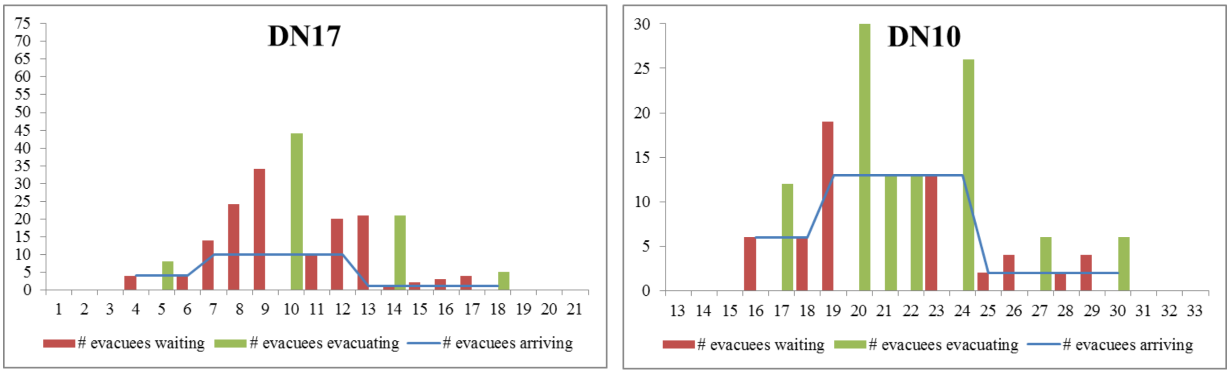


Figure 4.7 – Number of evacuees ready to evacuate, waiting, and evacuating at each time period for Demand Node 17 (DN17) and Demand Node 10 (DN10) for the problem with two types of vehicles.

4.5. Conclusions

This chapter presents a multi-period vehicle evacuation model for optimizing the operations by civil protection authorities during a flood evacuation.

Floods are dynamic events that evolve over time and affect different areas at different times. Thus, time is a crucial component when dealing with such events and needs to be incorporated in optimization models for more realistic modeling. Our model captures the dynamics aspects associated with floods, such as traveling times varying over time, increasing availability of civil protection authorities' resources over time, and simulating the behavior of evacuees after receiving an evacuation order. The model aims at managing civil protection authorities' resources by minimizing the traveling and waiting time of evacuees during the evacuation process. The model defines for each emergency vehicle which and when demand nodes and shelter sites are visited. Along with the optimization model, a time-space network is proposed and, to solve the problem, a rolling horizon approach is adopted.

A real world-based case study is used to illustrate the applicability of our model. The adopted optimization technique demonstrated that not only the flood evacuation problem can be solved in a reasonable amount of time but also the initial solutions allow civil protection authorities to start preparing the evacuation process while the problem is solved for later time periods. The model solution gives more information than the vehicles routing and scheduling. For instance, it is possible to analyze the variation over time of evacuees arriving, waiting and evacuating from each demand node. It is also possible to analyze the vehicles arriving, waiting and departing from each yard or shelter and understand other needs that these sites may require during the flood evacuation.

Although the results for the case study have shown the suitability of the proposed methodology to solve the multi-period vehicle evacuation problem, several steps can be considered to improve the applicability of this work. In this work we assume a sequential decision of the evacuation problem, i.e., shelter location are determined in advance and routing decisions are defined later, but routing decision integrated with location decision could provide better results. An integrated approach can be challenging in terms of computing times, which may not be compatible with an emergency problem, and therefore it will be necessary to improve the problem formulation and the solution methodology.

5. FLOOD EMERGENCY LOGISTICS MANAGEMENT: BAIXO MONDEGO CASE STUDY

5.1. Introduction

Floods are the most frequent type of natural disasters and affect the largest number of people (Wallemacq, 2018). Europe, as well as other continents, has been experiencing more frequent and severe flooding over the last years. The impacts are huge - lives, properties, and economic losses, infrastructures damages, and also environmental consequences – as seen in Western Europe in the summer of 2021. Accordingly to the World Resource Institute (Kuzma & Luo, 2020), the number of people affected by river flooding is expecting to double worldwide by 2030.

Reducing the negative flood consequences has been a concern for Europe and the Directive 2007/60/EC of the European Council and European Parliament of 23 October (2007) guides the Member States on the assessment and management of flood risks. The flood risk management plans focus on prevention, protection, preparedness, and recovery and learning and include: i) flood risk assessment results; ii) specific solutions to avoid floods, to predict floods, and to protect people and goods. In addition, the response operations, planning, and management during flood disasters are, in most countries, borne by civil protection authorities.

Civil protection authorities develop flood emergency plans that comprise the identification of all entities involved and the lines of action for each entity, as well as the definition of the management disaster structure. Apart from the complex hierarchy for the entities involved in the flood emergency disaster, these emergency plans also comprise lines of action for different and complex areas of intervention. For instance, the flood emergency plans guide on how to mobilize, request, and use means and resources necessary during the flood disaster; on how to guarantee the communication between all the entities involved in the disaster and the communication with the population; on how to provide full assistance to the evacuated population, to the non-evacuated population, and to all the entities involved in the emergency disaster; on how to maintain the public order; and on how to coordinate medical services and casualty transportation. Regarding the evacuation process, the flood emergency plans comprise the identification of the affected population, the possible shelter locations, and the roads to be used for the evacuation. Although these identifications are based on different flood scenarios, the evacuation decisions are only made when facing a real flood disaster. For instance, the evacuation of affected population is proposed by one of the entities responsible for the response and it is based on the experience of this entity. Then the proposed evacuation is validated by another entity involved in the disaster. Therefore the emergency procedures during a real flood situation are hierarchic and complex. Consequently, decisions are left for real judgements based on long time experience, previous emergency studies, and a set of standard procedures, resulting in reasonably effective flood disaster response, but with low efficiency and high costs (Simonovic, 2011).

In order to help civil protection authorities facing flood emergencies, a planning framework is presented. The aim is to support the decision to who execute the flood emergency plan as well as to bring resilience to the flood emergency plans. The planning framework comprises four stages: i) in the first stage, all necessary data – flood map, flood evolution, water level on the road network, affected areas and respective affected population, location of candidate shelter and yards where emergency vehicles are parked, traveling times between affected areas and shelter, etc. – are collected and structured; ii) in stage 2, a multi-period shelter location-allocation model with evacuation orders is applied. Taking into consideration the evolution of the flood, the model minimizes the traveling times between the affected areas and shelters while determining the location of a fixed number of shelters which become available in different time periods, the issuing time of evacuation orders for each demand area, and the allocation of each demand area to a shelter. After this stage, civil protection authorities can have an overview, not only of the disaster impact, but also on the response operation; iii) in stage 3, the solution obtained in the previous stage is the basis for designing the private car evacuation routes between each demand area and the allocated shelter and in line with the respective evacuation order issuing. Private car evacuation for non-shelter evacuees can also be simulated. The outcome can alert civil protection authorities to problematic zones in terms of congestion and, consequently, competent entities can be allocated to those zones to control and ensure the security of all evacuees; iv) in the last stage, the evacuation process of those who rely on emergency vehicles to reach a shelter is defined. A multi-period vehicle evacuation model is applied. The model aims at optimizing the evacuation and waiting time of evacuees while determining the emergency vehicles routes and schedules.

The proposed planning framework is able to cope with some of the practical challenges which characterize flood emergency logistics operations. Floods are predictable natural disasters, i.e., it is possible to know in advance when a flood will occur – approximately three to four days in advance according to Nadeem et al. (2020). Knowing this and using appropriate flood models, it is possible to predict the flood propagation (Melo et al., 2015). Since a flood evolves in space and time, its impacts are not felt simultaneously. The impacts can relate to road conditions and evacuation demand changing over time. Therefore, evacuation orders should also be issued over time. Evacuation orders do not prevent the flooding, but if issued at the proper time, may be essential to save lives. Therefore, the time component is essential when modeling a flood emergency and the flood planning framework includes it by considering that traveling times vary over time and evacuation order are issued at different times. Other challenge is the reaction to an evacuation order which is known for not being immediately. In fact, it follows a standard pattern, such as an S-shaped curve, as proposed in many time studies in the literature (Sherali et al., 1991; Rawls & Turnquist, 2012; Murray-Tuite & Wolshon, 2013; Li et al., 2013). Moreover, civil protection authorities have at disposable different resources that can be used during a flood emergency: public facilities, such as schools, day care centers, or sports halls can be used as potential shelters; emergency vehicles from different entities, such as fire departments or security forces, can be used to give support to those in need. However, shelters need to be equipped with support and medical staff as well as essential goods and supplies, and vehicles need drivers to be operational. Although authorities have resources at its disposable, they may not be immediately available. Other challenge faced during a flood emergency is an effective evacuation operation which can be achieved with the support of security forces which are essential to ensure public order and security. The flood planning framework takes this into account by evaluating the consequences of the evacuation process on the road network and assigning the security forces to the problematic areas.

The organization of the chapter is as follows. Subchapter 5.2 presents an overview on flood emergency operations works in the literature. In subchapter 5.3 the flood planning framework is presented and is applied to a real world-based case study in subchapter 5.4. In conclusion, subchapter 5.5 presents some final remarks on the work developed and on the future work.

5.2. Flood Evacuation Literature Overview

Flood disaster management comprises four sequential stages: 1) mitigation (before the disaster); 2) preparedness (to early signals); 3) response (during the disaster); and 4) recovery (after the disaster). The main goal of flood disaster management is to decrease human, physical, and economic losses, to reduce personal suffering, and to recover quickly (Rawls & Turnquist, 2012). To achieve this goal, several (structural and non-structural) measures are defined and implemented at each stage. Flood evacuation is one of the crucial measures to minimize flood disaster consequences, such as live losses and property damages (Na et al., 2012), during the response stage of the flood disaster management. Although it may be simply defined as the movement of people from the inundation area to a shelter outside the affected area, evacuation is a challenging process (Stepanov & Smith, 2009). Shelter location and availability, road network conditions, evacuation order issuing, evacuee behavior, evacuee transportation mode, and route assignment play a major role when planning for flood evacuation (Gama et al., 2016; Bennett et al., 2017; Yusoff et al., 2019; Samany et al., 2021).

According to Esposito Amideo et al. (2019), shelter location and evacuation routing are fundamental operations in the planning of the evacuation. The challenge is to consider both problems simultaneously, with focus on bus-based evacuation, and to incorporate the dynamic perspective of the disaster management (Bayram, 2016; Esposito Amideo et al., 2019).

Regarding flood evacuation, Sherali et al. (1991) presented the first location-allocation model under flood (or hurricane) conditions that optimally determines both shelter locations and evacuation routes for automobiles. The model considers that shelters have a limited capacity and that evacuees dissipate at a constant rate over time. Assuming that evacuees decide which shelter to evacuate and by which route, Kongsomsaksakul et al. (2005) proposed a bi-level location-allocation model. In the upper-level problem, the shelters are selected for the minimum evacuation time and it considers shelter and link capacities. The lower-level problem is a combined distribution and assignment problem which models evacuee route and destinations choices. Taking into account flood propagation, Yang et al. (2015) developed a flood evacuation planning algorithm which determines where to evacuate and defines the routes to take within the shortest distance. Including other dynamic aspects than the flood propagation, Gama et al. (2016) presented a multi-period location-allocation model. The model decides where and when to open a predefined number of shelters, when to issue evacuation orders, and how to assign evacuees to shelters over time while minimizing the overall evacuation time. The multi-period problem considers that travel times vary over time as a consequence of different water depths on the road network, shelters have a limited capacity and are not available at the same time, and evacuees reaction to the flood is also dynamic. More recently, Nadeem et al. (2020) considered the time between the flood forecast and the moment the flood starts to evacuate the utmost number of inhabitants from flood-prone to safer zones, using public buses. The evacuation planning framework comprises a set cover problem which determines the bus stops acting like pick up points and their assignment to shelters; a vehicle routing problem, solved heuristically, to determine the routes patterns; and a frequency setting problem which determines the dispatch sequence. In order to help decision-makers analysis and decisions, a simulation model is also developed.

Flood dynamics, in terms of propagation of the flood, have been considered in other aspects of the evacuation planning, such as walking evacuation route design (Lee et al., 2020; Park et al., 2020) and location of safe areas (Samany et al., 2021).

Considering the flood field within the literature, none of the previous studies combine resources management, such as shelter location and emergency vehicles evacuation routes and schedules, security forces management and flood dynamics such as flood propagation, availability of resources and evacuee behavior. Thus, we present a flood planning framework that considers the model developed by Gama et al. (2016) to determine shelters location and opening times, to issue evacuation orders, and to assign evacuees to shelters. These operation decisions are complemented with a congestion analysis and a multi-period emergency vehicle evacuation model using a time-space network which allocates a fleet of vehicles made available to civil protection authorities to evacuate the population between the affected area and the shelter.

5.3. Flood Planning Framework Description

This section presents a planning framework for a flood emergency problem. As represented in Figure 5.1, this planning framework comprises four stages: i) input data; ii) shelter location-allocation and evacuation orders issuing; iii) private car-based evacuation; iv) emergency vehicle-based evacuation. Each stage is described in detail below.

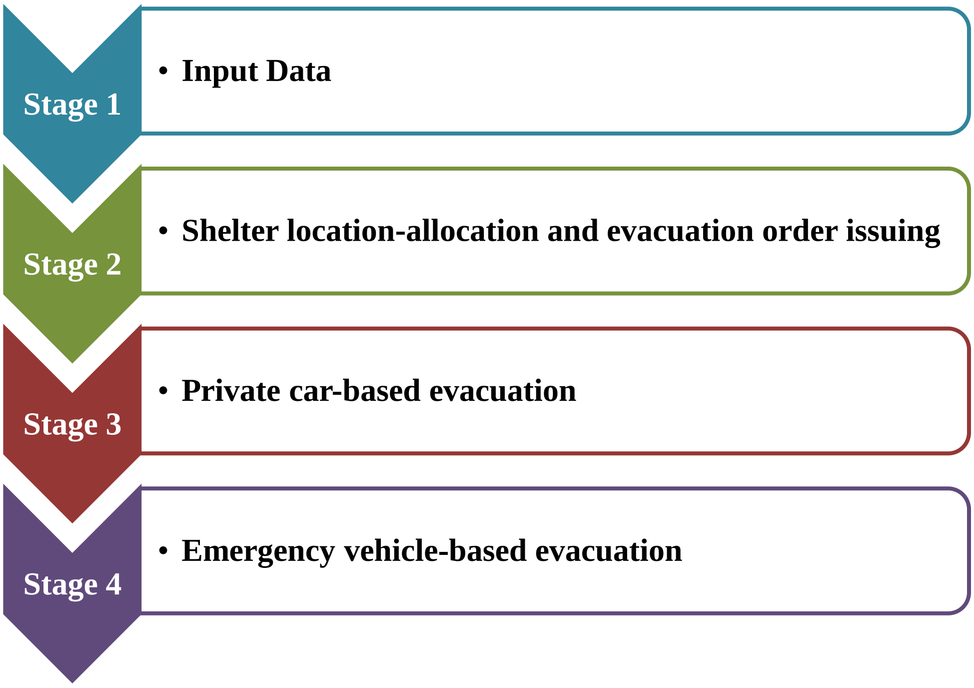


Figure 5.1 – Flood planning framework overview.

The main assumptions of our flood emergency problem are as follow:

1. The flood propagation is known in advance based on a flood model, i.e., the level of water on the road network is known and may change over time.
2. Therefore, road conditions and, hence, traveling times are time dependent.
3. Only a small percentage of the population affected by a flood evacuates to shelters (shelter evacuees) while the remaining affected population evacuates to relatives' or friends' houses or hotels (non-shelter evacuees).
4. Shelter evacuees from the same demand area are evacuated to the same shelter and some use their private vehicles, such as cars, to evacuate to a shelter while others only reach a shelter if using transport services provided by authorities.
5. Non-shelter evacuees evacuate using their own vehicles.
6. Both evacuees (shelter and non-shelter), after receiving an evacuation order, evacuate according to a pattern that is described by an S-shaped curve and based on Sherali et al. (1991) work: the initial reaction to the evacuation order is slow, but in the following time periods the percentage of evacuees gradually increases. At the end of the evacuation process and with few evacuees left, the percentage of evacuees decreases.
7. Resources, such as shelters and vehicles, become available in different time periods, with only a few of them available at the onset of the flood.
8. Shelter and vehicles have a limited capacity.

5.3.1. Input Data

The input data stage comprises the propagation of the flood, the road network, the demographic data, and the available resources by the authorities as shown in Figure 5.2. The flood propagation can be known in advance with the use of appropriate flood models which predict the extent and time evolution for different rainfall scenarios (Melo et al., 2015). The road network gives the information about the road type, the maximum speed, the length and consequently the traveling time of each arc of the network. The demographic data includes the total population, the percentage of population evacuating to a shelter, the percentage of shelter evacuees that use private vehicles and need help to reach a shelter, and the behavior of the population when facing a flood. The available resources comprise the infrastructures that can serve as shelters (e.g., schools, sport halls) and the staff and equipment needed in each shelter, the capacity of each shelter, the vehicles (e.g., buses, jeeps) that can be used in a flood emergency, the capacity of each vehicle, the yards where vehicles are located, and the availability of these resources.

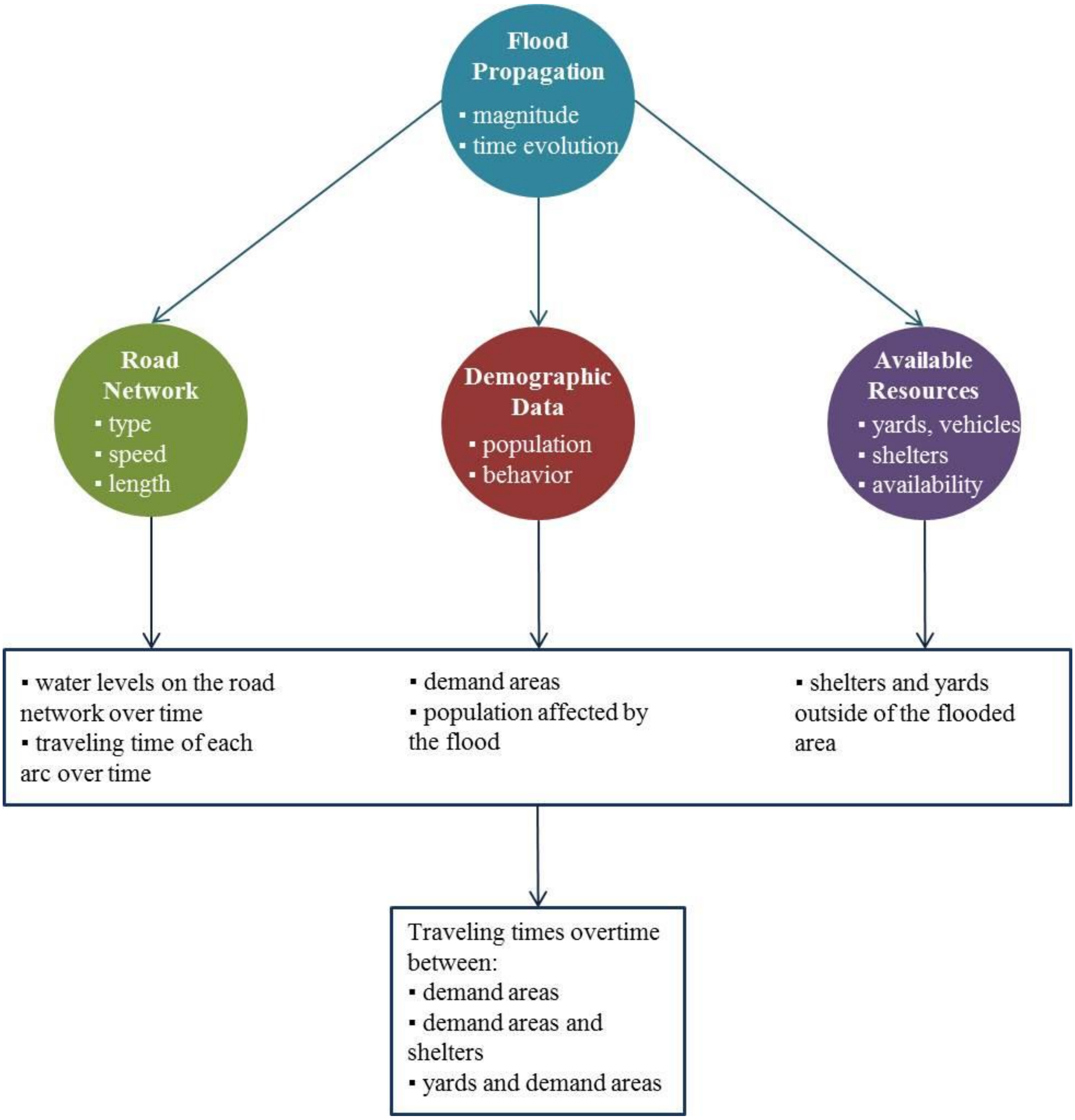


Figure 5.2 – Flood planning framework: stage 1.

The flood propagation together with the additional data results in different outputs:

- The flood propagation together with the road network predicts which roads are flooded and the levels of water on the road network over time. The flood has consequences on the traveling times, i.e., the increase of the water levels reduces the maximum speed on the road network and, consequently, increases the traveling times.
- The flood propagation together with the demographic data forecasts the residence areas that are flooded, designated as demand areas, and the respective affected population that, in order to be safe, needs to evacuate from the flooded area.
- The flood propagation together with the available resources foresees which shelters are outside of the flooded area and, consequently, can be used as safe places for evacuees, and which yards and vehicles can be used in the flood emergency.

Combining all data, the result is the traveling times over time between demand areas, between demand areas and shelters, and between yards and demand areas.

At the end of the first stage of the planning framework, we have the following data:

1. Flooded area and time horizon.
2. Demand areas and affected population.
3. Percentage of population evacuating to a shelter.
4. Percentage of population using private vehicles and using other transport services.
5. Behavior of the affected population when facing the flood.
6. Candidate shelters location and respective capacities.
7. Yards location, vehicles parked at each yard and respective capacities.
8. Shelters and vehicles availability over time.
9. Road conditions and consequently traveling times over time.

5.3.2. Shelter location-allocation and evacuation order issuing

In the second stage of the flood emergency problem, it is only considered the population that needs to go to a shelter during the flood disaster, independently of the mode of transportation. The allocation of this population from demand areas to shelters is defined in this stage. In addition, the location of shelters and the moment when they are opened are also determined as well as the moment when demand areas receive an order to evacuate. The objective is to minimize the overall evacuation time, i.e., the total traveling time between demand areas and shelters over the planning horizon, subject to a limited number of shelters to be opened over time, to a limited shelter capacity, to traveling times changing over time, and to evacuees following a pattern to evacuate after receiving an evacuation order.

The multi-period shelter location-allocation model with evacuation orders for flood disasters, developed by Gama et al. (2016) (see Chapter 3), is considered in this stage as well as the proposed simulating annealing heuristic to solve the problem in less time. The model formulation and the solution technique are the same as those presented in subchapters 3.3 and 3.4, respectively.

At the end of the second stage of the planning framework, the outcome for each time period is the following:

1. Location of the opened shelters.
2. Identification of demand areas receiving an evacuation order.
3. Identification of the selected shelter for the demand areas receiving an evacuation order.
4. Number of evacuees evacuating to the allocated shelter.

5.3.3. Private car-based evacuation

In the third stage of the flood emergency problem, routes for the private car-based evacuation are defined. Route definition will enable the identification of zones of the road network that may suffer from congestion during the evacuation process.

There are two different destinations for those evacuating in their private vehicles: shelters or other safe places such as relatives' or friends' houses or hotels. Regarding the evacuation to shelters, it is considered the outcome from the previous stage, i.e., for each demand area it is known the period of time when the evacuation starts, the number of evacuees evacuating at each time period and the shelter where they are allocated. For those who do not evacuate to shelters, there are several destination options. These different options are represented by super nodes and it is assumed that population evacuates to the closest super node and responds to the evacuation order determined in the previous stage.

The routes from each demand area to each shelter or super node are designed using the Dijkstra's Algorithm. Considering an average number of passenger per car, the number of cars on the road network are computed for each time period.

At the end of the third stage of the planning framework, the outcome for each time period is the following:

1. Identification of the arcs of the road network used for the private car-based evacuation.
2. Number of cars in each arc of the road network.
3. Identification of possible problematic zones regarding congestion.

This outcome enables authorities to allocate security forces to the identified congested zones in order to manage traffic and to avoid these zones during the evacuation using civil protection authorities' vehicles.

5.3.4. Emergency vehicle-based evacuation

In the fourth and final stage of the flood emergency problem, it is considered the evacuation of those without private vehicles. These evacuees evacuate to shelters with the support of the authorities. In this stage, routes and schedules for a fleet of vehicles are defined. The objective is to minimize the evacuation and waiting time of evacuees subject to a limited number of available vehicles over time, to a limited vehicle capacity, to traveling times changing over time, and to evacuees following a pattern to evacuate after receiving an evacuation order.

The multi-period vehicle evacuation problem for flood disasters using a time-space network, proposed in Chapter 4, is considered in this stage as well as the time-space network and the rolling horizon approach to solve the problem. The model formulation and the solution technique are described in subchapters 4.3.3 and 4.3.4, respectively.

At the end of the fourth stage of the planning framework, the outcome for each time period is the following:

1. Location of each vehicle.
2. Number of evacuees in each vehicle.
3. Number of evacuees waiting for the vehicles.
4. Number of evacuees already at each shelter.

5.4. Case Study

In this section, we use a real world-based case study to demonstrate the applicability of the proposed planning framework.

The flooding of the Mondego River, in 2001, was one of the most severe floods in the region of Baixo Mondego, in Portugal. Thousands of hectares were flooded, reaching 2 meters of depth in some zones. The consequences were devastating: villages surrounded by water and completely isolated, receiving support for survival by boats; roads and railways closed for circulation; requiring, in some cases, evacuations by helicopter; authorities with hundreds of assistance requests at hand; and houses, cars and other assets completely damaged (Pardal et al., 2022).

5.4.1. Stage 1: Input Data

<u>Flood Propagation</u>

The maximum flood surface (flood map), in Baixo Mondego, of a flood with similar characteristics of the one described above is presented in Figure 5.3.

The flood map and the levels of water were determined using Hec-Ras software. The methodology considered is similar to the one presented by (Khattak et al., 2016). Hec-Ras software modeled the Mondego River between Aguieira dam and Mondego River mouth, Ribeira dos Fornos, and Vala do Norte. The software considered a Digital Elevation Model, which represents the bare ground topographic surface, and was generated using the Portuguese Military Charters on a scale of 1:25,000 and a vertical accuracy of 5 meters. Regarding the geometric data, it was considered cross-sections, 150 meter spaced, and the respective transversal profiles as well as the longitudinal profiles of Mondego River, Ribeira dos Fornos, and Vala do Norte. The initial conditions entered in the software were as follows: i) 150 m^3/s for Mondego River; ii) 10 m^3/s for Ribeira dos Fornos and for Vala do Norte. For the upstream boundary conditions, hydrographs for Mondego River, Ribeira dos Fornos and Vala do Norte were defined considering the operating rules of Agueira dam and the hydrographs identified in 2001 during the Mondego River flood. For the downstream boundary conditions, it was considered the intersection of Ribeira dos Fornos and Vala do Norte, the intersection of Vala do Norte and Mondego River, and a riverbed slope of 0.2 %.

As a result, the level of the water surface was defined and using ArcGIS software it was possible to outline the maximum flooded surface. Subtracting the topographic level to the water surface level, it was possible to determine the water levels in several points of the road network, for each five minutes interval for a 72 hours horizon window.

The flood map covered four municipalities: Coimbra, Montemor-o-Velho, Soure e Figueira da Foz (Figure 5.3). Similar to Kongsomsaksakul et al. (2005), it was defined an emergency planning zone which comprises the flooded area and a buffer located 150 meters outside the flooded area.

Figure 5.3 –Mondego River (including Ribeira dos Fornos and Vala do Norte), the flood map, and the municipalities affected by the flood.

Three hours were added at the beginning of the flood planning horizon, resulting in a planning horizon of 75 hours. The three first hours represent the conditions before the flood begins while the remaining 72 hours translate the conditions during the flood. Considering intervals of five minutes, it resulted in a total of 900 intervals.

Although it is possible to solve a problem of this size, we believed that at stage 2 of the flood planning framework, it was more important to have a solution in less computing time than a more detailed solution which results in an increasing of the computing times. Therefore, for stage 2 the size of the problem was reduced by considering 150 intervals of thirty minutes. The new water levels on the road network were computed as the average in order to ensure that the water depths evolution was not lost.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1						2						3						4						5						6					
37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72
7						8						9						10						11						12					
73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108
13						14						15						16						17						18					
109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144
19						20						21						22						23						24					
145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180
25						26						27						28						29						30					
181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216
31						32						33						34						35						36					
217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252
37						38						39						40						41						42					
253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288
43						44						45						46						47						48					
289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324
49						50						51						52						53						54					
325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360
55						56						57						58						59						60					
361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396
61						62						63						64						65						66					
397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432
67						68						69						70						71						72					
433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468
73						74						75						76						77						78					
																		(…)																	
829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864
139						140						141						142						143						144					
865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900
145						146						147						148						149						150					

Figure 5.4 – Planning horizon divided in periods of time of five minutes (orange) and the respective correspondence for periods of time of thirty minutes (blue).

In the following stages, in order to have more detail in the evacuation operations, it was considered intervals of five minutes, resulting in a total of 900 intervals. Figure 5.4 illustrated the correspondence of a horizon window of 900 time intervals of five minutes and a horizon window of 150 time intervals of thirty minutes.

<u>Road Network</u>

The water depths on the road network vary over time, increasing or decreasing during the planning horizon. It was observed that some zones are already isolated when the flood starts and other zone become isolated during the flood. Isolation of a zone means that is not possible to use any road to evacuate.

Speeds on the arcs were defined for each network arc, according to the maximum speed allowed for passenger cars, in Portugal. The only exception was for arcs inside towns and villages, since it was considered 30km/h instead of 50km/h. The reason for this reduction of the maximum speed limit is to take into account possible stops on traffic lights and on pedestrian crossings.

Table 5.1 – Maximum speeds (km/h) for different free-flow speed roads according to water depth (based on Nayak & Zlatanova, 2008).

Type of road	Water depth in the road (m)				
	0	]0, 0.1]	]0.1, 0.2]	]0.2, 0.5]	>0.5
Type 1	120	48	24	1	0
Type 2	90	36	18	1	0
Type 3	70	28	14	1	0
Type 4	60	24	12	1	0
Type 5	50	20	10	1	0
Type 6	40	16	8	1	0
Type 7	30	12	6	1	0

The road network comprised two types of arcs: i) flooded arcs, within the flooded area; and ii) non-flooded arcs, outside the flooded area. For flooded arcs, maximum speed is affected by the water levels on the road network. Based on Nayak & Zlatanova (2008), the maximum speeds for seven different types of road according to water depth are presented in Table 5.1. For non-flooded arcs, speed is the same over the time horizon.

Given the length of each network arc and the maximum speed a car can travel along it, the travel time was determined for each arc and for each time period.

<u>Demographic Data</u>

The four municipalities – Coimbra, Montemor-o-Velho, Soure, and Figueira da Foz - had a total of 248,449 inhabitants, according to 2011 Census data. The total population affected by the flood was, as expected, the population of the surrounding areas of Mondego River, resulting in 9,816 inhabitants affected by the flood. Figure 5.5 displays the region under study, the affected areas, and the population per affected area. While in Coimbra city, Mondego River is surrounded by urban areas, in the other municipalities the river is mainly surrounded by farm lands.

The affected population was determined considering the population density: each BGRI (Geographic Base for Information Referencing) has an area and a total of resident population, according to 2011 Census data. The area of the flooded part of the BGRI, designated as demand area, is defined by the intersection of the BGRI and the flood map. The affected population is the population within the demand area. Due to some demand areas with small number of residents affected by the flood, it was necessary to aggregate them. The aggregation followed two directives: i) the sum of the population of each demand area needs to be higher or equal to 30; ii) the proportion of car usage on daily journeys (at the date of Census 2011) need to be similar. For aggregations of demand areas from different places of residence, the proportion of car usage is determined by the population-weighted average. For each demand area, the population was considered to be concentrated in a single demand node located in the centroid of the demand area.

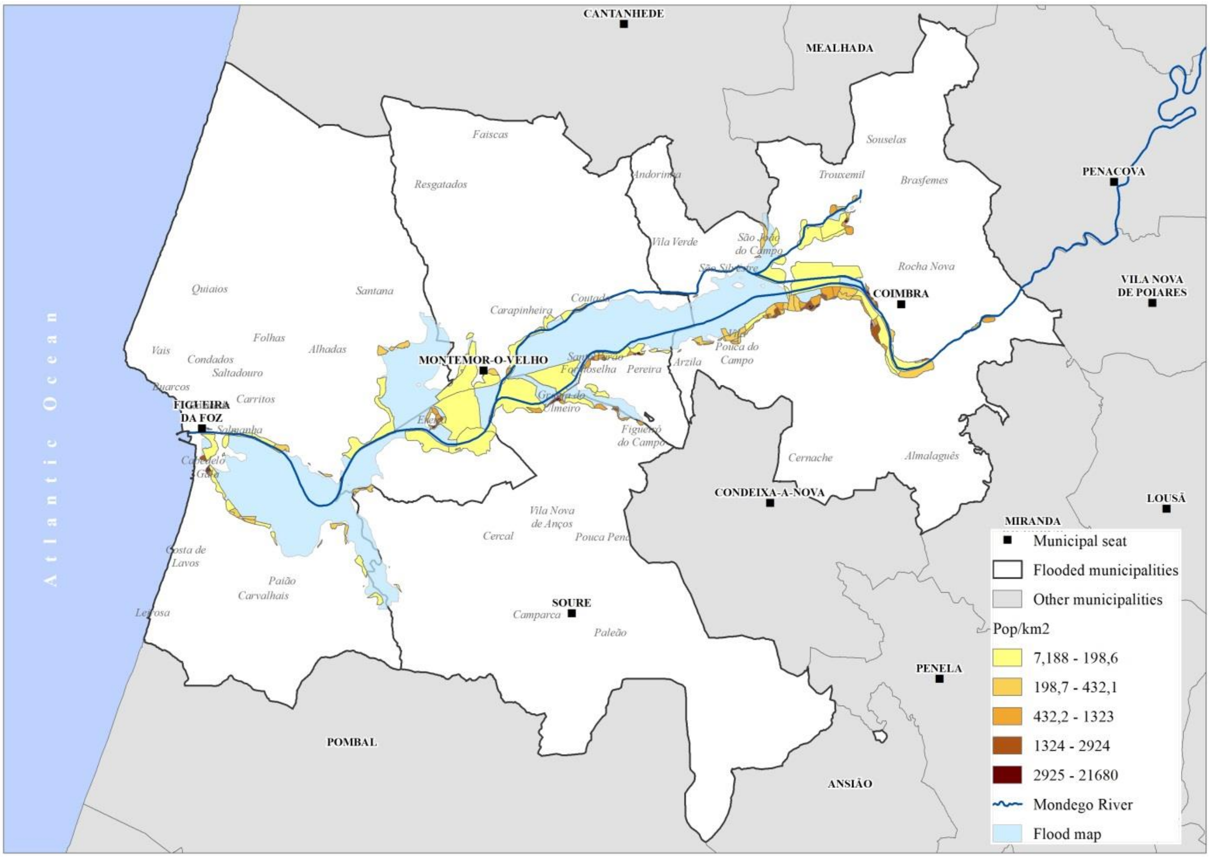


Figure 5.5 – Boundaries, affected areas, and population per area.

In practice, it is known that only a small percentage of the population affected by a flood seeks refuge in a shelter, while the remaining affected population evacuates to different destinations or does not leave their houses. This is also suggested in the literature. For instance, Li et al. (2012) consider that, for a hurricane scenario, only 8–16 % of the evacuation demand looks for a shelter. Thus, the population using a private car to evacuate was determined by the proportion of car usage on daily journeys of each demand area and the remaining population evacuated using other modes of transportation. For the population evacuating using a private car, it was assumed that 8 % evacuates to a shelter. For the population evacuating using other transportation modes, it was assumed that 16 % seeks for support in a shelter, evacuating with the help of authorities. This resulted in an overall demand of 1,196 evacuees looking for assistance in shelters with half of them using private vehicles to reach the shelter and the other half evacuating with the help of authorities.

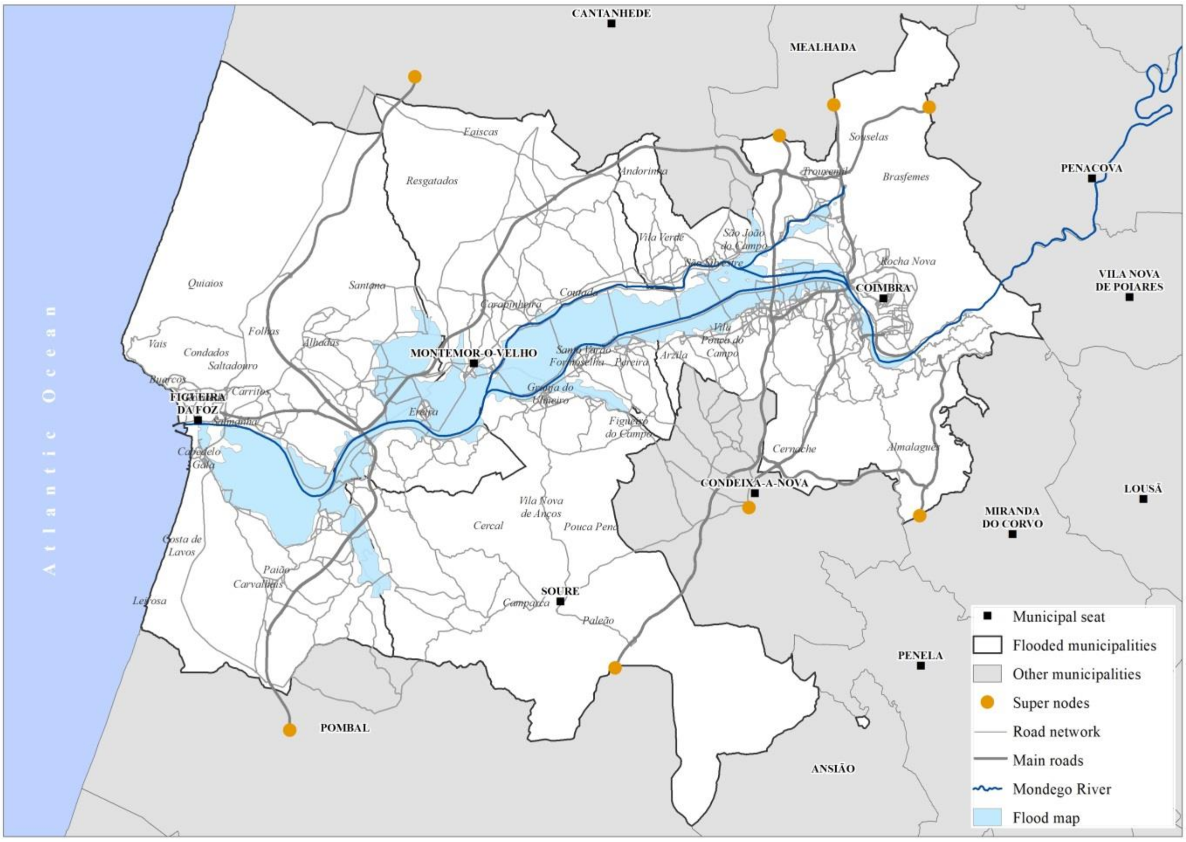


Figure 5.6 – Location of super nodes.

For those who do not evacuate to shelters, we considered that for demand areas that, at some moment of the planning horizon, experience isolation, evacuees seek for support at relatives' or friends' houses or even at hotel outside the flooded area, resulting in 4,609 evacuees. To represent the several destination options, nodes, designated as super nodes (Figure 5.6), were located in the main roads of the four municipalities, i.e., highways (A1, A13, and A17), primary (IP3) and secondary (IC2) routes. It was assumed that the population evacuates to the closest super node. Based on the 2019 Census data on the number of light passenger vehicles per 1,000 inhabitants, it was assumed that there are 1.9 evacuees per private car.

Thus, 9,816 inhabitants are affected by the flood with 1,196 inhabitants evacuating to shelters and 4,609 evacuating to other destinations. It is assumed that the remaining affected population does not leave their houses. Regarding the evacuation to shelters, 598 inhabitants evacuate using private vehicles while the remaining inhabitants evacuate with the help of authorities.

The evacuation process over time is the similar to the one described in the previous chapters and based on Sherali et al. (1991) work. Thus for stage 2 of the flood planning framework, after receiving an evacuation order, the evacuees evacuate according to a six time period S-shaped curve (Figure 5.7) where 5 % of the population evacuates in the time period the evacuation order is emitted, 10 % evacuates in the following period, 35 % and 40 % evacuates two and three, respectively, time periods after evacuations order, and 5 % of the population evacuates in the last two periods of evacuation.

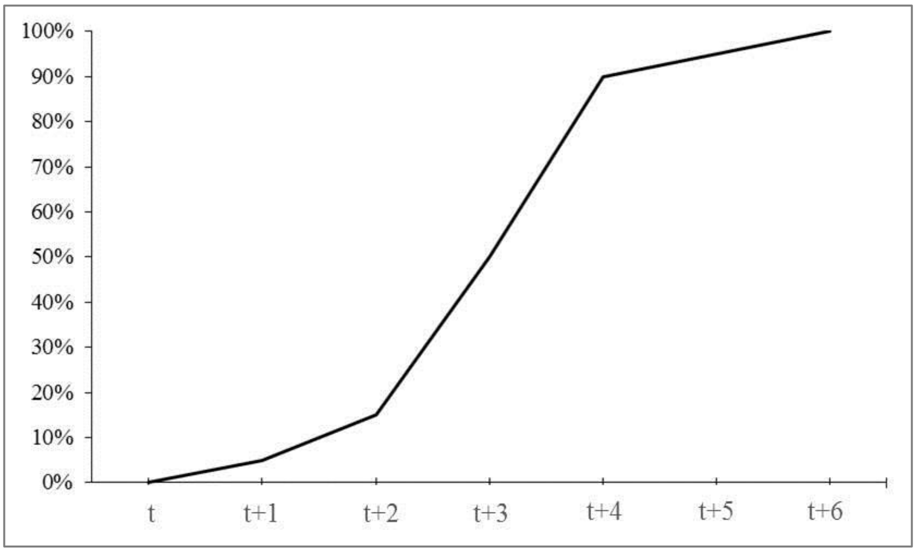


Figure 5.7 – Six-segment S-shaped curve representing the percentage of people evacuating in six time periods after receiving an evacuation order at time t [based on Sherali et al. (1991)].

For stages 3 and 4 of the flood planning horizon, the evacuation process, displayed in Figure 5.8, starts two time periods after receiving an evacuation order. Thirty minutes after the evacuation order was issued, 5 % of the evacuees are evacuated. In the next thirty minutes, i.e., in the next six time periods, 10 % of the evacuees evacuate. One and half hour after the evacuation order was issued, 30 % of the evacuees are evacuated and, in the next thirty minutes, this percentage rises to 40 %. The remaining 10 % of evacuees evacuate in the last hour, 5 % every half hour.

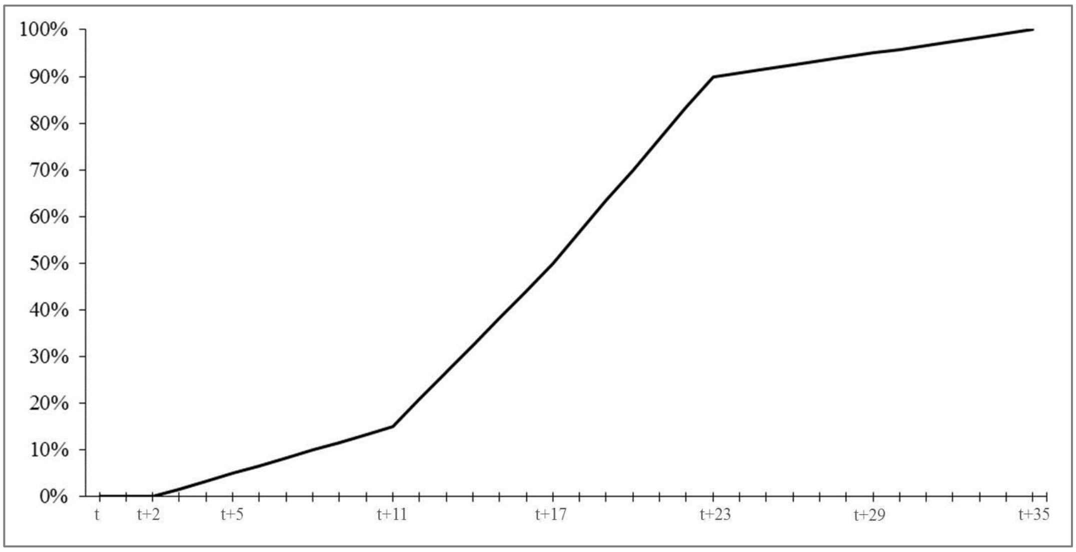


Figure 5.8 – Thirty six-segment S-shaped curve representing the percentage of people evacuating in six time periods after receiving an evacuation order at time t [based on Sherali et al. (1991)].

Taking into account the small amount of demand in some affected areas, it was defined that the total demand evacuating needs to follow the S-shaped curve, even if for some areas, the percentage evacuating in each time period is different from the one defined for the S-shaped curve. Therefore, it was applied the D'Hondt method, very well known in the electoral systems for proportional allocation of deputies.

Available Resources

Existing public buildings such as sport halls of middle and high schools, warehouses, multi-sport complexes and other sport halls, outside of the emergency planning zone were considered as candidate shelters. Each candidate shelter was represented by a node, designated as shelter site. The capacity of the shelters was computed based on the size of the sport halls and on a standard evacuation criterion according to which each person assisted in a shelter needs an average space of 3.5 m^2 (The UN Refugees Agency, 2007). It was considered that two-thirds of the area of the sport hall is effectively available to receive the evacuees. The rest of the area was considered to be for support of the assistance service provided to the evacuees or area not suitable to accommodate and assist people.

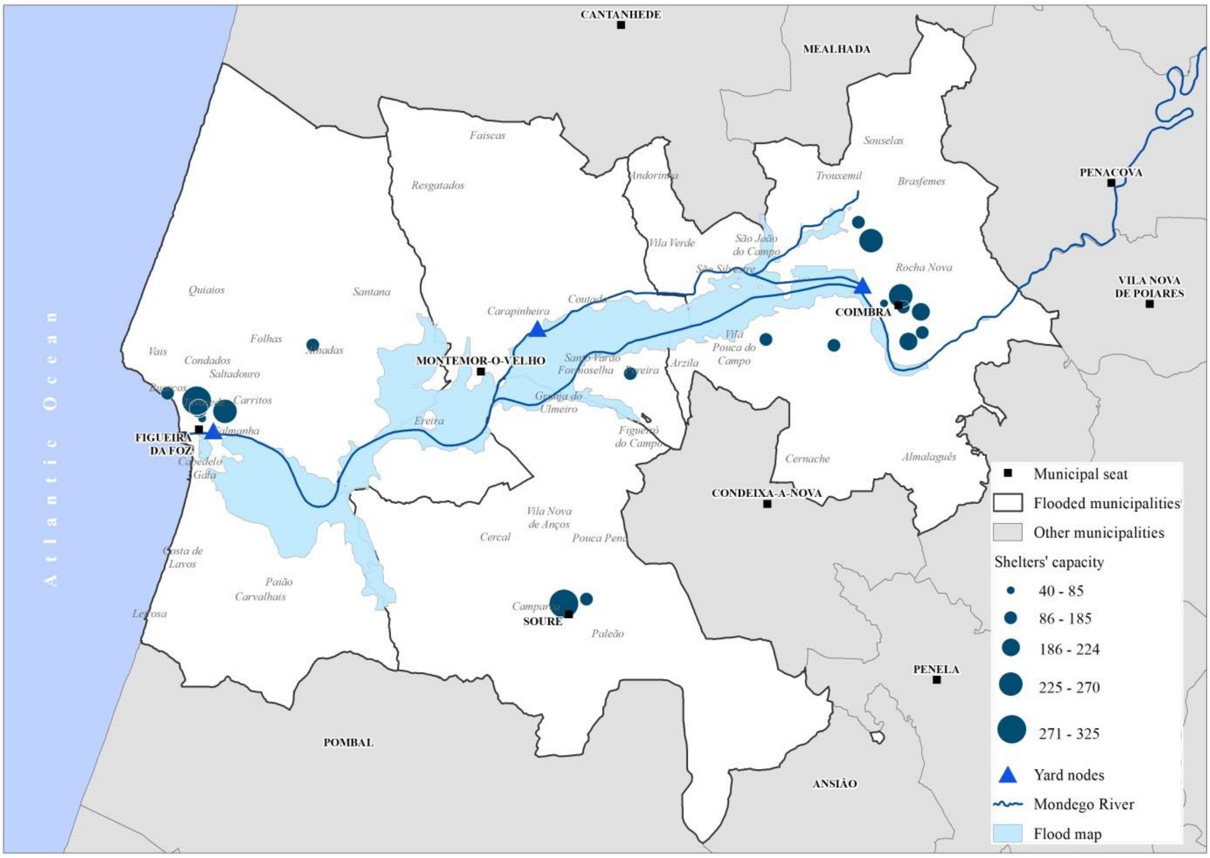


Figure 5.9 – Potential shelters location and capacities and yards location

A total of 19 sport halls of middle and high schools were used as potential shelter locations. These sport halls are spread across the four municipalities, with a higher concentration in the most densely populated areas in the center of the region. The capacity of the 19 shelters varies from around 40 to 325 people (Figure 5.9). We considered that authorities can open to a maximum of 7 shelters and are able to open 2 shelters in the first time period, i.e., three hours before the flood begins, and one more shelter after three hours, i.e., in Time Period 7. Then, authorities can open another shelter after every eight hours until a maximum of 7 shelters. Thus, in time periods 1, 7, 23, 39, 55, and 71, it is possible to have a maximum of 2, 3, 4, 5, 6, and 7 shelters opened, respectively.

Available evacuation vehicles, such as ambulances, minibus, or buses, were initially located at 3 yards across Baixo Mondego (Figure 5.9). There were two different types of vehicles available for the evacuation: i) type 1 with a maximum capacity of 9 seated passengers; and ii) type 2 with a maximum capacity of 15 seated passengers. The total number of emergency vehicles available was 30, ten per yard, but they were not all readily available. Thus, in the first time period each yard had 4 available vehicles of type 1. At Time Period 37, 4 vehicles of type 2 were available per yard. The remaining 2 buses of type 1 per yard became available at Time Period 73.

Finally, the shortest paths (in terms of time) between each demand area and shelters and yard were computed for all time periods using the Dijkstra's Algorithm for the shortest paths.

To sum up, Baixo Mondego region faced a flood, lasting a total of 72 hours and affecting a total of 9,816 inhabitants of four municipalities. The planning horizon comprised 150 time periods of thirty minutes and the first six periods (3 hours) represent the conditions before the start of the flood disaster, for stage 2 of the flood planning framework. For stage 3 and 4, the planning horizon comprised 900 time periods of five minutes and the first thirty six periods (3 hours) represent the conditions before the start of the flood disaster. A total of 1,196 evacuees had as final destination a shelter and half of them evacuate by private cars whereas the other half evacuate with the help of authorities. A total of 4,609 evacuees found support at other destinations, such as friends' or relatives houses or hotels. Authorities could open a maximum of 7 shelters but not at the same time: two shelters were opened in the first time period; one more shelter was opened at Time Period 7; and the remaining four shelters were opened one by one at time periods 23, 39, 55 and 71. Authorities had also available a total of 30 vehicles, 18 of type 1 which capacity is 9 passengers and 12 of type 2 which capacity is 15 passengers, in three different yards but not at the same time: at Time Period 1, each yard had 4 vehicles of type 1; 4 more vehicles of type 2 were available per yard at Time Period 37; and at Time Period 73, 2 more vehicles of type 1 were available per yard.

5.4.2. Stage 2: Shelter location-allocation and evacuation order issuing

5.4.2.1. Case study results

The shelter location-allocation problem was solved by considering the model and using the solution technique, with the same parameters, proposed by Gama et al. (2016). The problem was solved with the optimization solver Xpress IVE 8.5, implemented on an Intel Core 2 Quad CPU 2.50GHz PC running Windows 7 64-bits.

The solution for this case study was obtained after 455 seconds (approx. 7 minutes) and resulted in an objective function value of 12,504 minutes (i.e., total traveling time between demand nodes and shelters over the planning horizon). The number of shelters opened in each time period, the number of demand areas receiving an evacuation order in each time period, the population evacuating in each time period, and the overall travel time (OF) are displayed in Table 5.2. The location of the selected shelters, the allocation and the time period when evacuation orders are issued are shown in Figure 5.10.

It can be observed that most of the demand has to be evacuated in the initial time periods, especially in the third and fourth period. The demand areas evacuated in these initial time period are the most affected areas at the initial stage of the flood. In fact, demand areas which are isolated when flood begins (Time Period 7) receive an evacuation order in the first period. The demand areas less affected by the flood receive the last evacuation orders. In terms of geographic location of the selected shelters, these are spread over the territory with a higher concentration in the municipality of Coimbra, which has the largest demand. The initial shelters to be opened guarantee a quick evacuation for those areas that will be completely isolated when the flood starts. The follow shelter openings also prevent demand areas from being isolated in the following periods. The shelters to be opened last are located near the first shelters opened, complementing the coverage of these shelters.

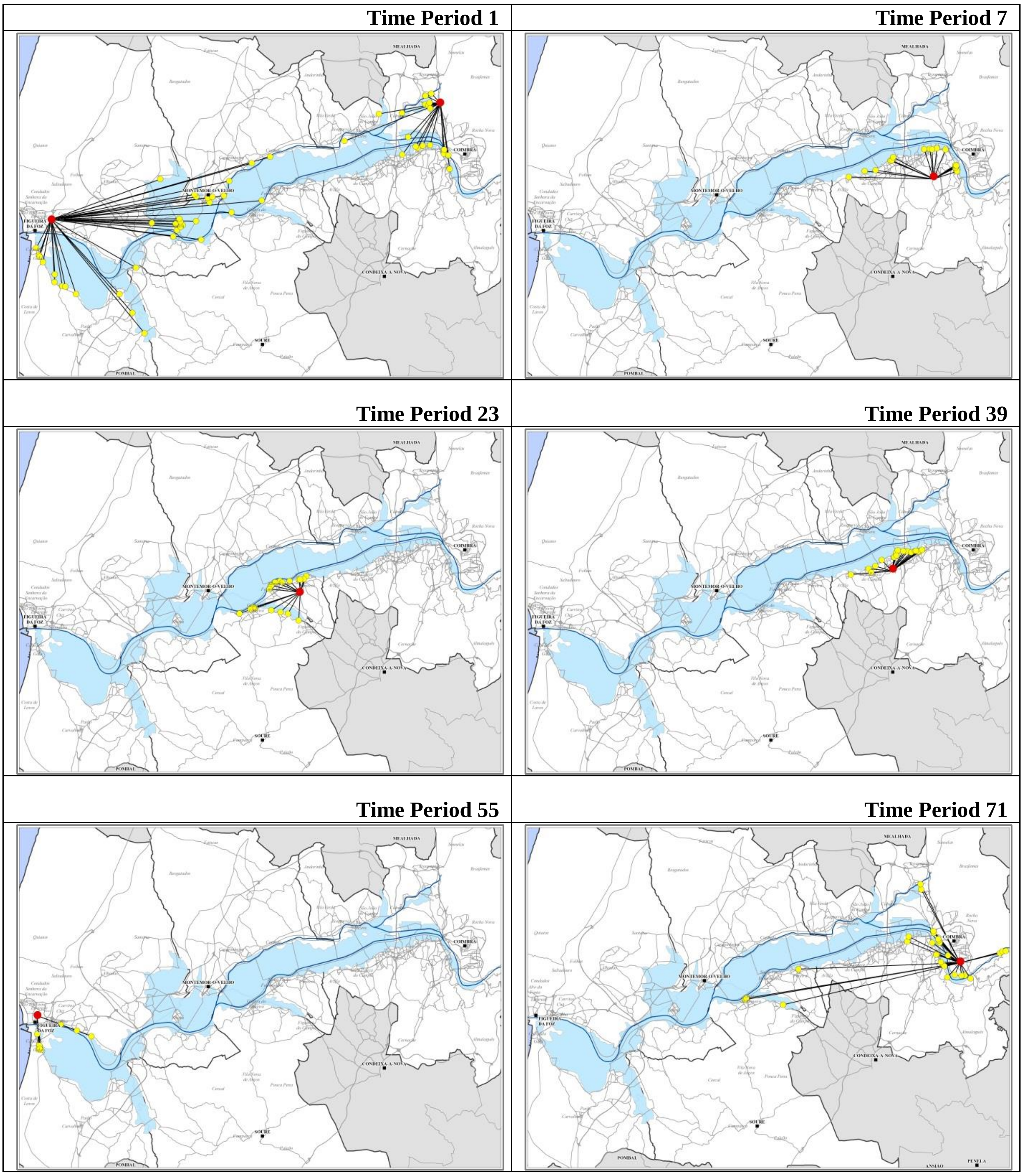


Figure 5.10 – Selected shelters location (red square), allocation (black arrow) and delivery times of evacuation orders.

Table 5.2 – Results for the shelter location-allocation problem.

Time Periods	# opened shelters		# evacuation orders	# evacuees
1	2		54	20
2	2		0	39
3	2		0	154
4	2		0	166
5	2		0	23
6	2		0	18
7	3		18	10
8	3		0	22
9	3		0	65
10	3		0	74
11	3		0	6
12	3		0	7
13-22	3		0	0
23	4		20	8
24	4		0	17
25	4		0	61
26	4		0	63
27	4		0	9
28	4		0	4
29-38	4		0	0
39	5		21	9
40	5		0	16
41	5		0	60
42	5		0	67
43	5		0	12
44	5		0	2
45-54	5		0	0
55	6		9	3
56	6		0	10
57	6		0	20
58	6		0	29
59	6		0	3
60	6		0	6
51-70	6		0	0
71	7		28	10
72	7		0	16
73	7		0	60
74	7		0	81
75	7		0	7
76	7		0	19
77-150	7		0	0
OF (min)	12,504	Total	150	1,196

In Time Period 71, it is possible to observe that three demand areas in the municipality of Soure and one demand area in the municipality of Montemor-o-Velho are allocated to a shelter in the municipality of Coimbra. These four allocations represent the maximum traveling times during the all evacuation process. The neighboring demand areas are allocated in Time Period 23 to the only shelter in that zone and, due to capacity constraints, it is not possible to accommodate all demand from that zone.

5.4.2.2. Sensitivity analysis

Regarding capacity, the first five shelters to be opened would be at their full capacity, whereas the last two shelters to be opened would be at approximately 84 % and 92 % of their capacity respectively. Since capacity may be constraining the solution, it is interesting to see what solution is obtained if a total of eight shelters can be opened. Therefore, it was considered that at Time Period 39 it is possible to open up to two shelters instead of one.

The solution for the full horizon was obtained after 1,268 seconds (approx. 21 minutes) and resulted in an objective function value of 11,848 minutes (i.e., total traveling time between demand nodes and shelters over the planning horizon), i.e., the opening of an eighth shelter allowed to reduce the total traveling time in 5 %. The location of the selected shelters, the allocation and the time period when evacuation orders are issued are shown in Figure 5.11. The solution - number of shelters opened in each time period; number of demand areas receiving an evacuation order in each time period; population evacuating in each time period; overall travel time (OF) – is compared with the previous solution and displayed in Table 5.3.

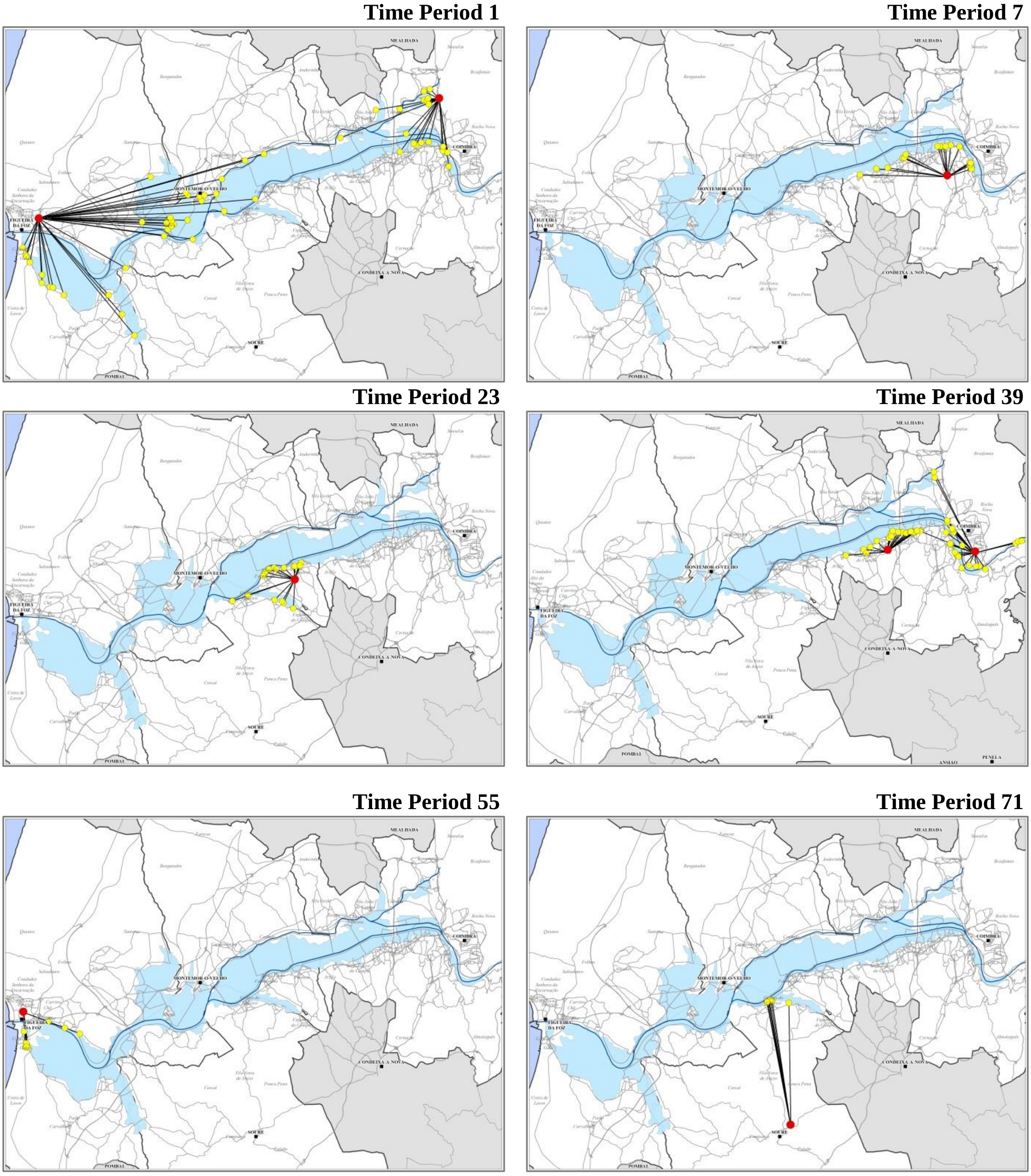


Figure 5.11 – Selected shelters location (red square), allocation (black arrow) and delivery times of evacuation orders for the problem of opening up to eight shelters.

The seven selected shelter from the previous problem are also selected in this problem and have the same opening times. The exception goes for the second shelter opened in Time Period 39 which is the last shelter to be opened in the previous solution. The eighth shelter to be opened allocates the demand areas that previously presented the higher evacuation times and, due to the proximity, the evacuation times are now shorter. Regarding the evacuation orders issued, there is an increase at Time Period 39 that is justified by the opening of the second shelter. On the other hand, at Time Period 23 it is observed a decrease in the number of evacuation orders issued. Demand areas which previously received an evacuation order at Time Period 23 are receiving it at Time Period 71 and are allocated to a closer shelter and, therefore, present shorter evacuation times.

Table 5.3 – Comparison of results for the shelter location-allocation problem.

Time Period	# opened Shelters		# evacuation orders		# evacuees	
	Up to 7 shelters	Up to 8 shelters	Up to 7 shelters	Up to 8 shelters	Up to 7 shelters	Up to 8 shelters
1	2	2	55	54	20	20
2	2	2	0	0	39	39
3	2	2	0	0	154	154
4	2	2	0	0	166	166
5	2	2	0	0	23	23
6	2	2	0	0	18	18
7	3	3	18	18	10	10
8	3	3	0	0	22	21
9	3	3	0	0	65	67
10	3	3	0	0	74	73
11	3	3	0	0	6	5
12	3	3	0	0	7	7
13-22	3	3	0	0	0	0
23	4	4	20	17	8	4
24	4	4	0	0	17	10
25	4	4	0	0	61	47
26	4	4	0	0	63	46
27	4	4	0	0	9	6
28	4	4	0	0	4	5
29-38	4	4	0	0	0	0
39	5	6	21	45	9	19
40	5	6	0	0	16	31
41	5	6	0	0	60	115
42	5	6	0	0	67	139
43	5	6	0	0	12	18
44	5	6	0	0	2	17
45-54	5	6	0	0	0	0
55	6	7	9	9	3	3

Time Period	# opened Shelters			# evacuation orders		# evacuees	
	Up to 7 shelters	Up to 8 shelters		Up to 7 shelters	Up to 8 shelters	Up to 7 shelters	Up to 8 shelters
56	6	7		0	0	10	10
57	6	7		0	0	20	20
58	6	7		0	0	29	29
59	6	7		0	0	3	3
60	6	7		0	0	6	6
51-70	6	7		0	0	0	0
71	7	8		27	7	10	4
72	7	8		0	0	16	9
73	7	8		0	0	60	17
74	7	8		0	0	81	27
75	7	8		0	0	7	5
76	7	8		0	0	19	3
77-150	7	8		0	0	0	0
OF (min)	12,479	11,844	Total	150		1,196	

As seen the opening of an eighth shelter reduces not only the total evacuation time but also the maximum traveling times. However, to achieve this, more resources (e.g., volunteers, medical teams, and relief supplies) from civil protection authorities are required and it is necessary to understand if it can be supported by authorities.

The solution considered in the following stages of the planning framework is the solution for the problem of opening up to 7 shelters.

5.4.3. Stage 3: Private car-based evacuation

At this stage the origin and destination of evacuees using private cars to evacuate are known. The destination shelters for the evacuees were determined in the previous stage and for non-shelter evacuees it is assumed that the closest super node is the final destination. Thus, it is possible to analyze the impact of this evacuation process on the road network.

Time Period 19 is the time period with a higher number of cars on the road network: 2,388 private vehicles. The distribution of the cars on the road network in this time period is as shown in Figure 5.12. The zones that may be considered problematic are the ones with a higher number of cars and, for this problem, these zones are the intersections that give access to the main roads of the four municipalities. The outcome of this analysis can help in defining the allocation of security forces to the identified zones in order to guarantee the public order.

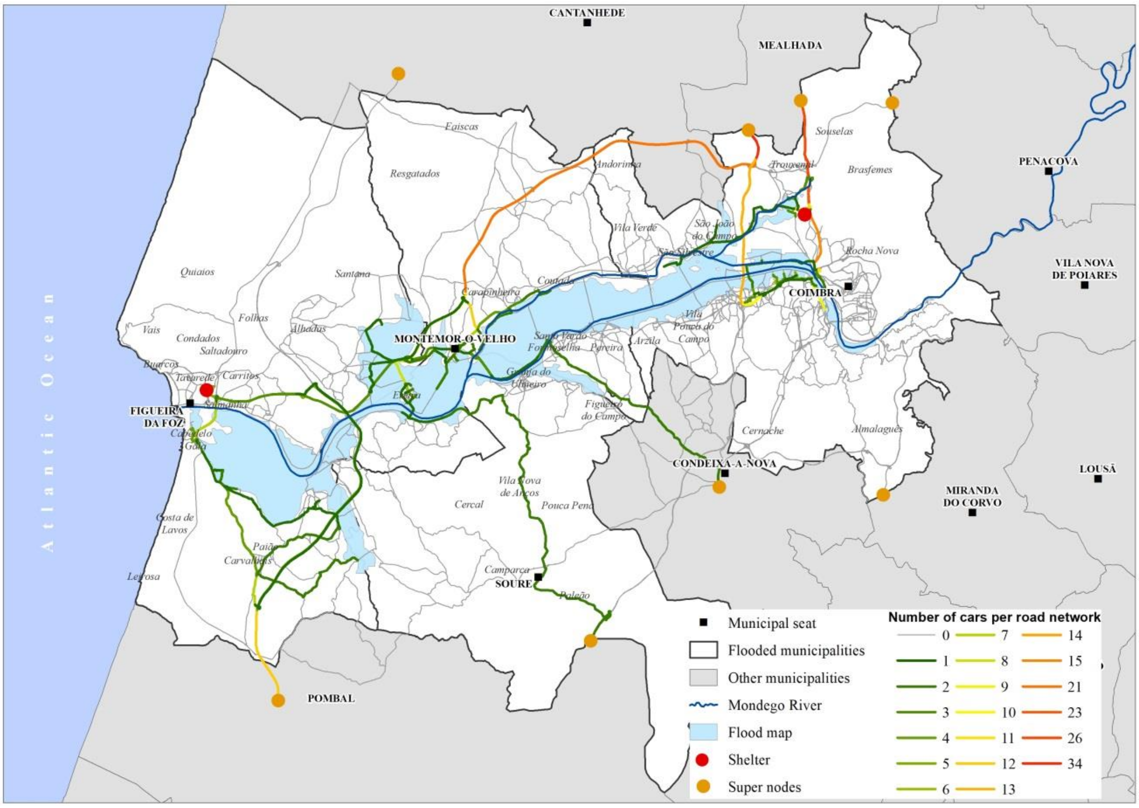


Figure 5.12 – Number of cars on the road network in Time Period 19.

5.4.4. Stage 4: Emergency vehicle-based evacuation

5.4.4.1. Case study results

At this stage it is already known the period of time when evacuees are ready to evacuate and which shelter is their final destination. It is also known when and where the emergency vehicles are available. Thus, it is possible to determine the routes and schedules of the emergency vehicles for the evacuation of the population that relies on authorities to reach a shelter.

The time-space network created for this problem comprised a total of 45,400 nodes, 371,325 movement arcs, and 730,947 waiting arcs. The emergency vehicle-based evacuation problem was solved by applying the rolling horizon approach for the time windows as described in Table 5.4. The time interval with a fixed solution, i.e., an optimal solution determined in previous time windows, the computing times for solving the multi-period vehicle evacuation model, and the gap, i.e., the difference between the best solution and the best bound, are also presented. For each time window, the (4.1) - (4.9) model was implemented using FICO Xpress Mosel modeling language and solved with the optimization solver FICO Xpress 8.7 on an Intel Core i7-870 CPU 2.93GHz PC running Windows 10 Pro 64-bits.

Table 5.4 – Rolling Horizon time windows and computing times.

Time Window	Time Interval with a fixed solution	Computing Times (s)	Gap (%)
1 – 20	-	42.5	0.00
11 – 26	1 - 10	405.7	2.36
19 – 34	1 – 18	300.5	5.23
27 – 42	1 – 26	300.1	2.98
35 – 240	1 – 34	502.1	0.00
138 – 343	1 – 137	304.9	0.00
241 – 446	1 – 242	733.3	0.00
344 – 549	1 – 343	740.5	0.00

Three important notes should be taken into consideration. First of all, the problem was not solved for the entire planning horizon since the problem was considered solved after all evacuees had reached the respective shelter. For three time windows, it was decided to finish the solving of the problem after 5 minutes (300 seconds). This resulted in a gap value different from zero meaning that the solution is not the global optimal solution. However, the behavior observed – a sudden decrease of the gap remaining unchanged over the time – leads to believe that the gap may be smaller than the presented one. Finally, the time windows do not present the same amount of time periods and this happens for different reasons: i) in the first time windows, the solution was obtained for 1 hour and 40 minutes of the planning horizon and therefore the computing times could not be very high; ii) for a fixed solution until Time Period 34, it was observed that optimal solutions could be obtained for longer time windows and therefore it was decided to solve 17 hours and 10 minutes of the planning horizon which allows to make sure that the consequences of the propagation of the flood and availability of emergency vehicles are taken into account.

The problem solving resulted in an objective function of 11,965 minutes, representing the total evacuation time over the planning horizon, including the total traveling time between demand nodes and shelters (8,635 minutes) and the total waiting time (3,330 minutes). This evacuation process has the following characteristics:

- It started at Time Period 1, when the first vehicles left the respective yards, and finished at Time Period 458 when the last evacuee arrived at the respective shelter;
- The first evacuations took place at Time Period 4, when eight evacuees were picked up, and the last evacuations occurred at Time Period 454, when five evacuees were picked up;
- The average vehicle occupancy for emergency vehicles of type 1 was 2.1 evacuees – the minimum occupancy was 1 evacuee and the maximum occupancy was 9 evacuees. The average vehicle occupancy for emergency vehicles of type 2 was 1.4 evacuees – the minimum occupancy was 1 evacuee and the maximum occupancy was 5 evacuees;
- The vehicles evacuation time, i.e., the vehicles traveling time between a demand node and the respective shelter, was, on average, 16.2 minutes and 12.0 minutes for vehicles of type 1 and 2, respectively;
- Only fifty four demand nodes had to wait for a vehicle and, on average, the evacuees waited 24.5 minutes;
- The thirty emergency vehicles available were all used in the evacuation process and, as shown in Table 5.5, not all the vehicles left the yards immediately. The first emergency vehicles left the yards at Time Period 1 and the last emergency vehicle left the yard at Time Period 343.

Table 5.5 – Number of vehicles of type 1 and 2 available (I), waiting (W), and leaving (O) each yard at each time period.

Time Period	Type 1									Type 2								
	Yard 1			Yard 2			Yard 3			Yard 1			Yard 2			Yard 3		
	I	W	O	I	W	O	I	W	O	I	W	O	I	W	O	I	W	O
1	4	3	1	4	3	1	4	4										
2	3	3		3		3	4	2	2									
3	3	3					2		2									
4	3	3																
5	3	1	2															
6	1		1															
7-36																		
37										4	4		4	4		4	4	
38										4	4		4	4		4	3	1
39-40										4	4		4	4		3	3	
41										4	2	2	4	3	1	3	3	
42-43										2	2		3	3		3	3	
44										2	2		3	3		3		3
45										2	2		3	3				
46										2	2		3	1	2			
47										2	1	1	1	1				
48-53										1	1		1	1				
53										1		1	1	1				
54-72													1	1				
73-140	2	2		2	2		2	2					1	1				
141	2	2		2	2		2	1	1				1	1				
142	2	2		2	2		1	1					1	1				
143	2	1	1	2	2		1	1					1	1				
144	1		1	2	2		1	1					1	1				
145-229				2	2		1	1					1	1				
230				2	2		1		1				1	1				
231-331				2	2								1	1				
332				2	2								1		1			
333				2	1	1												
334-343				1	1													
344				1		1												

5.4.4.2. Sensitivity analysis

The same problem was solved considering that all emergency vehicles were available at Time Period 1. The rolling horizon approach was applied and the time windows and the time periods for the fixed solutions were the same as in the previous problem. The computing times and the gap are shown in Table 5.6. Although the computing time may differ for each time window, at the end this problem was solved slightly faster than the previous problem.

Table 5.6 – Rolling Horizon time windows and computing times.

Time Window	Time Interval with a fixed solution	Computing Times (s)	Gap (%)
1 – 20	-	17.9	0.00
11 – 26	1 - 10	417.2	1.15
19 – 34	1 – 18	408.8	6.13
27 – 42	1 – 26	41.5	0.00
35 – 240	1 – 34	457.1	0.00
138 – 343	1 – 137	341.3	0.00
241 – 446	1 – 242	382.7	0.00
344 – 549	1 – 343	1,224.0	0.00

The problem solving resulted in an objective function of 8,805 minutes, representing the total evacuation time over the planning horizon, including the total traveling time between demand nodes and shelters (8,205 minutes) and the total waiting time (600 minutes). This evacuation process has the following characteristics:

- It started at Time Period 1, when the first vehicles left the respective yards, and finished at Time Period 458 when the last evacuee arrived at the respective shelter;
- The first evacuations took place at Time Period 4, when eleven evacuees were picked up, and the last evacuations occurred at Time Period 454, when six evacuees were picked up;
- The average vehicle occupancy for emergency vehicles of type 1 was 1.6 evacuees – the minimum occupancy was 1 evacuee and the maximum occupancy was 9 evacuees. The average vehicle occupancy for emergency vehicles of type 2 was 1.5 evacuees – the minimum occupancy was 1 evacuee and the maximum occupancy was 8 evacuees;

- The vehicles evacuation time, i.e., the vehicles traveling time between a demand node and the respective shelter, was, on average, 14.9 minutes and 13.6 minutes for vehicles of type 1 and 2, respectively;
- Only thirty demand nodes had to wait for a vehicle and, on average, the evacuees waited 12.3 minutes;
- The thirty emergency vehicles available were all used in the evacuation process and, as shown in Table 5.7, not all the vehicles left the yards immediately.

Table 5.7 – Number of vehicles of type 1 and 2 available (I), waiting (W), and leaving (O) each yard at each time period.

Time Period	Type 1									Type 2								
	Yard 1			Yard 2			Yard 3			Yard 1			Yard 2			Yard 3		
	I	W	O	I	W	O	I	W	O	I	W	O	I	W	O	I	W	O
1	6	4	2	6	6		6	6		4	4		4	4		4	4	
2	4	4		6	3	3	6	4	2	4	4		4	4		4	1	3
3	4	4		3	3		4	3	1	4	4		4	4		1		1
4	4	3	1	3	3		3	3		4	4		4	3	1			
5-6	3	3		3	3		3	3		4	4		3	3				
7	3	2	1	3	3		3	3		4	2	2	3	3				
8	2	2		3	3		3	2	1	2	1	1	3	2	1			
9	2	2		3	3		2	1	1	1	1		2	2				
10-11	2	2		3	3		1	1		1	1		2	2				
12	2	2		3	2	1	1	1		1		1	2	2				
13	2	2		2		2	1	1					2		2			
14	2	2					1	1										
15	2		2				1		1									

Although the evacuation process takes the same amount of time, it is clear that having all the emergency vehicles available at the beginning of the planning horizon decreases the total evacuation time. However, it is the total waiting time that decreases the most (82 %) while the total traveling time between demand nodes and shelters presented a reduction of 5 %. Both emergency vehicles types present similar average occupancy and average vehicles evacuation time when compared with the previous problem.

5.5. Conclusions

This chapter presents a flood planning framework in order to help civil protection authorities' decisions when facing flood emergencies.

Civil protection authorities deal with different entities and different emergency procedures during a flood emergency. Emergency procedures comprise the management of resources, such as shelters and emergency vehicles, which are not readily available; the communication between all the entities and the communication with the population, such as the issuing of evacuation orders; the assistance and the evacuation of the affected population, and the maintenance of the public order such as the allocation of security forces to problematic areas.

The proposed flood planning framework incorporates these challenges that civil protection authorities have to deal during a flood emergency throughout the four stages. The first stage comprises the data collection and processing. In the second stage, the location and opening times of the shelters, the time when the evacuation orders are issued, and the allocation of the affected population to the shelters are determined. The third stage comprises the identification of the congestion areas due to the evacuation process and the allocation of security forces to guarantee the public order. In the fourth and last stage of the planning horizon, the schedules and the routes for the emergency vehicles to evacuate the population are defined. The flood planning framework also incorporates the dynamic aspects of a flood emergency by considering that traveling times change over time and the population is not affected at the same time, resulting in evacuation order issued over time; by simulating the reaction to the evacuation orders; and by considering that shelters and emergency vehicles become available over time.

A real and more complex world-based case study is used to illustrate the applicability of the flood planning framework. The different stages are solved in a reasonable amount of time for an emergency situation and the sequential solving of the different problems allows civil protection authorities to start preparing the response to the flood emergency while other decisions are ongoing. The sensitivity analysis demonstrated that having more resources or resources available earlier lead to a decrease of the total evacuation time.

To further increase the applicability and reliability of the flood planning framework, several steps can be considered in the future. For instance, the flood planning framework should consider the location of the population by time of the day, e.g., if the flood occurs during the night, it is expected to have the majority of the population at home whereas if it happens during the day it is expected to have the majority of the population at work or school. In addition, the flood planning framework should be prepared to determine the necessary number of shelters and emergency vehicles over time, in order to achieve a specific goal, such as to evacuate the affected population within a specific amount of time.

6. CONCLUSIONS

Floods are a significant threat for most countries not only because they are one of the most frequent natural disaster but also because of the devastating consequences. According to the latest Intergovernmental Panel on Climate Changes' report (Ranasinghe et al., 2021), this scenario is not expected to change since floods are projected to increase considerably over the century.

Most countries have emergency plans that prepared them to face flood emergencies. These emergency plans are very complex because they are hierarchical, comprising different agencies with different lines of action and different emergency operations in different areas of action. Although these emergency plans are extremely extensive, they do not define exact response actions and consequently decisions are left for real judgments based on the experience of the entity responsible, on previous emergency studies, and on a set of standard procedures.

Disaster management and emergency logistics have been well studied within the scientific literature for the last forty decades. However, there is still scope for improvements on more realistic approaches and on new modeling techniques and solution methodologies. Focusing on the preparedness and response phases, shelter location, warning issuing, and evacuation routing are fundamental disaster operations to minimize the devastating consequences of flooding.

In a flood emergency it is important to understand the propagation of this natural disaster. Although it contains a significant level of uncertainty, it is possible to predict a flood magnitude and propagation. Since a flood evolves in time and space, its impacts are not felt immediately. For instance, different areas are affected at different times as well as road conditions, i.e., the levels of water on the road network change over time and may, in some time periods, be impossible to use the road network. Besides this, the affected population does not respond in the same way to flood warnings and evacuation follows a pattern, known as an S-shaped curve. The evacuation destination and mode of transportation can also be different, i.e., the affected population can evacuate to shelters or to other destinations, such as friends and relatives' homes, and can reach the safe destinations using private vehicles or with the support of authorities. Moreover, authorities' resources, such as shelters and emergency vehicles, are not readily available. For example, shelters need to be equipped to receive the affected population and emergency vehicles need drivers to be operational.

In order to help authorities facing these practical challenges, characterizing flood emergency logistics operations, this research proposed a flood planning framework comprising four stages: i) in the first stage, all necessary data is collected and processed; ii) in the second stage, both shelter location and evacuation decisions, such as evacuation order issuing, shelter opening times and shelter allocation, are optimized. The multi-period shelter location-allocation model with evacuation orders for flood disasters is applied and the problem is solved using a simulated annealing; iii) in the third stage, possible congested zones are identified and consecutively security forces may be allocated to them in order to guarantee public order; iv) in the last stage, emergency vehicles schedules and routes are optimized. The multi-period vehicle evacuation model with a time-space network is applied and the problem is solved using a rolling horizon approach. The flood planning framework includes the dynamic aspects of the flood emergency problem, such as road conditions vary over time, demand behavior follow a pattern over time, resource availability over time, and other constraints such as resources limitations. Therefore, the optimization models applied in the second and third stage are dynamic and aim at minimizing the overall evacuation time.

For instance, assuming that a flood is foreseen and its propagation is known, the flood planning framework can be executed. Civil protection authorities will know, in a short amount of time, which shelters need to be opened to rescue all the affected population and when the affected population should start evacuating. With this information, civil protection authorities can start preparing the first shelters with support and medical staff as well as essential goods and supplies and can also alert the population who need to evacuate first and thereby ensuring its protection. While the authorities are preparing the response to the flood emergency, the flood planning framework will provide information on the evacuation process. Civil protection authorities will know which and when each emergency vehicles will be necessary and can start allocating drivers and preparing the evacuation. In addition, authorities will know the most congestion zones of the road network where security forces should be allocated to guarantee the public order.

The sequential resolution of the flood emergency problem can be seen as a limitation, since the integration of some emergency operations could provide better solutions. An integrated approach can be challenging in terms of computing times, which may not be compatible with an emergency disaster, and therefore new problem formulation and new solution methodologies need to be proposed. To further improve the flood planning framework, a friendly-user interface, which integrates the optimization models and the solutions, has to be developed to enable the use of the flood planning framework in practice. For more realistic modelling, a scenario approach may be considered to cope with the uncertainty associated to emergency logistics.

This research validated the importance of the time component when modeling emergency disasters. Taking into account the challenges on disaster management, this research integrated different emergency operations, such as shelter location, evacuation order issuing, evacuation routing for those evacuating to shelters using private vehicles or with the help of authorities and for those evacuating to other destinations while considering resources limitations and availability and demand behavior. The coordination of different agents with specific lines of action, such as security forces to ensure public order, was also taken into account. In addition, this research promoted the interdisciplinary research by using appropriate flood models to predict flood propagation. This research also contributed to support the decision of decision makers as well as to bring resilience, not only to flood emergency plans, but also for other disasters whose propagation can be predicted, such as wildfires. Similar to floods, wildfires are expected to increase in the following years. According to the Intergovernmental Panel on Climate Changes' report (Ranasinghe et al., 2021), by 2050 more than half of the globe land area will experience a significant increase in fire weather. Within the literature, Miller et al.

(2015) proposed a bushfire spread prediction tool – SPARK - that provides information on the affected area over time.

REFERENCES

Abdelgawad, H., & Abdulhai, B. (2012). Large-Scale Evacuation Using Subway and Bus Transit: Approach and Application in City of Toronto. *Journal of Transportation Engineering*, *138*(10), 1215–1232. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000371

Altay, N., & Green, W. G. (2006). OR/MS research in disaster operations management. *European Journal of Operational Research*, *175*(1), 475–493. https://doi.org/10.1016/j.ejor.2005.05.016

American Red Cross. (2002). Standards for Hurricane Evacuation Shelter Selection. *ARC 4496*, *January*.

Anaya-Arenas, A. M., Renaud, J., & Ruiz, A. (2014). Relief distribution networks: a systematic review. *Annals of Operations Research*, *223*(1), 53–79. https://doi.org/10.1007/s10479-014-1581-y

Antunes, A., & Peeters, D. (2001). On solving complex multi-period location models using simulated annealing. *European Journal of Operational Research*, *130*, 190–201. https://doi.org/10.1016/S0377-2217(00)00051-5

Antunes, A., Seco, A., & Pinto, N. (2003). An accessibility–maximization approach to road network planning. *Computer-Aided Civil and Infrastructure Engineering*, *18*, 224–240. https://doi.org/10.1111/1467-8667.00312

Autoridade Nacional de Protecção Civil. (2016). *Proteção Civil*. http://www.prociv.pt/pt-pt/PROTECAOCIVIL/SISTEMAPROTECAOCIVIL/Paginas/default.aspx

Bayram, V. (2016). Optimization models for large scale network evacuation planning and management: A literature review. *Surveys in Operations Research and Management Science*, *21*(2), 63–84. https://doi.org/10.1016/j.sorms.2016.11.001

Bennett, G., Yang, L., & Simeonova, B. (2017). A heuristic approach to flood evacuation planning. *Proceedings of the International ISCRAM Conference*, *2017-May*, 380–388.

Berkoune, D., Renaud, J., Rekik, M., & Ruiz, A. (2012). Transportation in disaster response operations. *Socio-Economic Planning Sciences*, *46*(1), 23–32.

https://doi.org/10.1016/j.seps.2011.05.002

Bish, D. R. (2011). Planning for a bus-based evacuation. *OR Spectrum*, *33*(3), 629–654. https://doi.org/10.1007/s00291-011-0256-1

Bish, D. R., & Sherali, H. D. (2013). Aggregate-level demand management in evacuation planning. *European Journal of Operational Research*, *224*(1), 79–92. https://doi.org/10.1016/j.ejor.2012.07.036

Bretschneider, S., & Kimms, a. (2011). A basic mathematical model for evacuation problems in urban areas. *Transportation Research Part A: Policy and Practice*, *45*(6), 523–539. https://doi.org/10.1016/j.tra.2011.03.008

Bretschneider, S., & Kimms, a. (2012). Pattern-based evacuation planning for urban areas. *European Journal of Operational Research*, *216*(1), 57–69. https://doi.org/10.1016/j.ejor.2011.07.015

Caunhye, A. M., Nie, X., & Pokharel, S. (2012). Optimization models in emergency logistics: A literature review. *Socio-Economic Planning Sciences*, *46*(1), 4–13. https://doi.org/10.1016/j.seps.2011.04.004

Chanta, S., & Sangsawang, O. (2012). Shelter-site selection during flood disaster. *Lecture Notes in Magement Science*, *4*, 282–288.

Chen, C., & Chao, S. (2004). A Time-Space Network Model for Allocating Yard Storage Space for Export Containers. *Transportation Planning Journal*, *33*(2), 227–248.

Chen, Z., Chen, X., Li, Q., & Chen, J. (2013). The temporal hierarchy of shelters: a hierarchical location model for earthquake-shelter planning. *International Journal of Geographical Information Science*, *27*(8), 1612–1630. https://doi.org/10.1080/13658816.2013.763944

Chiu, Y.-C., Zheng, H., Villalobos, J., & Gautam, B. (2007). Modeling no-notice mass evacuation using a dynamic traffic flow optimization model. *IIE Transactions*, *39*(1), 83–94. https://doi.org/10.1080/07408170600946473

COM. (2004). *Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - Flood risk management - Flood prevention, protection and mitigation*.

CRED, & UNDRR. (2021). *2020 The Non-Covid year in disasters: Global trends and perspectives*. http://hdl.handle.net/2078.1/245181

Declaração (extracto) n.º 97/2007, de 16 de maio, do Serviço de Estrangeiros e Fronteiras, Diário da República: II série, n.º 94 2006 (2007).

Decreto-Lei n.º 114/2011, de 30 de novembro, do Ministério da Administração Interna, Diário da República: I série, n.º 230 (2011). https://dre.pt/dre/detalhe/decreto-lei/114-2011-146221

Decreto-Lei n.º 134/2006, de 25 de julho, do Ministério da Administração Interna, Diário da República: I série, n.º 142 (2006). https://dre.pt/dre/detalhe/decreto-lei/134-2006-539218

Decreto-Lei n.º 44/2019, de 1 de abril, da Presidência do Conselho de Ministros, Diário da República: I série, n.º 64 (2019). https://dre.pt/dre/detalhe/decreto-lei/44-2019-121748966

Decreto-Lei n.º 45/2019, de 1 de abril, do Ministério da Administração Interna, Diário da República: I série, n.º 64 (2019). https://dre.pt/dre/detalhe/decreto-lei/45-2019-121748967

Decreto-Lei n.º 56/2008, de 26 de março, do Ministério da Administração Interna, Diário da República: I série, n.º 60 (2008). https://dre.pt/dre/detalhe/decreto-lei/56-2008-246491

Decreto-Lei n.º 72/2013, de 31 de maio, do Ministério da Administração Interna, Diário da República: I série, n.º 105 (2013). https://dre.pt/dre/detalhe/decreto-lei/72-2013-513607

Decreto-Lei n.º 75/2007, de 29 de março, do Ministério da Administração Interna, Diário da República: I série, n.º 63 (2007). https://dre.pt/dre/detalhe/decreto-lei/75-2007-520461

Decreto-Lei nº 203/2006, de 27 de outubro, do Ministério da Administração Interna, Diário da República: I série, n.º 208 (2006). https://dre.pt/dre/detalhe/decreto-lei/203-2006-545640

Deghdak, K., T'kindt, V., & Bouquard, J. L. (2015). Scheduling evacuation operations. *Journal of Scheduling*, *19*(4), 1–12. https://doi.org/10.1007/s10951-015-0461-x

Dhamala, T. N., & Adhikari, I. M. (2018). *On Evacuation Planning Optimization Problems from Transit-based Perspective*. *15*(1), 29–47.

Dikas, G., & Minis, I. (2016). Solving the bus evacuation problem and its variants. *Computers and Operations Research*, *70*, 75–86. https://doi.org/10.1016/j.cor.2015.12.012

Directive 2007/60/EC of the European Council and European Parliament of 23 October, Official Journal of the European Union: L 288 (2007). http://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32007L0060&from=EN

Divisão de Planeamento de Proteção Civil. (2017). Manual de apoio à elaboração e operacionalização de Planos de Emergência de Protecção Civil. In *Cadernos Técnicos PROCIV* (ANPC, pp. 1–48).

Doostparast, M., Kolahan, F., & Doostparast, M. (2015). Optimisation of PM scheduling for multi-component systems – a simulated annealing approach. *International Journal of Systems Science*, *46*(7), 1199–1207. https://doi.org/10.1080/00207721.2013.815822

Esposito Amideo, A., Scaparra, M. P., & Kotiadis, K. (2019). Optimising shelter location and evacuation routing operations: The critical issues. *European Journal of Operational Research*, *279*(2), 279–295. https://doi.org/10.1016/j.ejor.2018.12.009

EXCIMAP. (2007). *Handbook on good practices for flood mapping in Europe*. https://ec.europa.eu/environment/water/flood_risk/flood_atlas/index.htm

Galindo, G., & Batta, R. (2013). Review of recent developments in OR/MS research in disaster operations management. *European Journal of Operational Research*, *230*(2), 201–211. https://doi.org/10.1016/j.ejor.2013.01.039

Gama, M., Santos, B. F., & Scaparra, M. P. (2016). A multi-period shelter location-allocation model with evacuation orders for flood disasters. *EURO Journal on Computational Optimization*, *4*(3–4), 299–323. https://doi.org/10.1007/s13675-015-0058-3

Glomb, L., Liers, F., & Rösel, F. (2021). A rolling-horizon approach for multi-period optimization. *European Journal of Operational Research*. https://doi.org/10.1016/j.ejor.2021.07.043

Goerigk, M., & Grün, B. (2014). A robust bus evacuation model with delayed scenario information. *OR Spectrum*, *36*(4), 923–948. https://doi.org/10.1007/s00291-014-0365-8

Hénonin, J., Russo, B., Roqueta, D. S., Sanchez-, R., Donna, N., Domingo, S., Thomsen, F., & Mark, O. (2013). Real-time urban flood forecasting and modelling – a state of the art. *Journal of Hydroinformatics*, *15*(3), 717–736. https://doi.org/doi: 10.2166/hydro.2013.132.

Huang, K., Jiang, Y., Yuan, Y., & Zhao, L. (2015). Modeling multiple humanitarian objectives in emergency response to large-scale disasters. *Transportation Research Part E*, *75*, 1–17. https://doi.org/10.1016/j.tre.2014.11.007

Janssen, M., Lee, J., Bharosa, N., & Cresswell, A. (2009). Advances in multi-agency disaster management: Key elements in disaster research. *Information Systems Frontiers*, *12*(1), 1–7. https://doi.org/10.1007/s10796-009-9176-x

Johnson, D. S., Aragon, C. R., McGeoch, L. a, & Shevon, C. (1989). Optimization by Simulated Annealing: An Experimental Evaluation; Part I, Graph Partitioning. *Operations Research*, *37*(6), 865–892.

Khattak, M. S., Anwar, F., Saeed, T. U., Sharif, M., Sheraz, K., & Ahmed, A. (2016). Floodplain Mapping Using HEC-RAS and ArcGIS: A Case Study of Kabul River. *Arabian Journal for Science and Engineering*, *41*(4), 1375–1390. https://doi.org/10.1007/s13369-015-1915-3

Kirkpatrick, S., Gelatt, C. D., & Vecchi, M. P. (1983). Optimization by Simulated Annealing. *Science*, *220*(4598), 671–680.

Kongsomsaksakul, S., Chen, A., & Yang, C. (2005). Shelter Location-Allocation Model For Flood Evacuation Planning. *Journal Os the Eastern Asia Society for Transportation Studies*, *6*, 4237–4252.

Kuzma, S., & Luo, T. (2020). *The Number of People Affected by Floods Will Double Between 2010 and 2030*. World Resources Institute. https://www.wri.org/insights/number-people-affected-floods-will-double-between-2010-and-2030

Leandro, J., & Shucksmith, J. (2021). Editorial-modelling of floods in urban areas. *Water*, *13*(12), 2–4. https://doi.org/10.3390/w13121689

Lee, Y. H., Kim, H. Il, Han, K. Y., & Hong, W. H. (2020). Flood evacuation routes based on spatiotemporal inundation risk assessment. *Water (Switzerland)*, *12*(8). https://doi.org/10.3390/w12082271

Lei n.º 27/2006, de 3 de julho, da Assembleia da República, Diário da República: I série, n.º 126 (2006).

Lei n.º 44/2017, de 19 de junho, da Assembleia da República, Diário da República: I série, n.º 116 (2017). https://dre.pt/dre/detalhe/lei/44-2017-107524707

Lei n.º 58/2005, de 29 de dezembro, da Assembleia da República, Diário da República: I série, n.º 249 (2005). https://dre.pt/dre/detalhe/lei/58-2005-469068

Lei n.º 65/2007, de 12 de novembro, da Assemblea da República, Diário da República: I série, n.º 217 8353 (2007). https://dre.pt/dre/detalhe/lei/65-2007-629393

Lei n.º 80/2015 de 3 de agosto, da Assembleia da República, Diário da República: I série, n.º 149 (2015). https://dre.pt/dre/detalhe/lei/80-2015-69927759

Lei Orgânica n.º 1/2011, de 30 de novembro, da Assembleia da República, Diário da

República: I série, n.º 230 (2011). https://dre.pt/dre/detalhe/lei-organica/1-2011-146220

Li, A., Nozick, L., Xu, N., & Davidson, R. (2012). Shelter location and transportation planning under hurricane conditions. *Transportation Research Part E: Logistics and Transportation Review*, *48*(4), 715–729. https://doi.org/10.1016/j.tre.2011.12.004

Li, J., Ozbay, K., Bartin, B., Iyer, S., & Carnegie, J. a. (2013). Empirical Evacuation Response Curve During Hurricane Irene in Cape May County, New Jersey. *Transportation Research Record: Journal of the Transportation Research Board*, *2376*(1), 1–10. https://doi.org/10.3141/2376-01

Li, L., Jin, M., & Zhang, L. (2011). Sheltering network planning and management with a case in the Gulf Coast region. *International Journal of Production Economics*, *131*(2), 431–440. https://doi.org/10.1016/j.ijpe.2010.12.013

Lim, G. J., Zangeneh, S., Reza Baharnemati, M., & Assavapokee, T. (2012). A capacitated network flow optimization approach for short notice evacuation planning. *European Journal of Operational Research*, *223*(1), 234–245. https://doi.org/10.1016/j.ejor.2012.06.004

Lorena, L. A. N., & Senne, E. L. F. (2004). A column generation approach to capacitated p-median problems. *Computers and Operations Research*, *31*(6), 863–876. https://doi.org/10.1016/S0305-0548(03)00039-X

Lu, W., Wang, F., Liu, L., Hu, G., & Mao, J. (2021). Pedestrian–bus route and pickup location planning for emergency evacuation. *Transport*, *36*(2), 176–184. https://doi.org/10.3846/transport.2020.13674

Melo, N., Santos, B. F., & Leandro, J. (2015). A prototype tool for dynamic pluvial-flood emergency planning. *Urban Water Journal*, *12*(1), 79–88. https://doi.org/10.1080/1573062X.2014.975725

Mileti, D., Sorensen, J., & O'Brien, P. (1992). Toward an Explanation of Mass Care Shelter Use in Evacuations. *International Journal of Mass Emergencies and Disasters*, *10*(1), 25–42.

Miller, C., Hilton, J., Sullivan, A., & Prakash, M. (2015). SPARK – A bushfire spread prediction tool. *IFIP Advances in Information and Communication Technology*, *448*, 262–271. https://doi.org/10.1007/978-3-319-15994-2_26

Murray-Tuite, P., & Wolshon, B. (2013). Evacuation transportation modeling: An overview of research, development, and practice. *Transportation Research Part C: Emerging Technologies*, *27*, 25–45. https://doi.org/10.1016/j.trc.2012.11.005

Murray, A. T., & Church, R. L. (1996). Applying simulated annealing to location-planning models. *Journal of Heuristics*, *2*(1), 31–53. https://doi.org/10.1007/BF00226292

Na, L., Xueyan, S., & Mingliang, Q. (2012). A Bi-objective Evacuation Routing Engineering Model with Secondary Evacuation Expected Costs. *Systems Engineering Procedia*, *5*. https://doi.org/10.1016/j.sepro.2012.04.001

Nadeem, I., Uduman, P. S. S., & Dar, A. A. (2020). An integrated bus - Based routing and dispatching approach for flood evacuation. *Yugoslav Journal of Operations Research*, *30*(4), 443–460. https://doi.org/10.2298/YJOR190415028N

Nayak, S., & Zlatanova, S. (2008). *Remote Sensing and GIS Technologies for Monitoring and Prediction of Disasters*. Berlin Heidelberg.

OECD. (2012). *OECD Environmental Outlook to 2050*.

OECD. (2019). *Applying the OECD Principles on Water Governance to Floods*. OECD. https://doi.org/10.1787/d5098392-en

Özdamar, L., Ekinci, E., & Kucukyazici, B. (2004). Emergency Logistics Planning in Natural Disasters. *Annals of Operations Research*, *129*, 217–245.

Özdamar, L., & Ertem, M. A. (2015). Models, solutions and enabling technologies in humanitarian logistics. *European Journal of Operational Research*, *244*(1), 55–65. https://doi.org/10.1016/j.ejor.2014.11.030

Pardal, J., Cunha, L., Oliveira Tavares, A., Santos, P. P., & Leitão, L. (2022). Impactos das grandes cheias do rio Mondego na região de Coimbra - uma resenha histórica. In A. Lourenço, L; Nunes (Ed.), *Risco de Cheias e Risco de Inundações Fluviais. Aprender com o Passado* (RISCOS-A, pp. 75–107). https://doi.org/10.34037/978-989-9053-12-0_10_4

Park, Sangki, van de Lindt, J. W., Gupta, R., & Cox, D. (2012). Method to determine the locations of tsunami vertical evacuation shelters. *Natural Hazards*, *63*(2), 891–908. https://doi.org/10.1007/s11069-012-0196-3

Park, Seula, Lee, G., & Kim, J. O. (2020). Flood evacuation mapping using a time-distance cartogram. *ISPRS International Journal of Geo-Information*, *9*(4). https://doi.org/10.3390/ijgi9040207

Qazi, A. N., Nara, Y., Okubo, K., & Kubota, H. (2017). Demand variations and evacuation route flexibility in short-notice bus-based evacuation planning. *IATSS Research*, *41*(4), 147–152. https://doi.org/10.1016/j.iatssr.2017.01.002

Qazi, A. N., Okubo, K., & Kubota, H. (2016). Short-Notice Bus-Based Evacuation under Dynamic Demand Conditions. *Asian Transport Studies*, *4*(1), 228–244. https://doi.org/10.11175/eastsats.4.228

Qazi, A. N., Okubo, K., & Kubota, H. (2017). Use of the Time-Space Network Technique for Modeling Gradual Flooding and Congestion Delays during Short-Notice Bus-Based Evacuations. *Ournal of the Eastern Asia Society for Transportation Studies*, *12*. https://www.jstage.jst.go.jp/article/easts/12/0/12_2444/_article/-char/ja/

Ranasinghe, R., Ruane, A. C., Vautard, R., Arnell, N., Coppola, E., Cruz, F. A., Dessai, S., Islam, A. S., Rahimi, M., Ruiz Carrascar, D., Sillmann, J., Sylla, M. B., Tebaldi, C., Wang, W., & Zaaboul, R. (2021). Climate change information for regional impact and for risk assessment. In Cambridge University Press (Ed.), *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen,*.

Rawls, C. G., & Turnquist, M. a. (2012). Pre-positioning and dynamic delivery planning for short-term response following a natural disaster. *Socio-Economic Planning Sciences*, *46*(1), 46–54. https://doi.org/10.1016/j.seps.2011.10.002

Renne, J. L. (2018). Emergency evacuation planning policy for carless and vulnerable populations in the United States and United Kingdom. *International Journal of Disaster Risk Reduction*, *31*(January), 1254–1261. https://doi.org/10.1016/j.ijdrr.2018.02.016

Resolução n.º 15/2008, de 21 de abril, da Assembleia da República, Diário da República: I série, n.º 78 (2008). https://dre.pt/dre/detalhe/resolucao-assembleia-republica/15-2008-249873

Resolução n.º 30/2015, de 7 de maio, da Comissão Nacional de Proteção Civil, Diário da República: II série, n.º 88 18 (2015). https://dre.pt/application/conteudo/67163565

Rodríguez-Espíndola, O., & Gaytán, J. (2015). Scenario-based preparedness plan for floods. *Natural Hazards*, *76*(2), 1241–1262. https://doi.org/10.1007/s11069-014-1544-2

Samany, N. N., Sheybani, M., & Zlatanova, S. (2021). Detection of safe areas in flood as emergency evacuation stations using modified particle swarm optimization with local search. *Applied Soft Computing*, *111*. https://doi.org/10.1016/j.asoc.2021.107681

Sayyady, F., & Eksioglu, S. D. (2010). Optimizing the use of public transit system during no-notice evacuation of urban areas. *Computers & Industrial Engineering*, *59*(4), 488–495. https://doi.org/10.1016/j.cie.2010.06.001

Sherali, H. D., Carter, T. B., & Hobeika, A. G. (1991). A location-allocation model and algorithm for evacuation planning under hurricane/flood conditions. *Transportation Research Part B: Methodological*, *25*(6), 439–452. https://doi.org/10.1016/0191-2615(91)90037-J

Simonovic, S. P. (2011). *Systems Approach to Management of Disasters: Methods ans Applications*. John Wiley & Sons Inc.

Simpson, N. C., & Hancock, P. G. (2009). Fifty years of operational research and emergency response. *Journal of the Operational Research Society*, *60*(SUPPL. 1). https://doi.org/10.1057/jors.2009.3

Stepanov, A., & Smith, J. M. (2009). Multi-objective evacuation routing in transportation networks. *European Journal of Operational Research*, *198*(2), 435–446. https://doi.org/10.1016/j.ejor.2008.08.025

Swamy, R., Kang, J. E., Batta, R., & Chung, Y. (2017). Hurricane evacuation planning using public transportation. *Socio-Economic Planning Sciences*, *59*, 43–55. https://doi.org/10.1016/j.seps.2016.10.009

The UN Refugees Agency, U. N. H. C. for R. (2007). *Handbook for Emergencies* (3th ed.).

Thévenaz, C., & Resodihardjo, S. L. (2010). All the best laid plans…conditions impeding proper emergency response. *International Journal of Production Economics*, *126*(1), 7–21. https://doi.org/10.1016/j.ijpe.2009.09.009

Wallemacq, P. U. C. (2018). *Economic Losses, Proverty and Disasters 1998-2017*. https://doi.org/10.13140/RG.2.2.35610.08643

WRI. (2015). *World's 15 Countries with the Most People Exposed to River Floods*. http://www.wri.org/blog/2015/03/world's-15-countries-most-people-exposed-river-floods

Yang, L., Liu, Q., Yang, S. H., & Yu, D. (2015). Evacuation planning with flood inundation as inputs. *ISCRAM 2015 Conference Proceedings - 12th International Conference on*

Information Systems for Crisis Response and Management, *2015-Janua*, 56–63.

Yi, W., & Özdamar, L. (2007). A dynamic logistics coordination model for evacuation and support in disaster response activities. *European Journal of Operational Research, 179*(3), 1177–1193. https://doi.org/10.1016/j.ejor.2005.03.077

Yuan, Y., & Wang, D. (2009). Path selection model and algorithm for emergency logistics management. *Computers & Industrial Engineering*, *56*(3), 1081–1094. https://doi.org/10.1016/j.cie.2008.09.033

Yusoff, S. S. A., Benjamin, A. M., Rahman, R. A., & Abdul-Rahman, S. (2019). Optimization model for a flood evacuation assignment problem: A case study. *AIP Conference Proceedings*, *2138*(August). https://doi.org/10.1063/1.5121104

Zhao, X., Ji, K., Xu, P., Qian, W. wen, Ren, G., & Shan, X. nian. (2020). A round-trip bus evacuation model with scheduling and routing planning. *Transportation Research Part A: Policy and Practice, 137*(May), 285–300. https://doi.org/10.1016/j.tra.2020.05.008

APPENDIX A

Table A.1 – Degree of severity (*Declaração (Extracto) n.º 97/2007, de 16 de Maio, Do Serviço de Estrangeiros e Fronteiras, 2007*).

Severity	Description
Residual	No injuries or fatalities. There is no withdrawal of people for a short period (12 hours). Little or no personal support required (no support at monetary or material). Meaningless damages. There is a low or inexistent level of constraints to the community. There is no impact on the environment There are no financial losses.
Reduced	Small number of injuries but no fatalities. Some hospitalizations and withdrawal of people for a period less than 24 hours. Some support staff and reinforcements are necessary. Some damage. Disruption (less than 24 hours). Small impact on environment with no lasting effects. There are some financial losses.
Moderated	Medical treatment required but no fatalities. Some hospitalizations. Withdrawal of people over a period of 24 hours. Some technical personnel required. Some damage. Some disruption in the community (less than 24 hours). Small impact on environment with no lasting effects. There are financial losses.
Accentuated	High number of injuries and hospitalizations. Large number of people withdrawn for a period exceeding 24 hours. Fatalities. External resources required to support staff. Significant damage that requires external resources. Functioning part of the community with some services unavailable. Some impacts in the community with long-term effects. There are significant financial losses and financial assistance needed.
Critical	Critical situation. Large numbers of injuries and hospitalization. Large-scale withdrawal of people over a long period. Significant number of fatalities. Support staff and necessary reinforcement. The community can no longer function without significant support. Significant environmental impact and / or permanent damage.

Table A.2 – Degree of probability (*Declaração (Extracto) n.º 97/2007, de 16 de Maio, Do Serviço de Estrangeiros e Fronteiras, 2007*).

Probability	Description
Confirmed	Real occurrence verified
High	It is expected to occur in almost all circumstances, and / or high level of incidents, and / or strong evidence, and / or strong likelihood of the event, and / or strong reason to occur, may occur once a year or more.
Medium-High	Will probably occur in almost all circumstances, and / or regular records of incidents and strong reasons to occur, may occur once every 5 years.
Medium	May occur at a certain time, and / or with an uncertain intervals, and weak random reason to occur, may occur once every 20 years.
Medium-Low	It is not likely to occur; No records or reasons to estimate that occurrence; may occur once every 100 years.
Low	May occur only in exceptional circumstances. May occur once every 500 years or more.