Flood Impacts on Road Transportation

Submitted by Katya Pyatkova to the University of Exeter

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I certify that all material in this thesis which is not my own work has been identified and that no material has previously been submitted and approved for the award of a degree by this or any other University.

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ABSTRACT

Flood disasters can penetrate every single aspect of human life and road transportation is no exception. However, flood impacts on road transportation is an area that has not been explored in detail in the past. The focus of this PhD study is on the performance assessment of a road network subject to flooding. In this work, several challenges were overcome with original ideas. The first was integrating the flood and the transport systems - both exhibiting strong temporal and spatial variations. This has been successfully achieved by implementing a novel methodology into a tool that modelled flood intensities output into a transport network constraint in a traffic model. The logic of the framework is intuitive – roads with shallow flood depth impose speed limitations, and roads with deep flood depth are closed for traffic. The developed tool enabled a quick and consistent technique to integrate the flood and the transport models in three different ways – static, semi-dynamic and dynamic. The static integration considers only one flood map to determine traffic conditions, whereas the semi-dynamic and the dynamic integrations use multiple maps to mimic the flood propagation in the traffic model. This thesis is the first to achieve semi-dynamic or dynamic integration of the two models.

The second challenge was the assessment of the impacts. Intangible impacts such as travel delays propagating as knock-on effects can easily be misrepresented or even misunderstood. Employing a microscopic transport model allows for the assessment of direct effects and the knock-on consequences on individual drivers as well as the whole traffic system. Results in one case study suggest that the average travel time rose with 45% on average for 75% of the vehicles in the most affected hour of the simulation. The monetary value of traffic delays may not be as significant as the flood direct tangible damage, but flood impacts on road transportation may be more straightforward to alleviate if traffic authorities follow contingency plans to reduce traffic demand or mitigate potential interruptions of traffic supply. To analyse how potential interventions affect the transport system performance, three interventions were implemented into the model.

The third challenge was the evaluation of the performance of a road transport system and the assessment of its resilience to flooding. Perusing this, a novel

rationale to assess the resilience of a transport network has been developed. This method distinguishes reliability from resilience to define the nonlinear bounds of standard dry weather conditions, and any fluctuation beyond these bounds is defined as exceptional conditions. By separating reliability from resilience, the extent of both magnitude and duration is refined and contributes to better understanding of the system performance.

This PhD thesis aspires to bridge the gap between flooding and traffic by providing a workable open source tool, which can be applied to other case studies and thus open the potential for further development in that area. As well as practical ideas, the theoretical contribution in assessing system resilience can be applied in other fields.

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LIST OF ABBREVIATIONS

AM	Ante meridiem: Before noon
CI	Critical infrastructure
CO	Carbon Monoxide
CO_2	Carbon dioxide
EU	European Union
GDB	Geodatabase
GHG	Greenhouse gas
GIS	Geographic information system
HC	Hydrocarbons
HBEFA	Handbook of Emission Factors for Road Transport
ID	Identifier
IM1	Intervention measure 1: Design
IM2	Intervention measure 2: Operational
IPAWS	Integrated Public Alert and Warning System
JOSM	Java OpenStreetMap Editor

NOx	Nitrogen oxides (NO nitric oxide, NO_2 nitrogen dioxide)
OSM	Open Street Map
PEARL	Preparing for Extreme And Rare events in coastaL regions (EC FP7 project)
PM	Post Meridiem: After noon
PMx	Particle mass
SUMO	Simulation of Urban Mobility
VSS	Variable Speed Signs
WTP	Willingness to pay
XML	eXtensible Markup Language

NOTATIONS LIST

i	Time step
No	Number of vehicles
Q(t)	Quality of service
Per	Performance
R	Resilience
Rel	Reliability
Sc	Scenario
ScX	Considered dry weather scenario
ScXf	Considered flooded scenario

1 INTRODUCTION

1.1 General background and motivation

Effective risk management appropriately allocates financial resources to minimise the negative consequences of a potential event. A better understanding of flood impacts can aid more informed decision making. Hence, much research has been dedicated over the years to flood impact appraisal. Although flood impacts have been modelled for decades, there is a lot of room for innovation. Flood impacts on road transportation are still not explored much. There are only a few applications in that area, and they did not have the required depth to describe the involved processes. To address this gap in the current research, this thesis aspires to develop a novel approach for capturing the interactions between flooding and road transportation.

Exploring an area of science which has not been previously studied much, is always tempting and challenging. Assessing flood impacts on road transportation is not an abstract topic of research, and it can affect many drivers on the way to their destinations. Traffic jams are an everyday experience to many, and it is not hard to imagine that a flood with a large geographical scope may lead to devastating consequences for transport. Even though this problem is recognised, it is surprising how little we know about it.

Flooding often is a result of a complex combination of various causes (coastal, fluvial and pluvial). Further, transportation systems are susceptible to external disturbances. By investigating the interactions between these two complex and dynamic systems, this thesis aspires to assess the knock-on effect of flooding on transportation. The motivation of this thesis is to shed light on that highly uncertain multidisciplinary research. Its aim is not just proposing a methodology, but also providing a software tool to facilitate further replication. Thus, the biggest aspiration here is to engage in a perhaps neglected area of research.

As this research is multidisciplinary, its *practical value* also lies in both flood impact appraisal and transport systems' management. Originally it was intended to provide an insight into a rarely estimated flood impact, but its potential application in traffic management may even be of greater importance. The knock-on effect of floods on transport systems may have unpredictable consequences which have to be examined. As with other indirect impacts, the locations of the most severe congestion may not be in the proximity of the flooded area. Identifying the most vulnerable roads enables the examination of the transport system's weaknesses and potential consequences. However, acknowledging the most endangered locations is arguably not enough for adequate risk management of dynamic systems. Consequently, intervention measures must be proposed, modelled and evaluated with a final objective to develop contingency plans which would facilitate a timely and effective traffic management response to system shocks and stresses.

After the extensive flooding in 2013-2014 in the United Kingdom, the Department for Transport (2014) reported the lessons learned after the blockage of vital transport corridors and stated that "no room for complacency in managing resilience". And indeed, transportation systems with their interconnectivity and temporal-spatial dynamics require resilience assessment. Therefore, this PhD also focused on improving the methods used to assess resilience as a system performance assessment.

1.2 Research questions

The successful completion of the thesis would address all the objectives and be able to resolve the following research questions:

1. How can flood and transport models be integrated?
2. What are the negative consequences of floods on a transport system?
3. What is the knock-on effect on the overall system?
4. Is dynamic integration of flood and transport models necessary?
5. How can the performance-based resilience of a transport system be assessed?
6. How can different intervention measures enhance the initial resilience of a system?

1.3 Aims and Objectives

The main aim of this thesis is to develop and apply a novel methodology in a workable tool for the assessment of flood impacts on road transportation. The development of a first of its kind tool is a prerequisite to accomplishing another aspiration of the research - the successful dynamic integration of flood and transport models. After achieving this task, the research aims at assessing the resilience of the transport system to flooding and investigating how various intervention strategies facilitate improvement in system resilience.

The study has the following objectives:

1. Examine the existing methods and consider the best available options for the proposed research, while considering available software.
2. Develop a novel methodology for the one-way dynamic integration of flood and traffic models.
3. Based on the methodology, build a robust tool to convert data from the temporary varying flood model output to temporary varying traffic model input
4. Develop a software tool, which can facilitate its application outside this research.
5. Demonstrate the application of the tool in a static, semi-dynamic and dynamic flood-traffic model integration
6. Assess flood impacts on traffic
7. Establish a framework for performance-based resilience assessment of a transport system
8. Assess the effectiveness of intervention strategies for the improvement of system resilience

1.4 Thesis structure

The thesis contains six chapters and their interaction with the objectives of the thesis are depicted in Figure 1-1.

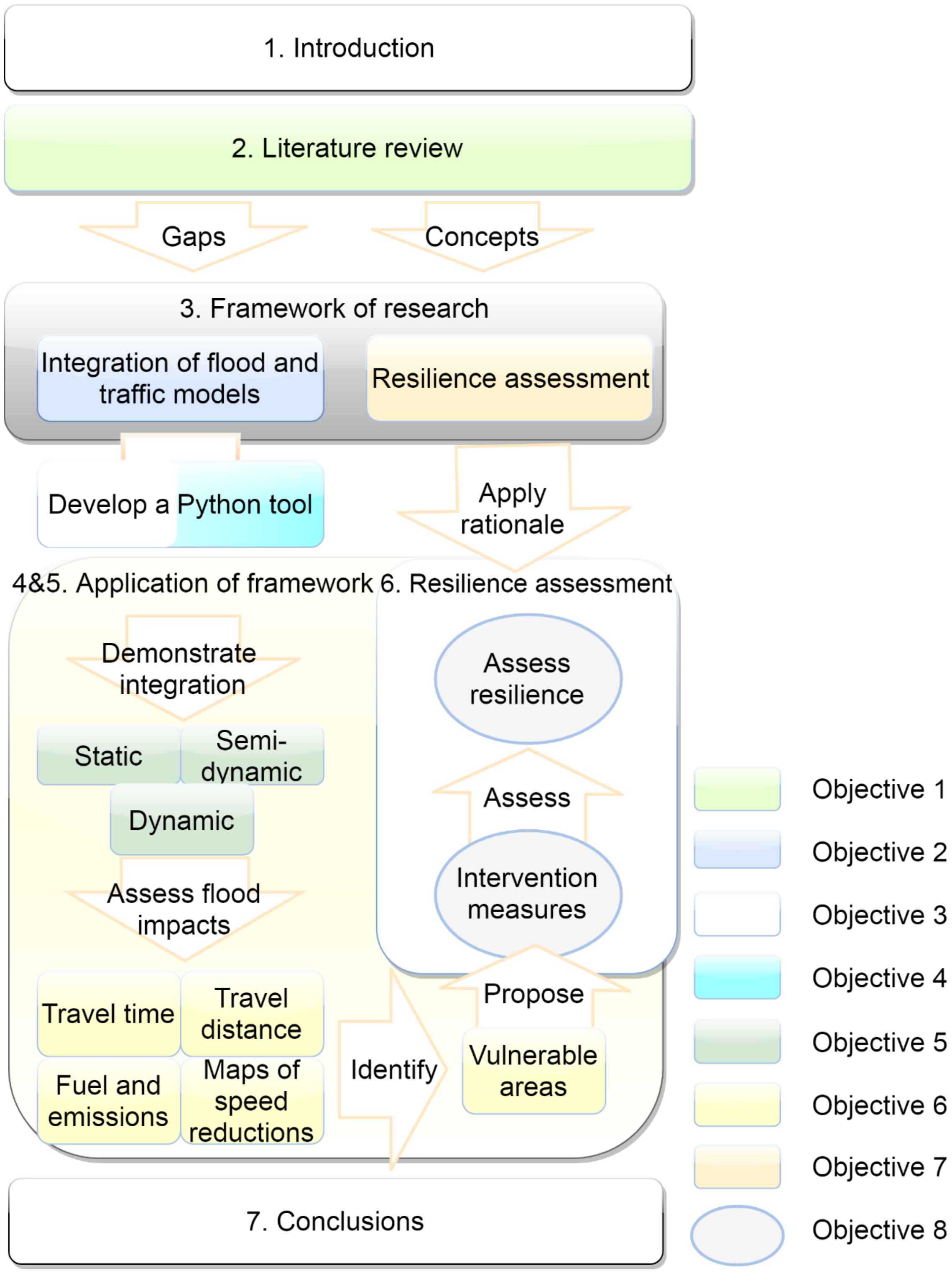

Figure 1-1: Interaction of the objectives within the chapters of the thesis

Chapter 1: Introduction

The chapter provides a short background into the field of the flood impact on road transportation and draws how the existing state of the art in that field have played a motivating role in initialising the research. Following the fundamental aims and objectives of the thesis are listed and depicted in a flowchart to explain how the research progresses within the thesis.

Chapter 2: Literature review

Due to the high interdisciplinarity of the research, the literature review started by describing fundamental definitions in both water science and transport systems. It critically assessed the disagreements between the two areas of engineering while considering how they could complement each other. The resilience assessment in transportation system is one step behind water systems, and some concepts from water science and the opportunities and hurdles were discussed.

The previous papers that have analysed flood impacts on transportation were discussed in order to identify gaps and potential areas of improvements. To further understand what happens when roads are flooded, the literature review focused on the high proportion of flood fatalities in vehicles and looked for answers about why people drive into flood waters. The most straightforward answer was that they are unable to predict the behaviour of their vehicle in flooded waters. A section discussed the stability thresholds of flooded vehicles and the findings determined the critical flood depth of a street closure in the methodology. Last but not least, the literature review discussed how travel delays are monetised in the literature. Using a monetary value per unit time provides an opportunity to compare flood impacts on transportation with other flood impacts.

In essence, the literature review looked at issues concerning water science, transport engineering, psychology, economics, experimental physics.

Chapter 3: Framework of research

This chapter describes how a novel approach to integrating flood and transport models was developed. The methodology was also presented at the Simulation of Urban Mobility (SUMO) conference 2015, Berlin and consequently a book chapter (Pyatkova et al., 2015, 2019b). As one of the central aims of the research is to integrate the flood and the transport model dynamically. To achieve this, the method was translated into a Python tool, which is straightforward to implement in other case studies outside this PhD thesis. The tool was submitted as one of the software outcomes of the European Commission project PEARL (PEARL, 2018).

A novel framework to assess the transport system's resilience was developed within the thesis. This framework aims at evaluating system performance resilience in the face of three indicators – duration, magnitude and severity. The original idea in the methodology is a proposal for discerning reliability from resilience and respectively standard from exceptional conditions.

Chapters 4 & 5: Application of the framework to case studies

The framework is implemented in two case studies in Spain and the Caribbean island of Saint Martin after a detailed description of the traffic model setup. Semi-dynamic integration of the flood and the traffic models are adopted in Saint Martin to demonstrate a possible approach towards the methodology and the tool. Static and dynamic integrations are applied in the case study of Marbella and the differences between the two are discussed. A comprehensive impact assessment of the flooded transport system is analysed with attention to – trip delays, additional travel distance, fuel consumption and greenhouse gas emissions, road speed reductions and impacts on specific journeys.

Some of the results from this chapter were discussed at the 2018 UDM conference in Palermo (Pyatkova et al., 2019a).

Chapter 6: Resilience of the traffic system and application of intervention measures

The resilience of the road transport system is assessed and compared to the resilience of new systems that have intervention measures implemented. These intervention measures all aim to improve the resilience of the transport system, rather than reducing the flood hazard intensities.

Chapter 7: Conclusions

This chapter draws upon the previous chapters and summarizes the fundamental findings, the surprises and the recommendations for further research.

2 LITERATURE REVIEW

2.1 Introduction

This chapter discusses the main definitions and concepts in the water science and the transport systems and then examines flood impacts and in particular flood impacts on road transportation. Particular attention is paid to the idea of resilience and the methods to describe it in both fields. One of the motivations of this PhD is to investigate how a transport system would respond to flooding, given that drivers do not pass through flooded waters. Avoiding flooded streets is essential for reducing flood mortality rates, and a section was dedicated to the flood fatalities associated with vehicles and a short discussion of drivers' behaviour and expectations during flooding. If drivers do decide to drive into flood waters, the literature review examines stability thresholds of vehicles in flood waters. The critical instability value is later incorporated into the methodology to define the requirements for a street closure. Flood impacts on transport disruption have many aspects: traffic delays, additional travelled distance, additional greenhouse gas emissions, frustration. These impacts are all significant and hard to quantify, and the literature review focuses on measures to monetise the most significant impact: traffic delays.

2.2 Relevant fundamental definitions and concepts

Due to the interdisciplinarity of this research, some definitions need to be adopted from the viewpoint of both water science and transport engineering. The examined concepts of vulnerability, risk and resilience have their particularities in both sub-disciplines of civil engineering due to specific characteristics of these fields. First, the water-related concepts are defined, and then the transportation ones are examined together with a critical comparison between the two areas of research.

2.2.1 Water science

By definition, the term flood is determined by the geographical location of the water: whether it is within its normal confines (Samuels, 2009) and 'accumulation of water on areas that are not normally submerged' (IPCC, 2012, p. 175). This definition avoids any prescription on units, driving forces or types of flooding. For the forthcoming definitions, the term hazard is also introduced. Hazard is a 'source of potential harm' (ISO, 2009). Floods can be considered as hazards, given the circumstances that not all floods result in negative consequences. UNISDR (2009) defined harm as a 'loss of life or injury, property damage, social and economic disruption or environmental degradation'. It is important to stress that the term hazard is not understood as an entirely natural phenomenon, but it is also related to possible intervention by humankind. This thesis will focus only on the negative impacts of floods, although positive effects are also possible (e.g. to biodiversity, or replenishment of the groundwater table).

At the dawn of modern floodplain management, White (1945) pointed out that 'floods are acts of God, but losses are largely acts of man'. This statement shapes the current understanding of disaster risk, consisting of two main blocks – disaster and societal vulnerability. It also emphasised the importance of the impact assessment within the risk analysis phase. Before discussing any disaster risk assessment insights, the term *vulnerability* is defined. There is considerable disagreement in the literature whether the vulnerability is the degree of loss due to a disaster (ITC, 2004) or is it associated with the resilience of a system characteristic and its ability to bounce back after a disaster (Sayers et al., 2003). Another discussion is related to the element prone to susceptibility: whether it is going to be a system or just a receptor. The term has many aspects: social, economic, institutional or environmental vulnerabilities (Birkmann, 2008). While describing the meaning of vulnerability, it is critical to note that it differs from exposure, which is the number of elements, located in a hazardous area (UNISDR, 2009). The vulnerability of these elements is a particular characteristic of the system related to a specific type of hazard (Samuels, 2009). The exposed elements are only those that will suffer direct impacts of the floods, while indirect impacts mainly affect elements outside of the flood extent, but are still vulnerable (Merz et al., 2010a). The system concept of vulnerability is essential for this research because one of its main objectives is the flood impacts on traffic congestion and the knock-on effects on the whole traffic system. As a result, this thesis will go beyond the boundaries of the exposed assets, showing the vulnerability of the entire traffic system under both static and dynamic flood conditions.

The previously introduced terms are essential building blocks of the definition of risk. The available descriptions include the idea of the likelihood of occurring hazard in amalgamation with the negative consequences it can cause (for example; Whyte and Burton (1980); Sayers et al. (2002); Schanze et al. (2007); ISO (2009); UNISDR (2009). Klijn et al. (2008) formulated the definition as follows:

$$Risk = hazard * (exposure) * vulnerability \qquad (2\text{-}1)$$

The exposure term is in brackets to underline that not only the directly exposed elements suffer negative consequences. This definition strongly emphasises that risk is something very subjective to humankind. If an area is not populated, no matter the magnitude and the intensity of the event, it will not be considered as a disaster. Still, many authors acknowledged that the two parts of the formula receive uneven scientific attention and recognize the need to enhance research in the flood impacts field for the production of more accurate flood risk results (Merz et al., 2010; Messner et al., 2007; Penning-Rowsell and Green, 2000; Sayers et al., 2002). The same authors agreed that more reliable flood impact assessment is an essential basis for a valid project appraisal procedure and a more informed decision-making process.

The main aim of the latest report of the Global Facility for Disaster Reduction and Recovery (GFDRR, 2017) is to reduce the disaster and climate impacts by creating more resilient societies that can manage and adapt to future risks. According to Bruijn (2004), resilience strategies will not only reduce negative consequences but enhance recovery and help to deal with uncertainty. But what is resilience? It was first introduced by Holling (1973) when describing the behaviour of ecological systems, exposed to shocks. He postulated that resilience describes the systems' ability to persist in changing and absorbing disturbance, while still maintaining its functions. Over the years the concept kept its core meaning, but it was slightly altered for the need for different purposes. Two main characteristics of the system behaviour while in stress were recognized: the rapidity of recovery (Jones and Schmitz, 2009) and building adaptive capacity to absorb changes (Folke et al., 2002).

Resilience is a concept that has not received a well-accepted definition yet. Djordjević et al. (2011) defined it as the ability of a system or community to maintain an acceptable level of functioning when exposed to hazardous events. This definition is an amalgam between the disaster resilience, that focuses on interventions and policies that enhance the social system to respond better to a disaster (Cutter et al., 2010) and the flood risk viewpoint of a system that is capable to absorb stress through resisting, recovering, reflecting and responding (Djordjević et al., 2011).

Butler et al. (2014) defined resilience as "the degree to which the system minimises the level of service failure magnitude and duration of its design life when subject to exceptional conditions". In this manner, the definition was formulated as:

$$Res = min\ (failure: magnitude, duration) \tag{2-2}$$

The formula can be subject to a wide interpretation, but it provides theoretical guidance for the assessment of resilience indices and most importantly the effectiveness of adaptation scenarios. Mugume et al. (2015) carried out such resilience appraisal for pipe failure scenarios by representing the corresponding failure as a severity index (flood peak volume times duration). Consequently, they applied two adaptation scenarios to assess the resilience of the system when subject to multiple failures.

Traditionally fail-safe approaches were introduced to ensure restriction of failures under specific conditions (return period). Prevention based procedures like these are necessary to address the day to day variability of the water systems. Therein, the reliability of a system subject to high probability events was guaranteed (Butler et al., 2017). If low probability or unprecedented events are considered, the fail-safe approaches may be too expensive or detrimental to other urban or environmental systems. Wildavsky (1979) argued that 'No risk is the highest risk at all' and that artificial feeling of safety can result in more displeasing consequences. Recognising that systems often have non-linear dynamics, thresholds and uncertainties is necessary for the application of safe-to-fail approaches (Ahern, 2011) that aim at minimising the duration and magnitude of failures. And this is precisely where resilience positions itself to describe the way a system adapts to rare and unprecedented conditions to minimise the magnitude and duration of negative consequences.

When we are considering system behaviour, we often describe resilience as bouncing back from a disturbance. However, from a disaster risk perspective, the notion of bouncing back after a disaster is not always appropriate, primarily if the high vulnerability was the cause of the disaster. Therefore Manyena et al. (2011) advocate that the best description of resilience as a concept is “moving on” and “bounce forward” after a disaster. That also resonates with the “build back better” notion to reduce risks (UNISDR, 2009). These concepts are relevant when a disaster has caused a significant disruption in the study area. This PhD thesis concentrates on the performance of the transport system during and after flooding without considering any infrastructural damage. Therefore, returning to normal system conditions after a disturbance is regarded as a successful system behaviour.

The differences in perceiving resilience between the water and the transport sector are discussed in the next section where the transport systems are described).

2.2.2 Road transport systems

The concept of disruption due to incidents has been a focal point in traffic management discussion for decades. These incidents include traffic accidents, road closures for maintenance, hydro-meteorological events, bridge collapses, power cuts or antagonistic attacks. Regardless what the nature of the incidents is, they always result in reduced traffic supply for a certain period and travel disruptions that can propagate in a large spatial scale.

A well-accepted definition in road transportation literature of *vulnerability* is the “susceptibility to incidents that can result in considerable reductions in road network serviceability” (Berdica, 2002). Unlike the definition of vulnerability in water engineering, this definition is very system oriented. In water management, the understanding of vulnerability is more fragmented as it often considers different levels of vulnerability for various elements. The system-oriented concept of vulnerability in transport engineering stems from the highly dynamic nature of transport, whereby the origin of shocks can be geographically far from the receptor of the actual traffic disruption.

Mattsson and Jenelius (2015) understood the vulnerability of the traffic systems only when it comes to events that have a low probability. The higher probability events that describe the daily variability (uncertainty) were characterized by the term *(un)reliability* of the system. Figure 2-1 illustrates this concept. Although the (un)reliability can be observed in the daily travel conditions, it is hard to determine under what circumstances exactly (un)reliability evolves into vulnerability. Mattsson and Jenelius (2015) emphasised the fact that for the lowest probability events, the threats might not be observed yet and have an unknown probability. The notion that reliability is the basis of vulnerability is not widely accepted in the water field although it is adopted by some (Butler et al., 2017, 2014). Reliability has been traditionally described as travel time that meets drivers' expectations (Small, 1982), where drivers expectations are usually the average time, needed to reach a destination, plus an extra time to buffer the travellers' observed daily variability (Susilawati et al., 2013). In this sense the driver's expectations depend on the predictability of the system – if the system is inconsistent, drivers may struggle with planning their best departure time (OECD, 2010).

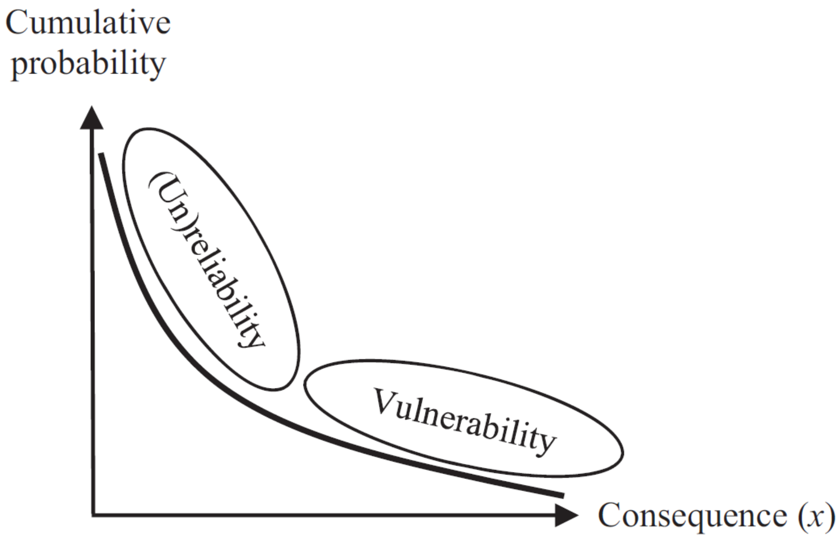

Figure 2-1: Risk curve presenting (un)reliability for high probability and vulnerability for lower probability (Mattsson and Jenelius, 2015)

Like in water science, the concept of risk in the transportation literature is also the product of likelihood and consequences. In transport science, where the threats are more diversified, the application of resilience is slightly different. For example, terrorist attacks are a focal point in transport risk perception. All big terrorist attacks were somewhat related to a transportation vehicle (aeroplane, train, bus, car). Cox et al. (2011) pointed out that unlike natural hazards, terrorists are capable of adapting their methods according to the current vulnerability of the system ("treat shifting"). For that reason, transport planners often consider the unknown unknowns which have never happened, therefore have an unknown probability. This makes estimating risk an arduous task and limits its practical application in road transport systems.

Most widely accepted definition of *resilience* is provided by Hollnagel (2011) whereby resilience is ''the intrinsic ability of a system to *adjust its functioning* before, during, or following changes and disturbances so that it can *sustain required operations* under both expected and unexpected conditions''. To distinguish resilience from risk management Hollnagel (2011) defined resilience as "improving the things that go right than reducing the things that go wrong". He postulated that a more resilient system ensures four cornerstones are achieved (Figure 2-2). The primary goal is an adequate **response** to the stress (knowing what to do), and it is a logical aftereffect of both **learning** (knowing what to do) and **monitoring** (knowing what to expect). **Anticipating** is another essential ability that copes with future threats and developments in the future. The learning and responding cornerstones ensure resilience is maintained over time.

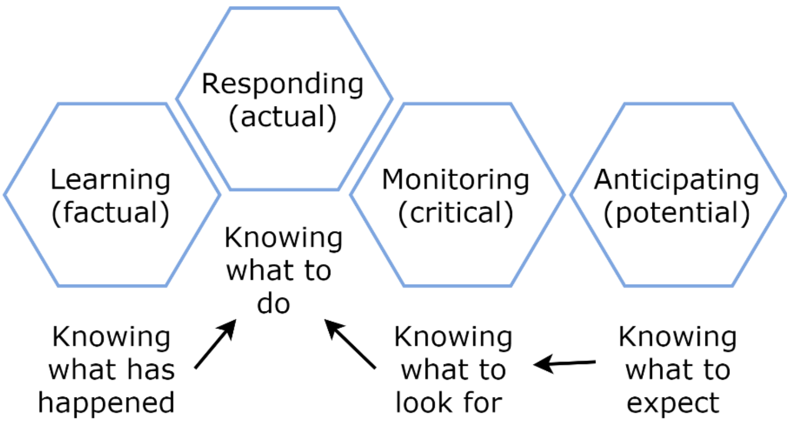

Figure 2-2: Cornerstones of resilience (Hollnagel, 2011)

Due to the dynamic nature of transportation, which requires a system approach, the concepts of vulnerability and resilience are very similar (except for being reciprocal). For example, the previously discussed definition of vulnerability (Berdica, 2002) is a good description of resilience as well (meaning that vulnerability is precisely the opposite of resilience). An essential characteristic of resilience from an engineering point of view is its dynamic nature and its swiftness to absorb the shock and return to normal conditions (Butler et al., 2014; Mattsson and Jenelius, 2015; McDaniels et al., 2008; Reggiani et al., 2015). Seeliger and Turok (2013) argued that this capacity to rebound is what separates resilience from vulnerability, which is more related to the system's susceptibility to being harmed. Although many researchers consider that vulnerability and resilience are mutually related, it is not straightforward to accept they are different sides of the same coin. However, this research reducing vulnerability and increasing resilience are recognised as interchangeable terms.

Department for Transport UK (2014) reviewed the flood impacts on transportation after a big flood in 2007 in the UK. They adopted a definition for transport resilience in the context of weather extremes, and this is "*the ability of the transport network to withstand the impacts of extreme weather, to operate in the face of such weather and to recover promptly from its effects*". They recommend Local Highway Authorities how to interpret resilience thinking in their planning and how to maintain economic activity during extreme weather conditions (more information about recommendations for improving resilience can be found in Section *2.4*).

A significant difference between the understanding of resilience in the water sector and transportation systems is the notion of failures. Unlike the water sector, the transport engineering field does not emphasize failures per se. Berdica (2002) argues that the transportation sector is more oriented towards the system performance rather than inefficiencies of the road network which could stem from physical structure failures. For example, a bridge collapse is often considered merely as a disruption (Zhu et al., 2010). As the notion of failures is not well accepted in transport management, the water-related definition of resilience cannot be applied directly in this thesis. The proposed approach to compare normal conditions with flooded conditions while distinguishing reliability from vulnerability/resilience.

2.3 Assessing the vulnerability of transport networks

The vulnerability of road transport systems is a concept that has received a lot of attention over the last two decades. Most papers have focused on identifying vulnerable links in the network to examine the network weakness and potential consequences of incidents. Mattsson and Jenelius (2015) distinguish two methods which have been widely used to approach vulnerability in road networks. The first one analyses the *topological vulnerability* to assess the efficiency of a road network. The second one is a *system-based vulnerability* which models both supply and demand by giving weights to links in a transport network. Both types of studies investigate the efficiency of the transport system by removing links (simulating street closures).

The topological vulnerability studies apply graph theory to estimate the betweenness of links in a road network. The betweenness parameter is calculated as a proportion of shortest paths that pass through a single node, and it is reassessed when links are removed from the network (Demšar et al., 2008). Thus, nodes with high betweenness are part of many shortest path routes. This idea is portrayed in Figure 2-3 where the nodes with blue colour depict the values with high betweenness, and the red ones show the lowest values. The assumption that values with high betweenness are more vulnerable is confirmed by Demšar et al. (2008) when in a large case study in Finland the roads with high betweenness coincided with the major roads in reality. Although the authors are aware of the limitations of this approach to capture the diversity of traffic conditions, they are confident that its simplicity provides a rapid assessment method for identifying critical locations in a road network.

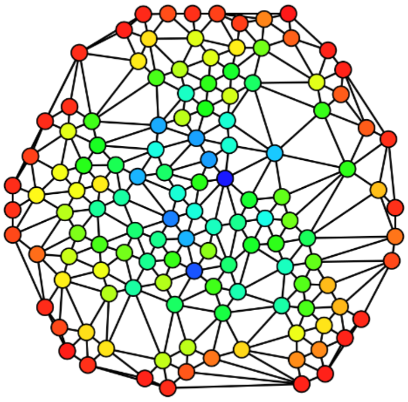

Figure 2-3: Visualization of betweenness. The blue colour has the highest value of betweenness, and the red has the lowest. Image: https://en.wikipedia.org/wiki/Betweenness_centrality#/media/File:Graph_betweenness.svg

Betweenness has been adopted by Duan and Lu (2014) to assess the robustness of six major global cities when exposed to incidents. By robustness, they understood the performance of a city road network under shock. Attacks are represented by successively removing links from the road network under four different strategies. The results suggested that would be most harmful to the system if nodes with high betweenness are targeted. Observing the way systems deteriorate, the authors concluded that networks could usually maintain operation while subject to a small number of random closures. They described that the system would continue functioning until it reaches a critical point after which it would segregate into small components. The segregation could be due to the continuous removal of links in the system, but unfortunately, the authors did not elaborate on why and when this phenomenon occurs. This question has crucial importance in distinguishing reliability from vulnerability, but unfortunately, it has not been studied in detail in the past.

The simplicity of the topological vulnerability approach makes it very appealing, because it is straightforward and has a consistent methodology, easily transferable, and has minimum data requirements. As much as the advantages, this method also has many limitations that make it unsuitable to represent traffic conditions realistically:

- Presenting transportation systems by only road networks neglects transport demand
- Even traffic supply is not merely a network, but the whole system of tools that operate the traffic (i.e. speed limits, traffic lights, speed bumps, traffic signs, road directions and number of lanes per carriageway)
- The shortest path is rarely the most sensible solution for traffic assignment
- It assumes static traffic flows and homogeneous demand
- Cannot represent congestion
- Does not give information about travel delays, which are considered the more significant impact of disruption than additional travel distance.

Graph theory has prominent potential in identifying locations of vulnerability, but nonetheless, it fails at providing solutions for an actual reduction in vulnerability in an existing study due to its inability to portray traffic conditions. Most commonly, single link disruptions have been assessed, and this is not a suitable approach to represent flooding, which usually affects large areas.

System based vulnerability examines the interactions between traffic supply and demand to appraise the consequences of disruptions to the transport system. Many approaches have assessed the overall vulnerability of a system after different links were closed for traffic and thus identified critical links in the network. Jenelius (2007) accessed the road vulnerability as trip delays after single links in a big road network were closed for traffic. Thus, the average trip delay after single link closures in each municipality in Northern Sweden was calculated. The traffic demand was constant over time, and congestion was not considered so that vehicles were assumed independent and driving at a constant speed. Knoop et al. (2008) employed a traffic simulator to model traffic disruptions with varying demand. They compared results from models with and without spillback and demonstrated that including spillback in the model significantly increases the travel delays. An exciting accent in the paper was the observed reduction in travel time delay if drivers were informed in advance for the road closure.

Taylor (2008) assessed system-based vulnerability through consumer surplus and inclusive value indices to identify congestion “hot spots”. These indicators allowed the author to estimate the social welfare cost of a tunnel blockage in Adelaide, Australia. Taylor also advocated the need to establish proactive approaches, which would be directed toward improving the performance of potentially critical locations, rather than react after an incident has occurred.

Pant et al. (2016) assessed the vulnerability of railway operations to flooding, considering how failures at functional assets and interdependent infrastructures can propagate within the system. The most critical assets were signalling, monitoring and heating, whereas the most significant infrastructural failures were electricity, ICT and water. The paper successfully captured the development of cascading effects of a system with high interdependencies. The research pointed out that impacts may not directly reflect the flood intensities when indirect impacts and cascading effects are considered.

Balijepalli and Oppong (2014) pointed out that most of the vulnerability research concentrates on accessibility in sparse regional networks and the vulnerability of urban road transport is overlooked. They argued that vulnerability indices, based on distance, are not appropriate for urban transport due to the following reasons:

1. Drivers value travel time more than travel distance
2. The urban environment has more route alternatives; hence diversion routes may not be prolonged significantly.

In conclusion, many papers have assessed the vulnerability of a transport network, but their approaches are not always relevant to the scope of the PhD thesis which explores traffic delays due to congestion in an urban environment. Here are some of the reasons:

- Most papers consider single link closure for vulnerability analysis. This approach is rarely valid when natural disasters are considered because natural disasters like floods usually contribute to multiple unrelated closures in the network.
- Most papers examine vulnerability in case of studies with sizeable geographical scope, where diversions can be very long. In urban settings, diversions may not increase significantly travelled distance.
- Most vulnerability research focusses on the traffic supply which can hardly represent traffic conditions and congestions
- Most papers do not describe the knock-on effect on the other roads and do not have a detailed description of congestion.
- The indices of the overall system performance after a street closure do not provide information about the way the systems are capable of recovering and how long it takes them
- The impact of mitigation and intervention measures to *reduce vulnerability* is a topic that has not been previously addressed in detail. Only Bell et al. (2008) assumed a scenario where a critical asset is protected and assessed cost related to that protection. Due to the limitations of the macrosimulation model, congestion and knock-on effects are not realistically represented.

Due to these limitations in the road transport systems vulnerability studies, the PhD thesis ventured into the area of the resilience of transportation systems with the hope to find more relevant studies that quantify the performance of a transport system under exceptional conditions.

2.4 Assessing the resilience of road transport networks

As previously discussed resilience is the capacity of a system to transform and adapt to absorb a shock while maintaining function. Although road transport resilience has been considered theoretically for two decades, there are only a few applications of its assessment. There are two types of techniques to approach road transportation resilience assessment: qualitative and quantitative.

2.4.1 Qualitative approaches

Qualitative approaches aim at evaluating different properties of systems to assess their overall score of resilience. Bruneau et al. (2003) conceptualised resilience as a blend of four interrelated dimensions: technical, organisational, social and economic. The technical aspect measures the ability of a system to perform acceptable levels of service during a perturbation. The organisational dimension relates to the ability of an organisation to manage critical infrastructure during disasters and to take decisions that can increase the systems redundancy, robustness, resourcefulness and rapidity. The social resilience looks at the community's ability to help each other and to push a speedy recovery. The economic dimension is associated with minimising both the financial and economic consequences of a hazard. Hughes et al. (2014) considered that only the technical and organisational resilience is required for traffic systems and assigned principles to both dimensions (Figure 2-4). Then each principle was broken down into categories that were graded individually on a scale [1:4]. This method can potentially serve as a guideline to pinpoint the weaknesses of the system. However, it evaluates the properties of the system instead of its actual performance and does not allow to investigate what-if scenarios.

A different approach to assess qualitative resilience was proposed by Imran et al. (2014) when evaluating the resilience of a region in New Zealand, that has been experiencing disruptions due to flooding and landslides. They proposed a Transport Resilience Indicator Framework that assessed resilience based on semi-structured interviews with key informants with prominent roles in transport management. The interview results assessed resilience in 6 different dimensions: engineering, services, ecological, social, economic, institutional. This assessment is holistic in its perspective, but it lacked the actual quantification of the state of different dimensions.

A qualitative resilience assessment pinpoint which parts of the transportation system require more attention to ensure uninterrupted and safe transport services. However, it is a subjective evaluation of a general condition of a system, that cannot prescribe system behaviour during disturbances. Moreover, qualitative models fail at providing any information about the potential recovery duration, which is a central building block of the resilience concept.

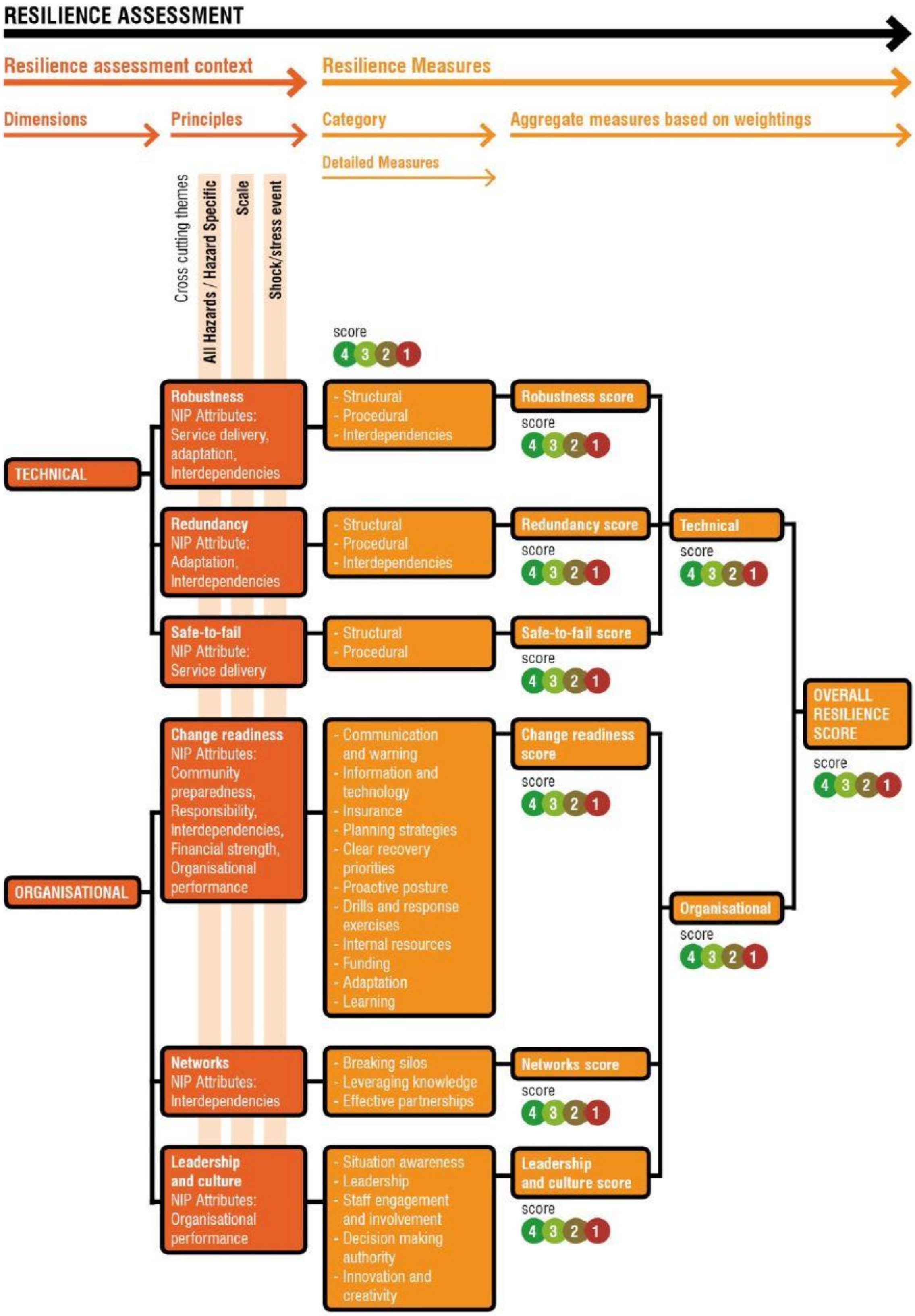

Figure 2-4: Transport resilience assessment (Hughes et al., 2014)

Going back to the water sector, Butler et al. (2017) warned that the performance of a system must be distinguished from the system properties. If a system scores low in a particular property, for example, redundancy, that does not mean that the overall performance is going to be low, especially if organisational mitigation and adaptation measures are in place to counteract a potential vulnerability.

2.4.2 Quantitative approaches

Unlike qualitative approaches, quantitative methods aim at assessing system performance. These approaches are usually based on computer modelling, that can simulate different traffic conditions in a road network. Similarly, they also enable the assessment of the effectiveness of varying intervention measures, which is the focal point in the current thesis. Resilience measures are all interventions that can support the system in returning to its pre-disaster condition (Faturechi and Miller-Hooks, 2015). These measures can be either ex-ante mitigation which aims at reducing the hazard intensity, or ex-post adaptation that improves the system ability to minimise the negative impact. Figure 2-5 depicts how decision making can influence system performance in case of a disaster. McDaniels et al. (2008) considered the robustness and the rapidity of recovery the main dimensions of resilience. They defined robustness as 'the extent to which a system is not driven to zero'. In transportation systems the notion of zero performance is quite vague, so instead of using robustness as defining the concept, the water-related definition can be adapted to interpret resilience as the product of magnitude times duration (Butler et al., 2014).

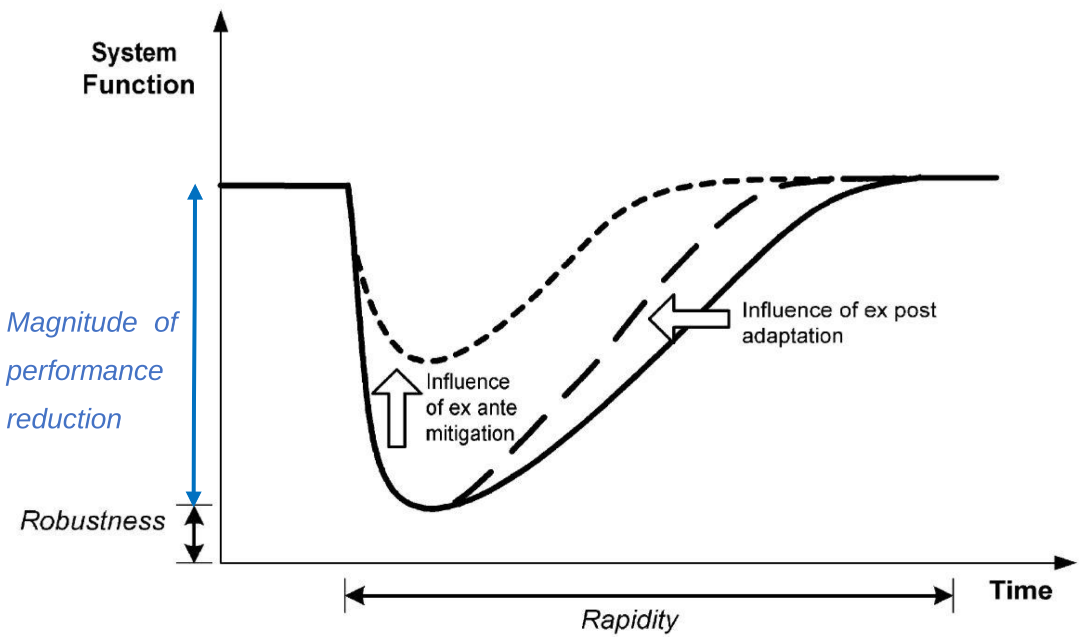

Figure 2-5: Effects of decision making on resilience (McDaniels et al., 2008). The blue arrow is added to the original figure to outline the concept of performance reduction magnitude

That notion of resilience was initially formulated by Bruneau et al. (2003) while assessing the seismic resilience of communities but could be applied in other fields. If Q(t) quality of service, then resilience (R) can be conceptually expressed as:

$$R = \int_{t_0}^{t_1} [100 - Q(t)]dt \qquad (2\text{-}3)$$

The 100 % is an expression of full-service quality during normal conditions. So, the degradation of service can be presented in Figure 2-5 as the difference between the performance between normal and flooding conditions (the magnitude of performance reduction). The difficulty in applying this logic in transportation systems is their non-linearity due to the change in traffic demand over time. If we are comparing off-peak traffic during normal and flooded conditions, the differences in vehicles may not be significant, but due to the overall low number of vehicles during that period, the percentage change may be very high. Generally, percentage changes are good at showing trends, they might misrepresent traffic conditions and congestions, especially in the off-peak hours.

An exhaustive resilient assessment of the rail transport has been constructed by Miller-Hooks et al. (2012) that assessed the resilience of a simple system towards multiple hazards – bomb, terrorist attack, flood, earthquake, terminal attack. They also analysed potential preparedness actions that could expedite recovery and increase coping capacity. Monte Carlo was used to generating a range of network conditions under different disaster scenarios that prompt network capacity reductions and travel time delays respectively. Recovery and preparedness activities were implemented to assess their benefits towards a resilience increase, and they concluded that a combination of recovery and preparedness measures scored the highest resilience among all disaster scenarios. Out of all disasters, the discussed case study had the lowest resilience to flooding, but the authors did not specify why the flooding was the most significant hazard. It could be due to the capacity reductions of multiple arcs at a time. As impressive this research may be for the assessment of resilience in a transport system, it is not currently applicable to road transportation case studies, which are significantly more complex.

Another point of view of estimating resilience was developed by Cox et al. (2011) that aimed at assessing the change in demand as a result of the fear factor after the London underground and bus bombings in 2005. They defined resilience as the percentage of transport modes shifts to passenger bombings and discovered that 77 % of the passengers were able to switch to different modes of transportation due to "fear factor", and it took four months for the system to come back to normal. This method measured whether users had alternative options for transportation, and it discovered that indeed passengers shifted quickly, but it failed to assess what that meant for the transport system regarding delays and travelled distance because of the peak in the use of personal vehicles in the aftermath of the attack.

2.5 Intervention measures to improve the resilience of a system

As previously discussed, the application of transport system performance assessment is not very common. Most articles addressed the theoretical aspect of enhancing resilience with general measures (Department for Transport UK, 2014; Lloyd's and Arup, 2017; Nicholson, 2007). A system's resilience can be improved, regardless of the applied definition of resilience or the way resilience is evaluated. The literature has recommendations for assisting in improving the resilience of transport systems. Lloyd's and Arup (2017) argued that improving resilience requires innovative thinking and up to date good quality maintenance of infrastructure. They recommended ensuring resilience with the following principles:

1. Planning

- Understand and manage crisis functions
- Diversify transport routes
- Diversify transport modes

2. Design

- Integrate "smart" technology
- Prioritise "smarter" infrastructure over more infrastructure
- Consider future mode shift

- Enhance design-life
- Design for remedial access

3. Operation

- Operate adaptively
- Manage demand
- Undertake risk-based maintenance
- Empower users with real-time information
- Promote equal access for all

Each one of the intervention principles is expected to improve resilience. If resilience is not evaluated and the weak parts of the system identified, the opportunity to invest in the most effective scenario may be lost. In the final Chapter 6 (p.147), a principle in each of the categories by Lloyd's and Arup (2017) is applied as an intervention measure, and its effectiveness towards the improvement of the system's resilience is assessed.

2.6 Flood Impacts

Floods can impact human activities in many ways, and therefore it is common to categorise these impacts. Flood consequence types were first classified by Penning-Rowsell et al. (1980) into direct or indirect, tangible or intangible, or a combination of both (Table 2-1).

Table 2-1: Types of flood impact (Penning-Rowsell et al., 2010)

		Measurement	
		Tangible	Intangible
Form of loss	Direct	Damage to buildings and contents	Loss of an archaeological site
	Indirect	Loss of industrial production	Inconvenience of post-flood recovery

Direct damages occur if the asset of interest is physically exposed to flood waters (i.e., buildings, people or environment). Indirect costs are outside the flooded area and usually take a long time to become distinguishable (Merz et al., 2010). A classic example of indirect losses is the interruption of production in a firm that might occur due to affected by flood supplier (Haraguchi and Lall, 2015). Such losses are not very well documented because typically they are not insured (Merz et al., 2010). Usually, this type of loss is estimated as flows, whereas the direct damages are assessed as stock (Okuyama, 2007). Hammond et al. (2013) pointed out there is no clear distinction between direct and indirect impacts. For example, Samuels (2009) considered the extra costs of emergency and other actions from flood event management as indirect damage, which Jonkman et al. (2008) classified as direct damages.

Although flooding can have a direct impact on the traffic infrastructure and vehicles themselves, traffic disruption on a system level is an indirect impact, especially if knock-on effects are considered. Flood impacts on traffic are often intangible: loss of time, frustration, environmental degradation due to additional CO_2 emissions. However, they can also have monetary dimensions: additional operating costs and fuel consumption have market prices, and loss of time could be monetised as well. Approaches to monetise the intangibles and the emerging importance of multi-criteria analysis for hazard impact assessments create the necessary conditions for the proper evaluation of flood impacts on traffic.

2.6.1 Flood impacts on road transportation

Traffic disruption due to flooding is considered an indirect impact because it evaluates the knock-on effects of floods on the whole transportation system. Its consequences are intangible: loss of time, frustration, environmental degradation due to additional CO_2 emissions, but can also have monetary dimensions: additional operating costs and fuel consumption have market prices, and loss of time could be monetised as well.

Floods have the potential to inundate large areas for long periods of time. As transportation is very sensitive to external disturbances, it is very likely that flood-induced capacity constraints to transport networks can have substantial impacts on road transport systems. Studies have previously highlighted a strong causal relationship between flooding and transport (Dawson et al., 2018; Pregnolato et al., 2017).

To this date traffic disruption due to flooding has received little attention in both descriptive studies and simulations of potential events. Several comprehensive studies have assessed the transport consequences of past flood events. The Department for Transport UK (2014) estimated that a single day flooding in 2007 on the M5 and M50 let to 2 % of the annual delays for the whole country and 10,000 people were stranded in traffic. Affleck and Gibbon (2015) described how a flood event destroyed several bridges in Workington and consequently turned a 15 minutes trip from one side of the river to another into a 2 hours detour journey. McDermott et al. (2017) assessed the costs of Storm Desmond in Ireland as an aggregate € 3.8 million. These estimates underline the necessity to study potential traffic system behaviour during flooding and to invest in improving transport systems' resilience.

Despite its practical significance, potential flood impacts on road traffic are not extensively studied. Even Penning-Rowsell (2010) recommended carrying out a traffic disruption study only if the expected costs are very significant because otherwise, its impacts are negligible compared with direct or indirect tangible costs. The basic approach to calculate traffic disruption follows four steps (Green et al., 2011; Penning-Rowsell, 2010):

1) Evaluating traffic conditions and costs under normal situation
2) Identifying the streets that will be closed
3) Assessing traffic conditions and costs under a flooded situation
4) Comparing 1) and 3)

Penning-Rowsell et al. (2010) provided national statistical data, obtained from the Department for Transport, UK. The statistical data included averages of traffic flow data per hour for different types of roads, proportions of types of vehicles for different roads, the total cost of travel as a function of speed. Using these tables, we can estimate the number of vehicles that will need to take an alternative road and then evaluate accordingly the additional mileage. The average speed for the updated number of vehicles on the alternative roads yields the total cost of the trips during the event. The described approach is straightforward, but it is but is troublesome to apply in urban areas, where passengers can take many alternative routes to reach their destinations. While it gives an idea about the number of vehicles, that can suffer traffic delays; it struggles to assess delays because it cannot consider congestion.

Two studies are investigating climate change impacts on flooding and the consequent effects on transportation systems. Suarez et al. (2005) looked at climate change effects on hydro-meteorological variables and used them as an input to model riverine, coastal and combined floods. The produced flood maps for different scenarios were used to identify which streets would be closed and a proportion of trips which would be cancelled. After that, a macro-simulation model, based on traffic analysis zones (TAZs) was run under the different flooding conditions. Finally, a comparison between the current and future scenario was carried on for the following variables – trips lost, vehicle miles travelled, and vehicle hours travelled. The main conclusion of the study is that climate change will have a significant effect on transportation and it is very likely to double travel times and cancelled trips.

Chang et al. (2010) made a similar study and also concluded that floods might cause significant delays in the vehicle hours, whereas the vehicle miles travelled would not change drastically. Their conclusions emphasised that flood impacts on traffic will be more prominent in categories, which are hard to monetise, namely lost business hours or frustration. The research focused on water depth beneath four bridges in an urban environment. The water depth in these cross sections determined whether the bridge would be closed to traffic due to flooding. This assumption limited the possibility of interaction between the flood and the traffic model. The flood model focused only on fluvial channel flow, which is not enough to represent urban flooding. Pluvial floods due to insufficient drainage capacity lead to road flooding and need to be addressed in urban catchments. For that purpose, a 1D-2D flood model could capture the interactions between drainage/riverine and urban surface.

Regarding the traffic model, Chang et al. (2010) introduced two novelties. First, it compared the traffic situation during pick hours and off-pick hours. Second, the future situation was not only represented by climate changes but also changes in travel volumes, based on assumptions on urban growth and the evolution of land use. The authors acknowledged that the use of microsimulation models would achieve a better representation of the dynamics of both flooding and traffic processes.

Sohn (2006) focused on network vulnerability to flooding with a return period of 100 years. The flooded roads were removed from the network individually, and an accessibility index for individual counties was calculated for the major arterial roads in Maryland, USA. To determine the retrofit priority of roads, two criteria were employed – distance and traffic flow. There are certain limitations to this approach which make it not suitable for urban areas – 1) oversimplified network reduces alternatives and is not optimal when detours are considered; 2) closing individual links is not realistic for most flood scenarios; 3) using daily average traffic volumes does not account for the hourly variation in traffic demand. Despite the limitations, the vulnerability assessment of a large-scale road network can serve the purposes of identifying potential problems on a system level.

Balijepalli and Oppong (2014) measured the vulnerability of a road network to flooding in the city of York. They proposed a new measure to assess vulnerability and compared it to four existing vulnerability measures that were previously used to determine accessibility in a large case. Nine roads were considered prone to flooding, and they were either closed for traffic, or with reduced serviceability. The assumption to treat these streets independently is not very adequate, because floods usually impact large areas and it might happen that all of the roads will need to be closed for traffic. The traffic supply of the model presented the whole network together with traffic lights, priorities and one-way streets. The traffic demand was based on detailed zoning of the city – 219 zones ensured a large amount of OD combinations. The compared indexes in the paper gave an overall assessment of either the vulnerability or the robustness of the system and identified which roads, prone to flooding, were essential to the system. The primary interest of this PhD thesis, namely the flood impacts on road transportation, was not addressed in this paper. Nevertheless, the article provides an excellent theoretical viewpoint for evaluating vulnerability in dense urban networks.

Pregnolato et al. (2016) assessed the betweenness centrality of links in a transport network under baseline and flooded scenarios with the purpose of identifying potential hotspots of high flood exposure and high traffic flows.

Consequently, they also applied two adaptation strategies to reduce the intensity of the flood hazard and analysed how the reduced flood intensities result in better traffic conditions. The paper provides a rapid framework for identification of vulnerable links in the network and it has a broad application to many sites. Limitations of the method are its lack of congestion description, travel time estimation and temporal variation of traffic demand.

Pregnolato et al. (2017) recognised that a flooded road is not necessarily closed for traffic and used video analysis of flooded streets to derive a function that relates flood depth with speed reduction. They compared traffic counter data between dry conditions and flood conditions in several locations in Newcastle. The flood depths during the Newcastle flood events were not recorded, and the counters registered a decline in traffic, but it was unclear whether that decline was due to blocked roads or drivers' choice to delay the beginning of their trips. Therefore, the proposed depth-speed reduction function was not validated by measurement data. By studying traffic in isolated links of the road network, an important detail about the indirect impact of flood waters can be overlooked, because other links might have experienced traffic delays as a result of using other routes to complete journeys.

To appraise the vulnerability of cities' services to flooding, Coles et al. (2017) took an alternative approach. They mapped the accessibility area of emergency services that cover 8 – 10 min targets of journeys from the fire and the ambulance stations. Such logic is applied to assess the accessibility areas during flooding where restrictions are applied on roads with flood depth above 25 cm. Moreover, the locations of possibly vulnerable areas such as care homes are discussed within the newly computed access areas. The Life Safety Model (Lumbroso and Tagg, 2011) also focused on the importance of emergency planning and integrated dynamically a flood and an ABM model to simulate interactions of people, vehicles and buildings with the flood. The model made assumptions about travel times to safe havens but did not discuss traffic conditions.

Adverse atmospheric conditions also affect transportation systems as drivers have longer reaction time during intense rainfall (Jaroszweski et al., 2010; Keay and Simmonds, 2005; Koetse and Rietveld, 2009; Michaelides, 2014) and the findings in these studies can be used to set preconditions before the flood event.

Including adverse weather conditions into the flood interaction with transport has not been addressed in the prior research on flood impacts to traffic. The available papers in the field assume that the flooded situation occurs in a normally functioning traffic system. In reality, the traffic system may be profoundly affected by heavy rainfalls before the flood accumulates in the urban catchment (Keay and Simmonds, 2005; Michaelides, 2014). Tsapakis et al. (2013) discovered a 4-6 % in travel times during heavy rainfall events whereas Cools et al. (2010) acquired only a 2% reduction in vehicular speed. However, Hooper et al. (2014) did not identify particular trends precipitation intensity and vehicular speeds after analysing high-resolution data about vehicle speeds on two UK motorways. They examined that the beginning of rainfall could be a potential threshold for a speed change but pointed out that other factors such as local capacity and drainage could have equal influence at speed reduction. The paper assessed average speeds on road sections between junctions on motorways which may not be very representative for general vehicular movement on other roads and may fail to capture speed changes in short duration intense rainfalls.

There is no indication that the results of flood impacts on traffic have been applied outside academia. The main reason is the complexity of the integration between flood and road transport systems, which are both very dynamic. The second reason being the intangible impacts associated with the transport systems – lost time distributed among many passengers may be underestimated. The third reason is that some of the research in that area may be too abstract for practitioners as it discussed climate-induced changes to simplified flooding and then to a simple traffic model (Suarez et al., 2005; Chang et al., 2010). This PhD thesis aspires to address each of the identified gaps in the discussed research.

2.7 Other topics relevant to the research

When transportation meets flooding, various aspects of the impacts must be considered. First, the reason to enter flooded vehicles in water is discussed while recognising the significant mortality rate of drivers and passengers in vehicles passing through flooded waters. Some of the reasons drivers venture into dangerous flood waters are reviewed. Afterwards, the behaviour of vehicles is examined considering that the existing research in that area focuses only on flooded static cars, rather than moving vehicles (i.e. hydroplaning). The stability criteria of flooded vehicles is a central concept in methodology and it determines the threshold for street closure. Another relevant topic discussed in this section is related to the monetization of traffic delays, which fits nicely in the flood impact appraisal.

2.7.1 Loss of life while driving on flooded roads

Flooding in 2016 claimed the lives of nearly 5000 people globally (Munich RE, 2017). A considerable amount of people lose their lives in their vehicles. For example, in the past 30 years in the USA flood fatalities due to driving in flood waters amount to more than a half of all flood victims (Jonkman and Kelman, 2005; Sharif et al., 2015). Drobot et al. (2007) carried out surveys to understand why people chose to drive in flood waters, while considering many factors (previous flood experience, flood warnings, age, type of flood, flood danger knowledge) and found out that a surprisingly high number of respondents stated they would drive through flood waters (40% in Denver). Not taking warnings seriously and not understanding dangers were the most often reasons for risky behaviour. Pearson and Hamilton (2014) used the augmented theory of planned behaviour to explain drivers' intentions when driving through flooding in Australia. They concluded that people might not be able to distinguish low from high-risk situations and the respondents that had experience of driving through flood waters were more likely to embark in such a situation again. Haynes et al. (2017) observed an overall reduction of the victims of floods in Australia but underlines that the proportion of fatalities in vehicles is on the rise, especially four-wheel drive and pick-up vehicles (accounting for 11% of the fatalities since 1960). There is an agreement that drivers often have unrealistic expectations about vehicle behaviour in flood water, and this is a severe safety concern (Drobot et al., 2007; Pearson and Hamilton, 2014; Salvati et al., 2018; Smith et al., 2017).

2.7.2 Stability threshold of flooded vehicles

To avoid fatalities and financial loss, it is necessary to examine the flood conditions under which vehicles become uncontrollable. Vehicles' stability in flooded waters is becoming an increasingly relevant topic in the context of growing urbanisation and climate change. This field of research has been mainly experimental, and it investigates the behaviour of flooded small-scale model vehicles under different flood conditions. Theoretically, cars float, slide or topple in flood waters (Shand et al., 2011b). Smith et al. (2017) analysed how vehicles lost control in flood waters and discovered that due to the heavier front part, the rear is more buoyant and it would be lifted first. They pointed out that if the flood waters are fast, the rear side will swing until the vehicle rotates toward the direction of the flow. For that reason, Smith et al. (2017) defined the instability of a vehicle “the point at which any axle (two wheels) loses traction, and the vehicle rotates or translates sideways”.

Comprehensive literature reviews on the subject were done by Shand et al. (2011; Martínez-Gomariz et al. (2016). Conclusions about the vehicles’ behaviour in flood water have been mainly drawn from experimental research. Vehicle models in different scales were flooded with the aim to delineate thresholds of vehicle instability in flood waters (Shu et al., 2011; Xia et al., 2011; Teo et al., 2012; Toda et al., 2013; Martínez-Gomariz et al., 2016; Smith et al., 2017).

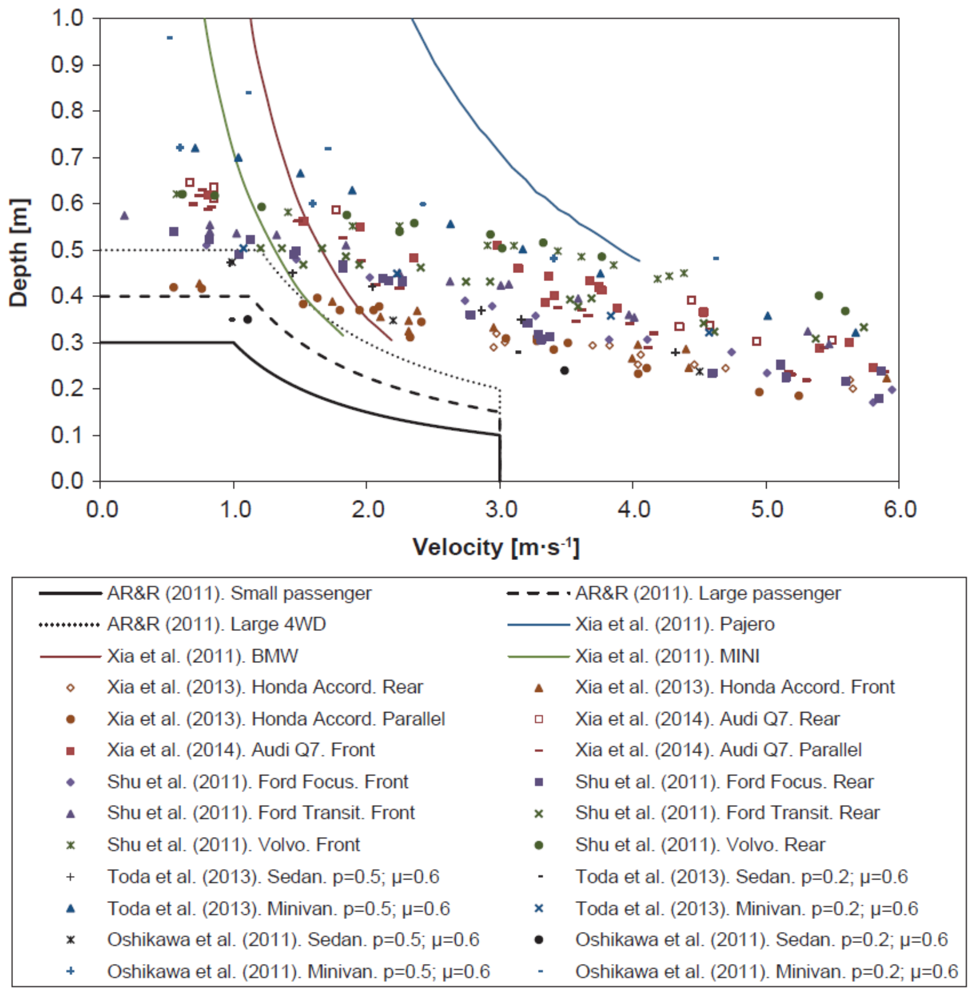

Figure 2-6: Results from recent studies depicting vehicle stability thresholds under different combinations of flood parameters (Martínez-Gomariz et al., 2016)

Figure 2-6 illustrates the results of vehicle stability thresholds obtained by recent experimental research. Different vehicles' characteristics (weight, shape, ground clearance) determine their ability to withstand combinations of flood intensities (product of depth and velocities). The experiments were carried on with different vehicle orientations with regards to the flow and most proved that if the cars perpendicular to the flow is more vulnerable. According to Toda et al. (2013), the friction coefficient of vehicles' tyres with a perpendicular orientation to the flow is significantly lower than the aligned ones (respectively 0.26 and 0.57 for sedans). Haynes et al. (2017) looked into the circumstances of flood fatalities in Australia and discovered that the highest proportion (45 %) of all flood fatalities occurred when trying to cross a bridge or a road and it is very likely that these vehicles were perpendicular to the flow (Smith et al., 2017).

Martínez-Gomariz et al. (2017) were the first to test how different scale models of the same vehicle react to flood conditions – Mini Cooper in scales 1:14, 1:18 and 1:24. The redundancy in that research gave confidence in the development of a general methodology for the friction and buoyancy of real flooded vehicles. The results for a small passenger car are illustrated in Figure 2-7.

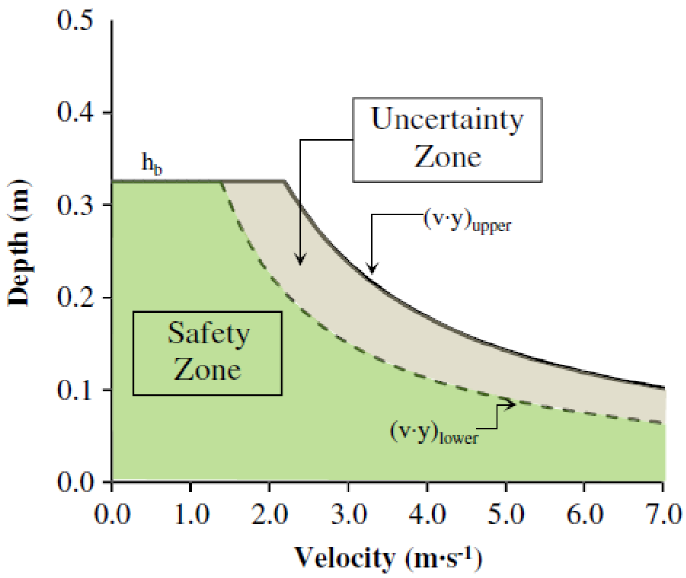

Figure 2-7: Safety zone and uncertainty zone of the vehicles' stability in flood waters (Martínez-Gomariz et al., 2017)

Smith et al. (2017) were the first to test full-scale vehicles' traction in varying static water. They used a small vehicle (Toyota Yaris) and a typical large 4WD (Nissan Patrol). The use of a 4WD was justified by the increase of 4WD related fatalities in Australia (Haynes et al., 2017). The experiments confirmed the reduction of traction with deeper standing depths of water (Smith et al., 2017). The analyses showed that the Toyota Yaris completely floated at 0.6 m depth, and the Nissan Patrol floated at 0.95m.

It was observed that there was a leakage in the cars of around 50 l and because of its increased weight, it slightly delayed the floating point of the car. They also tested scale model vehicles (1:18) under hydrodynamic conditions and discovered that the tested vehicles are more stable than the current recommendations (ARR refers to Shand et al., 2011a). Figure 2-6 depicts the discrepancy between the ARR recommendation and the results from the current research. Despite the newly discovered details about real vehicle's behaviour in flood waters, Smith et al. (2017) advised the ARR recommendations to be respected due to many reasons, but more prominent were:

1) Impact of turbulent flow was not considered;
2) Some small passenger cars have smaller road clearance and kerb weight than Toyota Yaris;
3) Moving cars can become unstable easier than parked ones;
4) Flood waters usually bring debris.

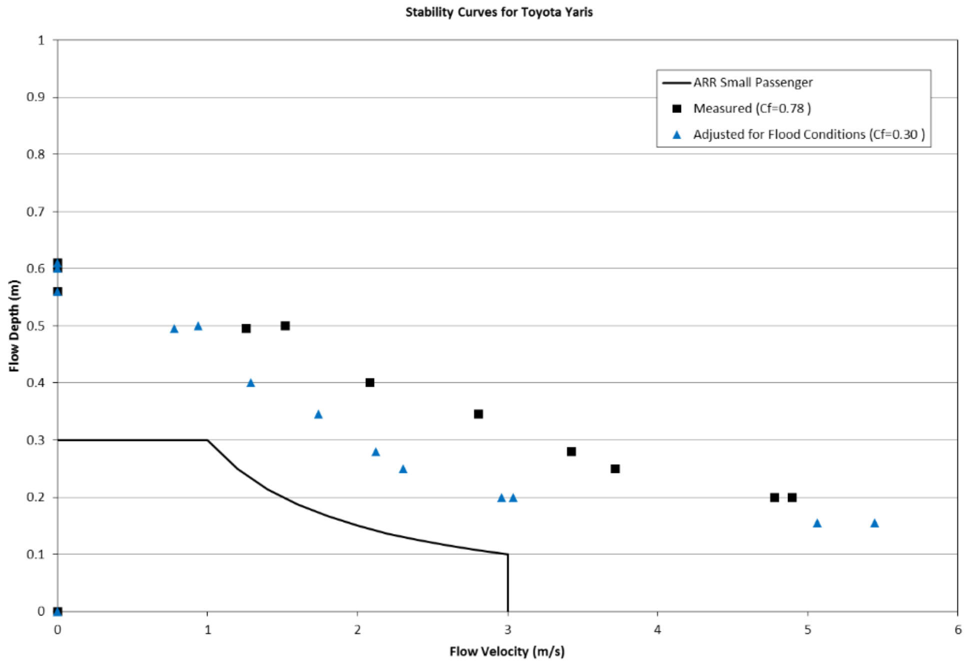

Figure 2-8: Small passenger car stability. ARR refers to (Shand et al., 2011a). The figure is taken from Smith et al. (2017)

On this basis, Smith et al. (2017) recommend the use of the existing ARR thresholds for vehicle stability (Table 2-1).

Table 2-2: Flood hazard thresholds for vehicle stability (Shand et al., 2011a). The values correspond graphically to the line in Figure 2 6.

Class of Vehicle	Length (m)	Kerb Weight (kg)	Ground Clearance (m)	Limiting Still Water Depth[1]	Limiting High Velocity Flow Depth[2]	Limiting Velocity[3]	Equation of Stability
Small passenger	< 4.3	< 1250	< 0.12	0.3	0.15	3.0	D.V ≤ 0.3
Large 4WD	> 4.5	> 2000	> 0.22	0.5	0.3	3.0	D.V ≤ 0.6

[1] At velocity = 0 m/s; [2] At velocity = 3 m/s; [3] At low depth

The purposes of the flood impacts on road transportation require a single and uniform rule that will affect all vehicles on the road. Therefore, street closures will be applied when the minimum instability conditions for small passenger cars are fulfilled. According to the most comprehensive studies (Shand et al., 2011a; Martínez-Gomariz et al., 2017; Smith et al., 2017), the flood depth threshold for standing waters is 0.3 m, and this threshold will be used in the methodology as a criterion for a street closure.

2.7.3 Monetizing traffic delays

The reduced efficiency of the traffic supply during flood conditions results in longer travel times for many drivers. Previous studies in the field of flood impacts on traffic congestion (Chang et al., 2010; Suarez et al., 2005) indicated that wasted time is the most significant flood impact on traffic. Therefore, it is necessary to monetise business hours lost in transit to compare them to other tangible flood impacts such as damage to built-environment or business interruption. To assess the cost of delays in transportation Vickerman (2000) considered both the travel costs of the person and the additional operating cost of the vehicle. The study distinguished between different type of person (driver or passenger) concerning their employment status. The operating costs of the vehicles consider different vehicles types. Different monetising results and the main methods used are assembled in Table 2-3.

Two European Commission funded sister projects WEATHER and EWENT investigated the impacts of weather-related extremes on transportation (Doll et al., 2014). The projects assessed economic costs of future climatic extremes by monetising the cost of potential: infrastructure, infrastructure operations (traffic police and fire brigade in the time of emergency), vehicle damage cost, vehicle operations (additional fuel consumption and wear and tear), time costs, accidents. The delay time cost for the year 2050 is an average of research for all EU countries based on van Essen et al. (2011). Monetising travel time was assessed using wage data to assign monetary values per hour for different trip purposes - business, commute or leisure (Tervonen et al., 2010). They estimated that the average value of 1-hour delay in Finland is € 26.70 which is a sum of the average cost for time lost and the average cost for fuel consumption and wear and tear. This value is very close to the value used for time cost in the projects WEATHER and EWENT, but for a different reference year, bearing in mind the projects employed the reference value for Finland to represent all EU countries' cost.

Table 2-3: Monetization of travel delays by different authors

Author	Reference year	Method of estimation	Personal travel delay cost per hour				Vehicle operating cost per hour	
			Working driver	Working passenger	Non-working driver	Non-working passenger	Work	Non-work
Vickerman	1994	Wage	£ 13.0	£ 10.7	£ 3.2	£ 3.2	£ 14.1	£ 5.5
Tervonen at al.	2000	Wage + survey	€ 24.1	€ 4.1	€ 4.1	€ 4.1	€ 36.3	€ 8.1
HEATCO D5	2002	Wage + WTP	€ 25.95		Commute € 10.9		-	
Doll et al.	2050	Wage	€ 13				€ 13	
Douglas et al.	2000-2001	Survey (WTP)	Peak - AUD 9.9		Off-peak- AUD 7.4		-	
Department for Transport, UK	2010	Survey (WTP)	£ 27.06	£ 20.52	Commute £ 6.81		Calculated per distance	
Brownstone and Small	1996-2000	Revealed + stated preference	$ 20 $ 9					

Douglas et al. (2003) assessed travel time's monetary value after a detailed stated preference survey in Australia that assessed the willingness to pay (WTP) of the residents. They identified differences in the cost of travel time between different modes (public transport, car, a combination of both) and differences in the purpose of the trip (work or leisure) and time of the trip (peak or off-peak).

Department for Transport UK (2014) published estimated values of travel time for the UK. They are based on 'willingness to pay' surveys and distinguish significantly between the working travel time and the non-working one (the commute is considered non-working time). Once estimated, these values are altered using GDP deflator on the base of Consumer Prices index. It is important to note that travel time cost can potentially be very different than the traffic delay cost. The travel costs are something the travellers have made a conscious choice to use that particular travel plan. They have not anticipated delays, and often the delay might spread over business hours. Brownstone and Small (2005) examined the results of revealed and stated preferences to assess commuters' value of saved time in a case study in Southern California. An interesting finding is that the revealed preferences (choice to pay for toll facilities) are twice as high as the stated preferences. If the commuting costs are previously known, and the commuter has agreed to them, the travel delay should have a different value than the typical travel cost per hour time. This distinction has not been studied in detail in previous studies.

An entirely different approach to estimating time delays is developed by Mackie et al. (2003) that assigns different time cost values depending on the duration of each delay. The various costs are estimated based on stated preferences. According to the research, wasted time does not rely on the sign of the difference between two situations and reaching destination too early should be monetised as a loss together with traffic delays. This monetising technique is logically correct, but there were concerns about using stated preference in isolation to monetise time.

Another EC funded project HEATCO (2006) assessed the value of time spent in congestion based on wage data and willingness to pay. The average value of time for car commuters in the EU countries was estimated to be € 23.82, whereas for Spain it was € 25.95. The costs of the time were validated with a willingness to pay to account for uncertainty. This study is considered the most comprehensive and therefore this thesis adopted its results to assess time delays. The project recommended 0.7 % increase per year to account for pay rise over time. As the reference year of the study was 2002, it was estimated that the value of time in 2018 would increase to € 29.01 per hour for Spain.

2.8 Modelling techniques

2.8.1 Flood modelling software review

Hydraulic models reproduce fluid motion and their accuracy have improved significantly over the recent decades. Traditionally flood models are classified into three main categories: one-dimensional (1D), two-dimensional (2D) and three-dimensional (3D). The 1D models solve a one-dimensional equation for typically channel and pipe flow which is interpolated based on changes of the cros-sections. They can produce accurate results for flooding but require many assumptions and post-processing. Although 1D models are fast and stable, they lack a representation of the overland flow which is essential for urbanised environments such as the case studies in the thesis. The 2D hydraulic models represent floodplains distribute flow on a raster field by approximating a two-directional shallow water equation. They are useful in case studies that do not have a prevailing direction of flow (Manfreda et al., 2015) and have a more detailed representation of changes in velocity and direction, backwater effects and can consider structures such as buildings, defence structures, bridges. Such models are also valuable in simulating storm surges in regard to overland coastal flooding. For that reason, a 2D model was selected to simulate the combination of coastal and surface flooding in the case study of St Maarten. The most popular 2D hydraulic flood models are MIKE 21[1] (Warren and Bach, 2003), SOBEK[2], HEC-RAS[3], Flood Modeller[4], InfoWorks XPStorm[5]. There is another type of 2D models that instead of solving the shallow water equation, simulate overland flow with transitional rules. Models like CADDIES (Guidolin et al., 2016) employ machine learning to speed up the computational cost in order to run multiple intervention scenarios (Webber et al., 2018). As the storm surge in St Maarten plays a crucial role in the flood event, the main selection criteria being a model that has a good integration of coastal and inland and overland flooding. Such coupling gives a valuable insight into situations where backwater effects are expected because the higher sea level with waves can block the movement of

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[1] https://www.mikepoweredbydhi.com/download/mike-2017-sp2/mike-21?ref=%7B40160C10-5509-4460-A36F-FA2759EAC02F%7D
[2] https://www.deltares.nl/en/software/sobek/
[3] https://www.hec.usace.army.mil/software/hec-ras/
[4] https://www.floodmodeller.com/products/
[5] https://www.innovyze.com/en-us/products/xpstorm

overland water and contribute to more intensive flood extent. Only MIKE 21 matches such requirements, as the other flood models are more focused on riverine and/or urban areas.

For the case study of Marbella (Spain), the intense rainfall, the terrain and the insufficient drainage capacity were the most critical driving factors for flooding (PEARL, 2017). Such urban flooding would be underrepresented using only overland flood models because they lack representation of the existing drainage systems and structures. The best type of model would be a 1D-2D model that would couple a representation of the sewer (1D) with a 2D surface flow component that would act as an urban floodplain. The most prominent 1D-2D models are MIKE URBAN, HEC-RAS (US Army Corps of Engineers, 2016), SOBEK (Deltares, 2017), InfoWorks ICM (Innovyze, 2016). HEC-RAS has a 1D-2D capability, its 1D model is not suited for drainage flow. SOBEK presents the links between the 1D and 2D models as weirs and may not be the best to model insufficient drainage capacity (Rangari et al., 2015). As often happens with software selection, the modeller does not have full access to all available software. Both MIKE URBAN and InfoWorks ICM have a very strong focus on sewer systems but having flexible mesh makes InfoWorks ICM slightly faster than IKE URBAN. It is important to underline that the flood modelling was employed by partner institutions, which often have tendencies to use certain software. For the purposes of the this, it was crucial to develop a methodology that works equally well with both raster (MIKE 21) and vector (InfoWorks ICM) results.

2.8.2 Traffic modelling

The most commonly used type of transport model is a macroscopic model that establishes a relationship between flow and concentration of vehicles on the road (Lighthill and Whitham, 1955). Compared to macro-simulation, a micro-simulation technique facilitates a more detailed representation of the traffic processes. Microscopic transport modelling simulates every single vehicle in the transport system. It is capable of modelling pedestrians, different transport modes and their driving behaviour. There are several reasons to adopt a micro-simulation technique for the assessment of flood impacts:

1) General traffic

- The intermodal description of different vehicle types is essential for the overall consumption of fuel and greenhouse gas emissions. Different modes of transportation also indicate varying costs of travel delays and thus contributes to a realistic representation of fuel consumption and

- As results are produced for individual vehicles, impacts on individual trips can be investigated. This is very important when traffic delays are being calculated because while comparing journey duration with and without the flood, can estimate the number of delayed vehicles and their time delay duration.

2) Congestion

- Provides a comprehensive representation of congestions, because it models the interactions among vehicles rather than their concentration.

- Through the congestion propagation provides comprehensive detail about knock-on effects both on the system and on individual vehicles;

3) Rerouting

- When a street is closed due to flooding, each vehicle will be rerouted individually, according to its destination. Hence, the rerouting algorithm ensures a detailed representation of the traffic condition during flooded conditions. Automating this process is particularly important if there are numerous flooded streets throughout the whole network;

- Microscopic traffic models can simulate the dynamics of the flood propagation both spatially and temporally. For instance, depending on the flood severity, it can allow closure of only one lane, while keeping the traffic active in other lanes.

There are many available microscopic models and the selection of the most suitable model was mainly based on its ability to reroute vehicles while a street is closed due to flooding. Perhaps one of the most commonly used models, VISSIM (Fellendorf and Vortisch, 2010) features that capability. Judging from the same paper and a user's manual (PTV, 2011), the rerouting mechanism (which is called dynamic routing in VISSIM) did not appear to be available back end solution. This was necessary for the automatization of the whole integration process. Then it became clear that an open-source model would be better suited for that purpose. MATSim (Axhausen and ETH Zürich, 2016) is an open-source model, which represents rerouting due to a change in destination and this was not suitable in the context of flooding. The selection of a transport model finally landed on SUMO (Simulation of Urban MObility) developed in the Institute of Transportation Systems at the German Aerospace Center (Krajzewicz et al., 2012). It is an open source model, which enabled access to scripts and various schemes. It has a rerouting mechanism which closes certain streets for traffic and assigns vehicles new routes. The purely technical procedure of rerouting had a certain logic, that allowed the automation of the scheme. Like most open-source models, it had a viral community and getting a reply from the developers never took more than a few days. Having all these points checked, the selection of a traffic model was complete and there was no need to look further for another transport model.

2.9 Literature review summary

The flood impacts on road transportation is interdisciplinary research, and therefore a very wide-range literature review was composed. It was compiled by a theoretical section that described the fundamental terms in both water science and transportation science followed by practical sections that answered particular questions related to the construction of the methodology. While writing up the thesis, it became apparent that although its focus was the actual flood impacts, there are many remaining questions about the performance of the transport system and how well it copes with the disturbance in the name of a flood with a specific return period. To assess the performance of a system under strain; the term resilience was described in detail. The water sector is currently ahead in the resilience assessment, but its definition of resilience could not be applied directly in transportation, because the water science understanding of resilience is strictly associated with the notion of failures which is more intricate to apply in road transportation systems.

Following the theoretical parts, a section discussed how flood impacts on road transportation had been already approached, the gaps and the opportunities for improvement. Firstly, representing the flood with a 1D-2D model contributes to a more realistic spatial distribution of the flood. Secondly, a microscopic traffic model captures the knock-on effects on the transport system. Thirdly, dynamically integrating the two models would bring a new quality of the results. To address these opportunities, the thesis addressed each of the discussed three points.

The literature review also looked at how specific parameters, required for the methodology are assessed. After a thorough review, the global parameter for a street closure was selected to be 0.3 m flood depth. Similarly, the adequate representation of a monetary value of traffic delays is € 29.01 per hour (for Spain).

The literature review had a profound effect on shaping the methodology and even on the practical aspects of the research. The flood impacts on transportation may not have been studied in detail in the past, but many small pieces of the puzzle supported the research in different areas of science.

3 FRAMEWORK OF RESEARCH

3.1 Introduction

This chapter addresses the previously identified gaps in the current state of the art by developing a novel methodology to interpret the processes involved in the shared space between water modelling and the traffic modelling systems. These two seemingly remote domains must be integrated so that their interactions can be examined. Moreover, these systems exhibit very dynamic characteristics in both space and time. To explore these dynamics, the framework of research necessitated a universal integration logic that can be iterated for each timestep to establish temporal dynamic integration of the models. For that purpose, a two-component tool is developed to ensure that all possible flood conditions are translated into a traffic model input in a consistent and homogenous way. The tool is written in Python and runs in an ArcGIS environment.

After the description of the framework for integrating flood and traffic models and the development if the tool that facilitates the framework, a novel framework for assessing resilience in a transportation network is developed. The methodology is an amalgam of water science and transport systems concepts, and it introduces a way to distinguish normal from exceptional conditions. By discerning the former two, reliability and resilience are differentiated accordingly into two categories. Once the system performance under extraordinary conditions is recognised, three different indicators demonstrate the system performance – duration, magnitude and severity.

This methodology incorporates novelties on many levels:

1) Microscopic traffic model has never been applied in flood impact assessment previously. That type of model enables the description of congestion as well as the production of very detailed results and allows different rerouting techniques for different vehicles;
2) Distinguish direct and indirect consequences to the road transport system;
3) Dynamic and semi-dynamic integrations between the flood model and the transport model;

4) The flood depth defines the traffic condition – shallow water depth leads to speed reduction and deep-water depth results in a street closure[6];

5) A novel framework for resilience assessment based on system performance

3.2 Overview of the methodology of flood and traffic model integration

The main aim of the flood and traffic model integration is to ensure a robust exchange of information between the two models. The flood and the traffic models are developed in entirely different platforms (commercial and open-source), and they were not designed to be integrated. For the development of the methodology, the capabilities of both models are thoroughly examined to identify how interactions can practically operate.

The conceptual framework for the assessment of flood impacts on road transportation is outlined in Figure 3-1. The logic to integrate the two models is very intuitive – the flood conditions determine the network capacity in the transport model. Based on a stability threshold of flooded vehicles (p. 48) the flood depths are divided into two categories- shallow and deep flood. Roads that are flooded with a shallow flood depth will endure speed limitations, whereas roads with deep flood water will be closed for traffic. Both speed limitations and road closures reduce network capacity, but road closures also prompt changes in traffic assignment. Due to the road closures, vehicles that are initially passing by a flooded road with deep water depth must choose an alternative way to reach their destinations. The expectation is that when constraints are applied the network capacity, the negative consequences for the road transport systems are going to be significant. By all means, the severity and the duration of the flood would determine the scale of the traffic consequences. It is important to note that the considered flood scenarios do not necessitate any evacuations and the thesis focuses on how daily trips would be impacted by the flood and how the transport system can recover from a major shock, while still maintaining a certain level of service.

[6] Discussion of the criteria of the street closure can be found in *2.3. Stability threshold of flooded vehicles*

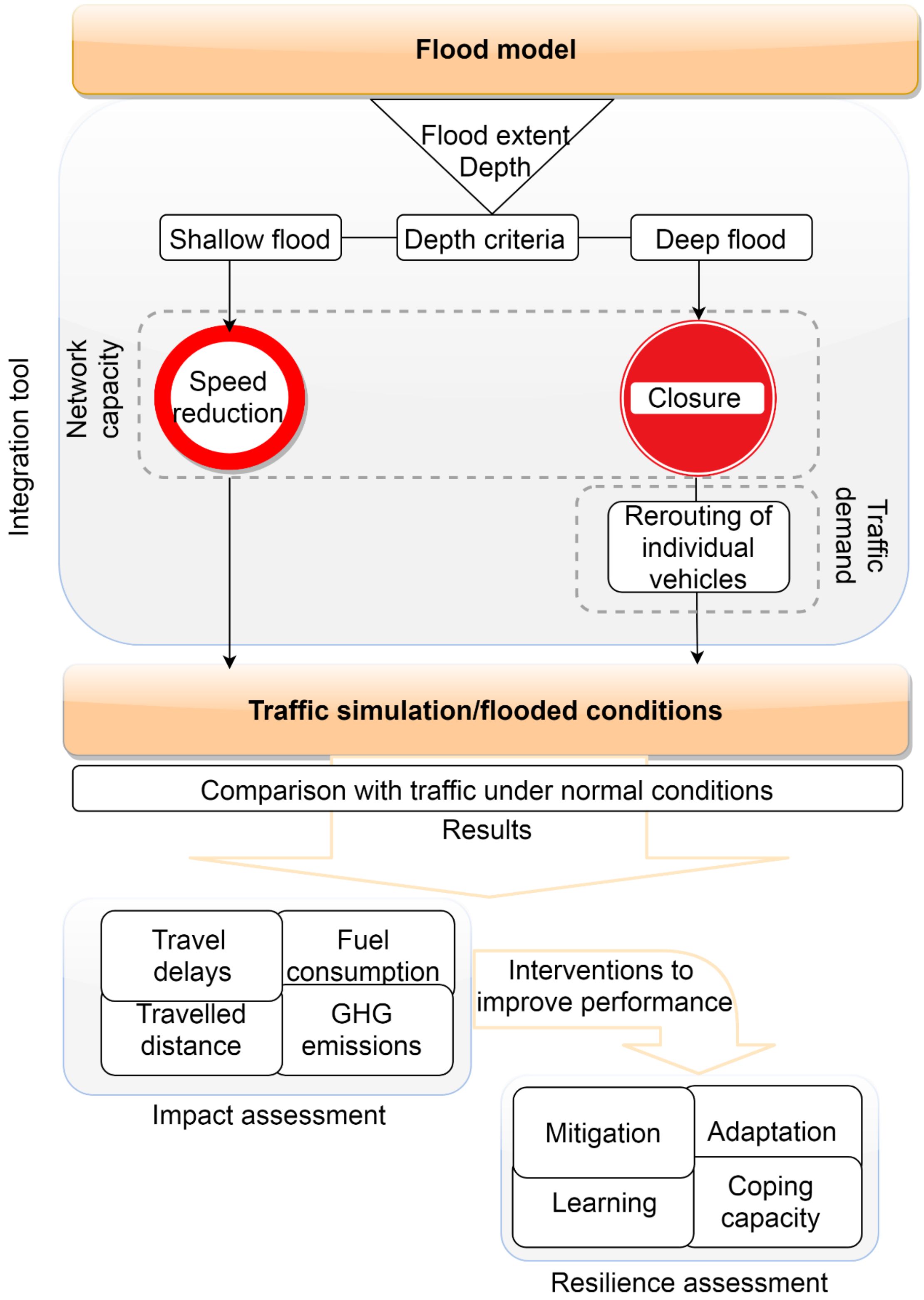


Figure 3-1: Flowchart of the proposed methodology

The rerouting process assumes that drivers have no initial information that a part of their route has been flooded. Their route diversion is made as they approach the link closure and then a new route is assigned based on the shortest path to their specific destination. The research divides the routes in two - the ones that are rerouted have suffered the direct consequences of the flood and all other vehicles experience the indirect consequences of the reduced network capacity. Considering how dynamic traffic is, a distinction between direct and indirect impacts is vital but it has not been achieved in the past.

The interoperability of the rerouting and the speed reduction mechanisms are ensured by a specifically designed python tool translating the spatially varying flood output into a transport model output. There are three ways of applying this framework – static, semi-static and dynamic. The static integration uses one flood map with a global duration of flooding for each flooded road. This method is rapid and straightforward, but it is unable to describe flood propagation. This type of integration could be sufficient for groundwater flood event which usually is prolonged and does not change very significantly over time. The main reason being is that if a long-term event lasts several days, the spatial differences in duration may not be very significant. The semi-dynamic approach is also based on one flood map, but this map shows the flood durations at each location. Thus, a spatially varying information about flood duration/road closures can be obtained. For quickly developing floods, an adequate representation of the flood propagation is essential for the description of the flood event in the traffic model. The dynamic integration of flood and traffic models follows the same methodology, but it is run in a loop multiple times using different flood maps of the flood propagations.

Once the transport model is run with the flooding information, the differences between the transport model results under normal conditions and flooded conditions yield the actual flood impacts induced to traffic. The impacts on the transport system are expressed in travel delays, additional travelled distance, additional fuel consumption and additional CO_2 emissions. As the knock-on effect is expected to be considered in both temporal and spatial dimensions, a system approach is necessary to evaluate the performance of the system. Therefore, a resilience assessment method was developed to assess the changes in system performance if different resilience interventions are to be implemented in the transport system.

Accomplishing the integration of flood and transport models was the fundamental cornerstone of this PhD thesis which enabled interoperability between two models that have not been previously integrated. Consequently, it allows for a straightforward implementation of the methodology into different case studies or different transport scenarios. Although the tool is an achievement on its own, it does not answer research questions, but instead makes answers possible.

3.3 Pre-processing of road network data required for model integration

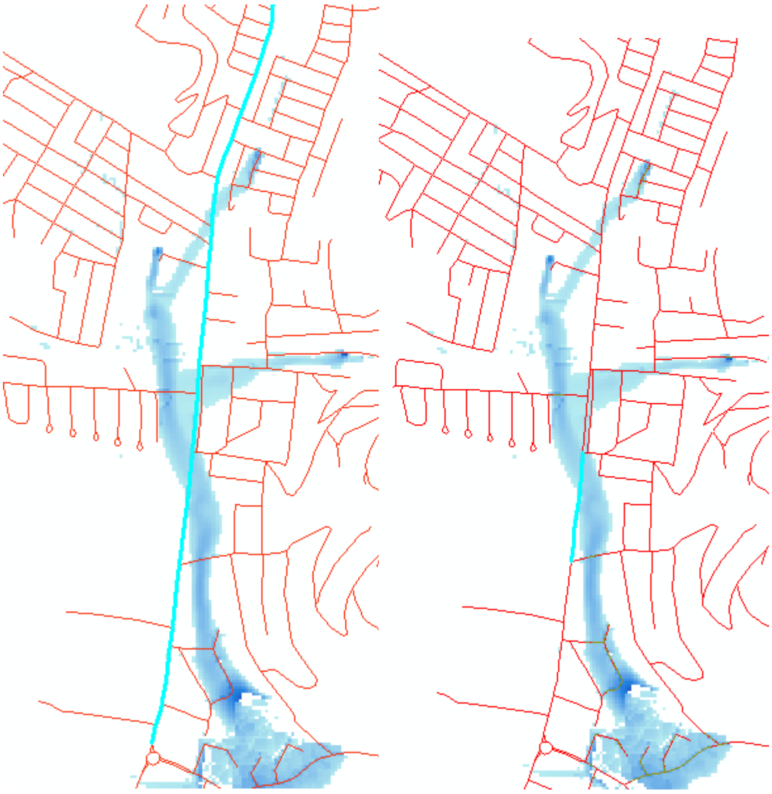
Full interoperability of flood and transport models has not been previously achieved due to many reasons. The leading cause being that the previous studies that investigated flood impacts on traffic had a very crude representation of both flood and traffic systems and could not benefit from a sophisticated model integration. Due to technological advances, the use of detailed 1D-2D flood models is becoming a norm, and microscopic traffic models are more commonly employed. Therefore, it is more likely that such an interdisciplinary issue would capture the imagination. However, there are many hurdles before achieving a dynamic integration between two models that are not compatible and have never been intended to communicate. A logical choice for a medium environment to integrate the two models is GIS because of its powerful ability to process complex spatial tasks while containing spatial data attributes. The compatibility problem is quite significant because SUMO uses XML (eXtensible Markup Language) format files which cannot be opened in a GIS environment, so a workaround that ensures a smooth data transfer was needed. Another significant obstacle to the integration is related to the rerouting scheme in SUMO, which is initially developed for simulating incidents on the road. This scheme is not developed for large spatial scale road closures that are common when flooding occurs. It requires an overly complicated description of the street closures and the adjacent streets that will be used for rerouting. Moreover, it treats clusters of flooded streets differently than single flooded streets, which significantly contributes to the increased complexity of the flood description. The following sub-sections describe how these hurdles were overcome and how the workflow of the methodology was assembled into a workable tool.

To ensure robust communication between the flood and the traffic models, the compatibility issue is addressed to formulate a way to transfer information between the flood and the traffic models. It is crucial for ArcGIS and SUMO to be able to exchange information about the exact location of the floods. For that purpose, both platforms must be using identical road networks with corresponding IDs of the streets.

SUMO has a capability to import a transport network from shapefile, but this scheme does not save important information like street type and their corresponding maximum speed limits. As a result, the imported road network keeps only the geometry of the roads without any information about their capacity. By contrast, Open Street Map format (.osm) can be converted to SUMO environment without any loss of data, and it is also manageable in ArcGIS. Moreover, after conversion from the .osm format, the newly established network in SUMO keeps the original OSM ID of streets in the network. It is important to note that ArcGIS can open OSM files, but it cannot save as an OSM file meaning that updates cannot be automated between the platforms. Given these points, OSM is considered an appropriate medium between the two platforms by opening and managing the same OSM file in both platforms. This workaround made the integration possible, but it lacks flexibility because if data in one platform is updated there is no way to send it to SUMO and updating networks manually is tedious and could potentially corrupt the system integration.

In addition to that, a large-scale adjustment of the road network had to be executed in ArcGIS. After a priliminary inspection of OSM files in ArcGIS, it was clear that it is not straightforward to identify the exact location of the flood because each street is represented by one line and its respective ID. Figure 3-2 illustrates the mismatch between the current OSM file logic (a) and the desired structure to identify the flooded locations precisely in the traffic model (b). When each street is represented by one line (Figure 3.3 a), the whole street is going to be closed for traffic in the traffic model. To translate more accurately flood locations on the road, each polyline of the streets has been divided into segments up to every intersection. However, this action does not reflect on the OSM IDs that remained the same after the segregation of the streets. To conclude, two problems must be solved – finding a way to save updates made in ArcGIS and creating OSM IDs that are unique for every road and being able to transfer them to the SUMO road network file.

After exhausting all alternatives related to ArcGIS functionality, the way SUMO converts OSM files was examined. For this conversion, SUMO employs a scheme called netconvert which uses specific OSM IDs. Reinventing netconvert in ArcGIS is almost impossible mainly because it is quite complex and poorly documented. The focus was on a second media that can open shapefiles and consequently save them as OSM files. JOSM (Java OpenStreetMap Editor) has a functionality of reading shapefiles and saving them as OSM and it filled nicely the gap between ArcGIS and SUMO. All in all, the missing part of the workflow turned out to be quite trivial data conversion issue but deciphering it was time-consuming.



a) *b)*

Figure 3-2: a) Typical representation of a road network in OSM (every street has one ID) and b) desired description – each segment of the road has a unique edge ID

The workflow ensuring the ArcGIS and SUMO uses the same language regarding OSM IDs is depicted in Figure 3-4 (p. 69). In conclusion, there are three software packages that are employed to make sure SUMO is going to use the road network file with transferable road IDs to ArcGIS. The OSM map file containing the information about road types, speed limits and other traffic signs is first segregated into small sections in ArcGIS and then saved as a shapefile, which can, later on, be opened in JOSM and saved as a new OSM file. When the new OSM file is generated, new OSM IDs are assigned to all the roads, and therefore each segment can now be identified. This new OSM file can now be used by netconvert in SUMO which keeps the OSM IDs as the IDs of the roads in the XML network file.

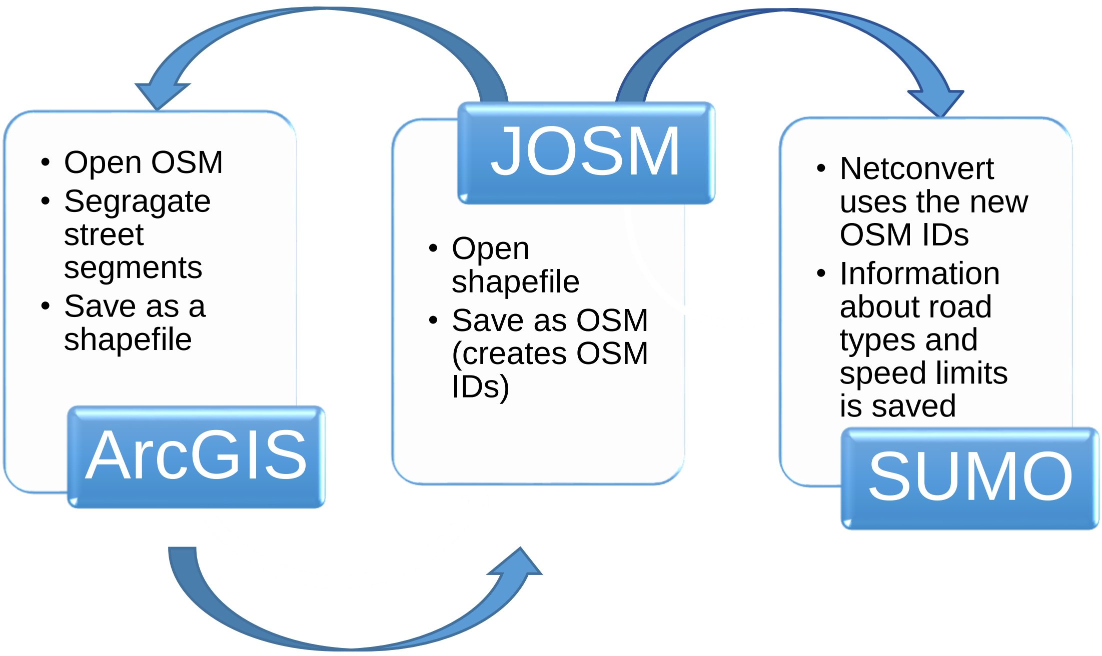


Figure 3-3: Procedure ensuring ArcMap and SUMO uses the same street IDs

3.4 Implementation of the flood-traffic integration tool

3.4.1 A brief description of the tool

The flood-traffic integration tool is developed to provide a comprehensive assessment of the flood impacts on road transportation. This tool translates flood maps into a specific input for the traffic model SUMO. The tool integrates flood and road transportation modelling via two Python models that run in ArcGIS environment. The primary motivation to develop this tool was driven by innovation because it enables filling the gap in the current state of the art. To this date, flood and transport models have not been integrated dynamically. The tool makes this possible by providing a consistent and homogeneous method to combine temporally varying flood propagation with a temporally varying traffic supply in the

SUMO model. Another aspect of the tool is that it allows multiple flooding and traffic scenarios to be easily set up and simulated.

The tool facilitates the previously described framework where flood conditions dictate the situation in the road network description in the traffic model. A shallow flood depth on the road surface will lead to a speed reduction of traffic. If the flood depth is deeper[7], that road is closed for traffic and vehicles initially passing through that road will be rerouted. This rationale of rerouting individual vehicles represents drivers' choices in a very detailed, realistic and robust way, as opposed to the existing methods that made assumptions based on homogeneous traffic flow on each link (Chang et al., 2010; Suarez et al., 2005). The rerouting of SUMO assumes that the flood conditions affect drivers in various ways – the ones that cannot reach their destinations via the planned routes will have to choose alternative routes, but others will be indirectly affected by additional traffic in the non-flooded roads. Hence, the results identify the difference between the journeys that were directly impacted by the flood (the rerouted) and the journeys that were indirectly affected by the resultant congestion.

A major contribution of the tool is that it automates the integration and thus facilitates a robust execution of multiple simulations that can represent scenarios or timesteps. By running the tool with changing flood conditions, the propagation of the flood can be easily translated into SUMO input.

3.4.2 A technique to translate the methodology into a tool

The general function of the flood-traffic integration tool is illustrated in Figure 3-4. The primary purpose of the tool is to automate the communication between the flood map and the traffic model. That involves generating hundreds of files automatically. For a dynamic integration of the flood and transport model, the tool must be run multiple times with different maps that can act as snapshots of the flood propagation.

The first component of the tool is the ArcGIS based model. Its goal is to identify the operational status (i.e. speed reduction or closure) of roads directly affected

[7] More information about the definition of shallow and deep flood depth can be found in 2.9 Stability threshold of flooded vehicles

by floods. The status is defined by a parameter that determines what flood depths are perceived as shallow and what is perceived as deep. That distinction regulates the type of intervention that will be introduced on each of the flooded roads. The first component tool can be run from Python, but it also can be run from the ArcGIS toolbox, which has an interface for input and output files.

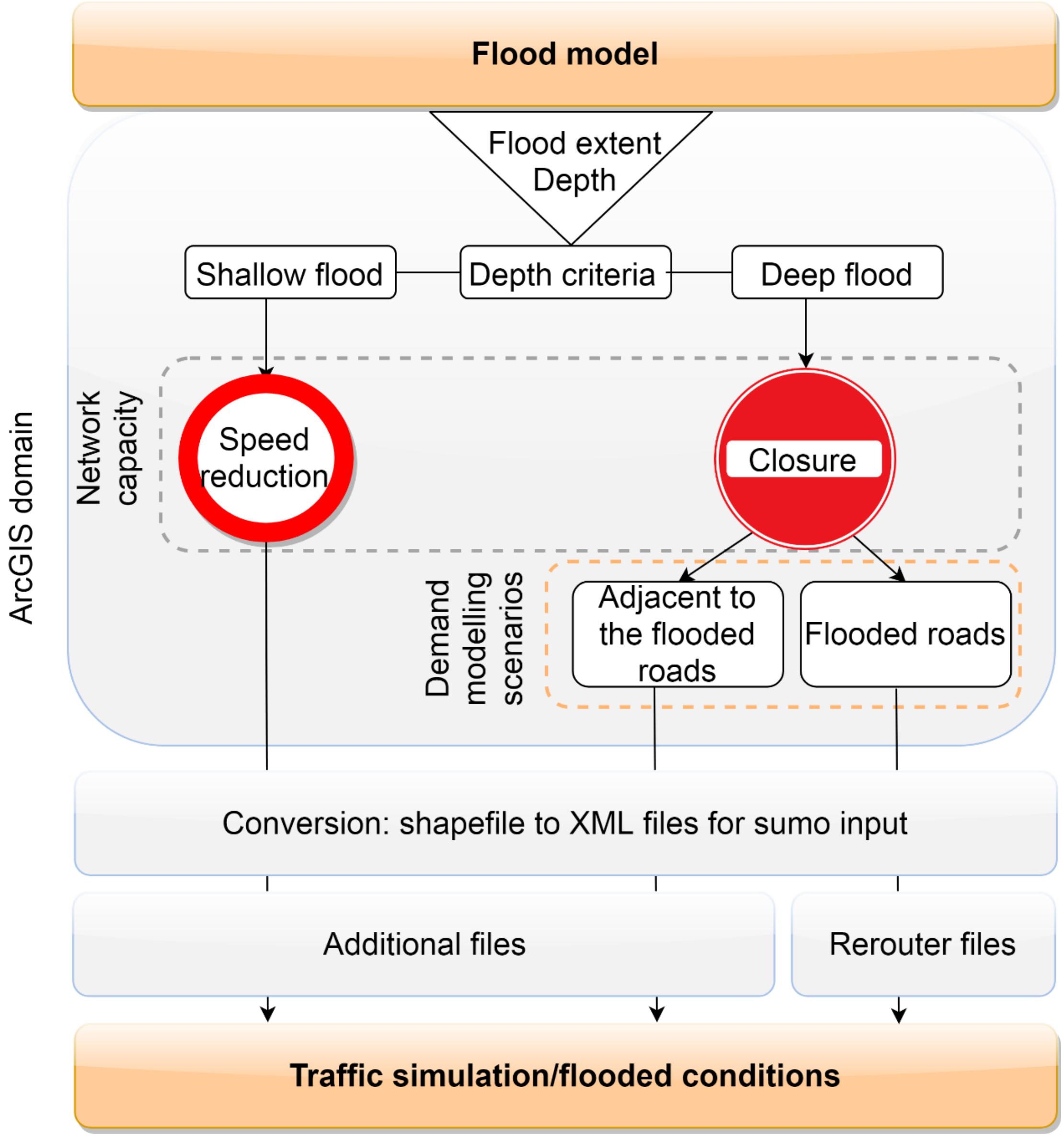


Figure 3-4: Flowchart of the function of the flood-traffic integration tool

The processing of information must match the SUMO requirements of input XML files. Therefore, a bottom-up approach was necessary to ensure adequate communication between the flood and the traffic models. The rerouting mechanism in SUMO requires the IDs of the flooded roads and the IDs of the adjacent roads to be supplied in separate files (respectively rerouter and additional files in SUMO). First is the *rerouter file*, which specifies which edges in the network will be closed for flooding and the period of closure within the simulation. In theory, each rerouter file is responsible for a road closure, but this closure can be defined either as single road closure or a cluster of connected closed streets. Therefore, an approach is needed to distinguish single flooded roads from clusters of flooded streets and consequently to identify each individual cluster of flooded streets.

The second file type is called the *additional file,* and it stores broad information (e.g. variable speed limits, traffic lights programs, rerouters). In the case of rerouting, the additional file must supply the adjacent roads to each individual rerouter file (the streets bordering with the closed streets). The provided adjacent roads are the locations where drivers are informed about the forthcoming road closure. The additional files also store information such as variable speed signs which is the method employed to reduce speed limitations on the locations with shallow flood depth.

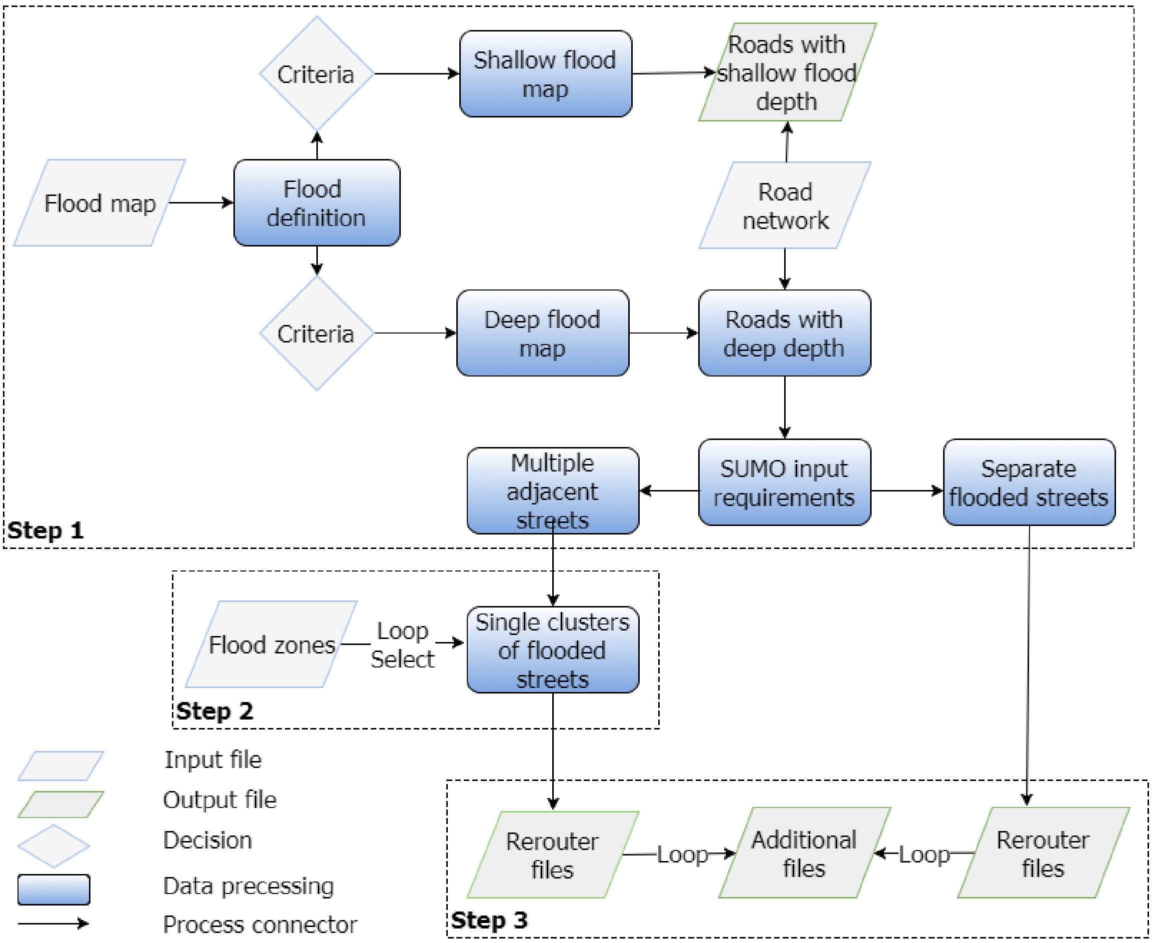


*Figure 3-5: Step by step interpretation of the **first** component of the tool*

Figure 3-5 illustrates a step-by-step logic of the first component of the tool and the processes needed to complete the required data output. The first step of the first component of the tool separates the supplied flood map into two maps according to the defining criteria for the shallow and deep flood. The road network is then overlaid with the flood maps to identify roads flooded with either shallow or deep flood water. If one road is flooded by two separate ponds and one has a deep and another pond of shallow flood depth, that road is selected among the roads with deep water depth. The roads with shallow depth are saved into a file that is ready for processing from the second model in Python. The requirements in SUMO for a street closure are very specific, and the next steps of the ArcGIS model ensure appropriate execution. The rerouting mechanism in SUMO requires each rerouter file to be supplied in a separate file. This is straightforward when it comes to individually flooded roads but requires a refined process for clusters of flooded roads that each cluster is recognised as an individual rerouter. At this stage, the model separates the individually flooded streets, as they are ready to be written as rerouter files, from the clusters of flooded streets that require further processing.

Step 2 of the ArcGIS model divides each cluster of flooded streets into separate files, and this necessitates a manual intervention in the workflow. Identifying the clusters of flooded streets is achieved by manually creating different polygon feature classes for each cluster of flooded streets. The main reason to use feature classes is that they can quickly be iterated once stored in a file geodatabase (GDB). These flood zone feature classes are drawn based on a maximum flood depth map that guarantees maximum flood extent. Thus, the flood zone feature classes could be universally applied to different flood maps based on flood propagation, because only the clustered roads from each zone are used as an output. If there are no flooded clusters of roads in a particular zone, the model directly skips that zone while writing the outputs. If there are single closures in that zone, they are filtered on the previous step and treated as individual closures.

Step 3 of the ArcGIS model is preparing the result files. The rerouters are saved in separate files using a loop. As mentioned previously, the rerouting scheme in SUMO requires the streets adjacent to the flooded ones to be supplied in additional files to the traffic simulation. The roads, written in the additional file are also identified by running a loop through the rerouter files and “Select by attributes” function in ArcGIS. Thus, each rerouter file has a corresponding additional file, necessary for the traffic simulation. If a dynamic integration is intended, it is crucial the names of the rerouter and the additional files are updated so that they would not overwrite the previous results. Generally, the rerouter IDs of clusters of flooded roads are named after the flood zone, whereas the rerouter ID of the single flooded roads is assigned after the OSM ID of the road. The rerouter IDs are essential because they are used to connect the additional file to each rerouter file. The first component has a processing time of 6 min and 22 seconds (when running from ArcGIS) and 4 min and 12 seconds (when running from Python) on a high-performance laptop.

The second component of the integration tool is the Python script that translates the shapefile output from the ArcGIS model into the required XML output. The roads in ArcGIS are represented by lines and do not have any information about directions, or the number of lanes. To acquire the required detail, the model writes XML files, assuming two opposite directions for each street (Figure 3-6). Once the XML files are written, they are checked automatically against the real road network, and the non-existing lanes and directions are removed. The former method is applied to both the rerouter and additional files, and the same procedure addresses reducing the speed limits, but on the level of individual lanes. It is worth mentioning that for the dynamic integration of the flood and traffic models, the time segment has to be updated accordingly prior to every run of the script.

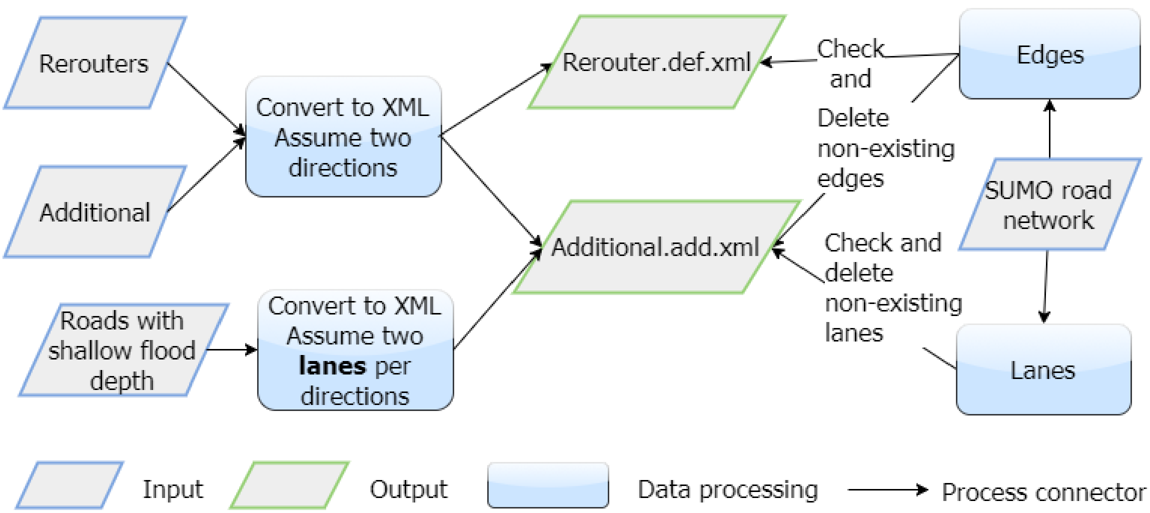


Figure 3-6: Flowchart of the ***second*** *component of the tool*

A technical description of the tool can be found in Appendix A: Using the PEARL tool (p.186). This description includes a summary of the code, its requirements, printouts of the interface and instructions for simulation and a list of required input and output files. The Python scripts of the first component and the second component can be found in Appendix B (p.191) and Appendix C (p.207) respectively.

3.4.3 Concluding remarks

This section described the motivation, the methodology, the execution and application of the flood-traffic integration tool. This tool facilitates flooding situation into traffic conditions. The flood impacts on traffic disruption have been overlooked in the past because they are not as costly and not as straightforward to calculate as the tangible direct damage. The tool addresses this disproportion while making it more accessible to integrate flood and traffic models. Several big cities use SUMO for traffic modelling, e.g. Dresden and parts of Vienna and they can benefit from this tool. Dresden, in particular, has suffered several destructive floods in the past that have paralysed both road and train transport.

Urban mobility is very dynamic and vulnerable to external disturbances (Pyatkova et al., 2019b). Therefore, identifying which parts of the transport network might be problematic in times of disasters, is a critical step in the journey to creating more resilient cities.

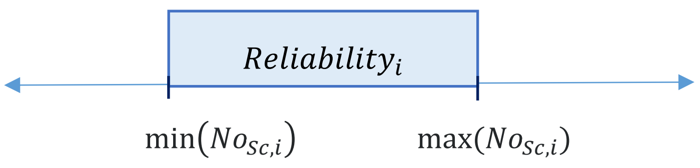
3.5 Resilience assessment

Resilience assessment has the potential to reveal how systems might behave in a variety of situations. Despite its obvious benefits, resilience assessment has not been widely assessed in practice (Section 2.4, p.35). The water sector several has several attempts: a qualitative approach (i.e. Batica and Gourbesville, 2016) and quantitative approach (Mugume et al., 2015). Even though transport resilience has been theoretically discussed for more than a decade, there are fewer attempts to appraise the resilience of the road transport systems (more details in Section 2.4 (p. 35). Butler et al. (2017) encompassed the most important attributes of resilience – time for recovery and severity of the event as a measure of service failure (Res = min (failure: magnitude, duration) (2-2 p. 27). The magnitude is the maximum deviation from normal conditions, and the duration is the time needed for the system to adjust and return to normal conditions. But what are normal conditions and how do we measure normality? This thesis takes a fuzzy approach to normality for resilience appraisal. As discussed in the literature review, there is no clear distinction between reliability (or unreliability) and resilience. This is potentially problematic, especially if the aspiration is a quantitative approach to resilience. Therefore, this PhD thesis proposes a method to differentiate the two by determining a range of daily traffic variation. This range of daily traffic variation is established from multiple simulation runs with a varied traffic demand set up. The difference between the time-varying maximums and minimums of the simulation results determine the time-varying daily reliability/variability range. Reliability is often defined as the day-to-day variability and predictability of the transport conditions in a given the time of day (Mattsson and Jenelius, 2015; Wang, 2015). Another definition describes the reliability as the time needed to reach a destination (Small, 1982) and it is logical that this time will be varying during the hours of the day. As the average time to complete a certain route is dependent on the number of vehicles (noted as No) in the network, it can be assumed that the changing number of vehicles represents reciprocally the change in the time needed to complete a route. And therefore, the reliability bounds (Rel) are formulated as the range of vehicles between the minimum and maximum performance of the measured or modelled daily variability for a specific time of the day:

$$\{Rel_i \in \mathbb{R} \mid Rel_i \in [\min(No_{Sc,i}), \max(No_{Sc,i})]\} \quad (3\text{-}1)$$

i = time step/time of the day

$Sc = 1{:}n$



And so, the minimum and maximum vehicle variation over time are recorded to establish the reliability bounds and define the ranges of normality. To associate these ranges of normality to different scenarios of flooding, first, they must be compared to any dry weather scenario, which will consequently be flooded. For this purpose, the maximum and minimum reliability ranges are subtracted from a considered dry weather scenario (noted with ScX).

$$\max\left(Rel_{ScX,i}\right) = No_{ScX,i} - \min\left(No_{Sc,i}\right) \quad (3\text{-}2)$$

$$\min\left(Rel_{ScX,i}\right) = No_{ScX,i} - \max\left(No_{Sc,i}\right) \quad (3\text{-}3)$$

Defined this way, the temporary fluctuating min-max range is the same, but its location against each scenario is specific to the unique performance of the system for that scenario. Given this formulation, the system performance of a reference scenario lies as a straight line within a fluctuating reliability range. To compare the temporal variation in the performance of the flooded scenario (noted as $Per_{ScXf,i}$), it is also subtracted from the dry one.

$$Per_{ScXf,i} = No_{ScX,i} - No_{ScXf,i} \quad (3\text{-}4)$$

Hence the flooded scenario deviation from the reference scenario and consequently form the reliability range can be examined.

As the flooded situation starts accumulating vehicles, which have been delayed on their way to their destinations, the difference between the two situations is presented as a negative performance. Once this negative performance is beyond the reliability range, the system is under exceptional conditions, and its resilience is being assessed. The choice to use reliability ranges reduces both the magnitude and the duration of the event because instead of starting when the performance first deviates from its original state, the resilience indicators start only when the performance deviates from the reliability range. Figure 3-7 illustrates the differences between the extents of both duration and magnitude if we consider or disregard the reliability of the system. The figure is inspired by Figure 2-5 (p. 38) McDaniels et al. (2008) and the ideas of degradation of service quality developed by (Bruneau et al., 2003). In the thesis the notion of the degradation of service is presented as a performance decline. It is worth mentioning that the reliability bounds are rarely straight lines in reality due to the highly dynamic demand. It can be expected that the reliability bounds are wide during the peak hours and narrower during the off-peak hours.

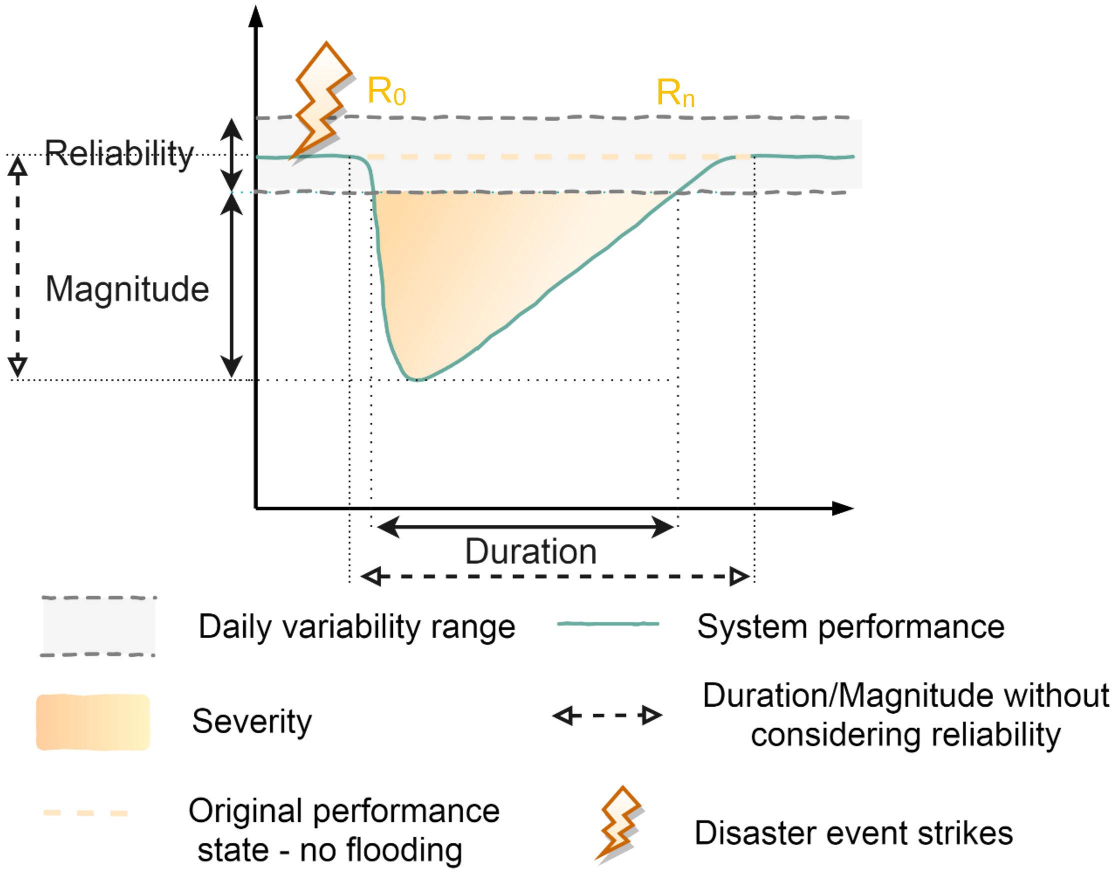


Figure 3-7: Visual representation of resilience with its three indicators: duration, magnitude and severity.

Three indicators represent resilience in this thesis - magnitude, duration and severity. The magnitude is defined as the absolute maximum difference between dry and flooded conditions, outside of the reliability range. And similarly, the duration of the resilience situation is the time needed for the system to recover after being pushed out of the reliability range. McDaniels et al. (2008) refer to this notion as 'rapidity of recovery' but they have not specified the conditions of recovery (what normal conditions are). As both duration and magnitude are maximums, the severity characterises the internal variations of the number of vehicles exceeding the standard conditions. Such variations can be indicative of the system performance, for instance, double merged peaks are observed in the results. Therefore, the severity of a given scenario n (Sev_i) is defined as the area of varying vehicles over time under exceptional conditions:

$$Sev_n = \left| \int_{Ro}^{Rn} f(t) \partial t \right| \tag{3-5}$$

Where R_o is the beginning of resilience event when the system performance exceeds the zone of reliability (standard conditions) to the zone of resilience (exceptional conditions). Respectively R_n is the moment where the system returns to standard conditions. The value of the severity is calculated as an absolute value because the difference between some vehicles between normal (dry) and flooded conditions yields negative values. Mugume et al. (2015) also considered the duration, magnitude and severity as indicative for the system performance. They also defined severity as an area but described it as a rectangle.

According to the methodology, a more resilient system is successful in minimising the duration, magnitude and severity. Assessing the resilience indicators while considering different intervention scenarios highlights the effectiveness of these measures and underpins how specific changes affect a highly dynamic system in a non-linear way.

Separating resilience from reliability would inevitably reduce the resilience indicators or even the overall impact of the disaster event. Reducing negative consequences is not something engineers would intuitively want to achieve, but theoretically, it is meaningful to be able to approach the perception of what normality/reliability is and what its bounds are. Discerning reliability from resilience is a convenient way to define exceptional conditions for any system that lack a clear definition of failure.

3.6 Assumptions and uncertainties

Assumptions made in the development of the framework inevitably lead to uncertainties in the research. Herby the assumptions are categorized as follows:

1. Rerouters:

- The street closures are valid for all vehicles. In the real world busses and emergency vehicles have a different threshold for flood instability and may pass through deeper flood depths. There is no research about the instability of busses and emergency vehicles, and SUMO is currently not able to model specific reroutes for different vehicles types.

- Rational diversions – drivers use the shortest alternative path to reach their original destinations which require a perfect knowledge of the road transport network.
- The rerouters close entire sections of roads, and thus vehicles do not travel to the flooded area but reroute before the flooded road. This representation of rerouters slightly simplifies what drivers may experience in reality, which is travel to the flooded area, make a u-turn and then reroute. As the road segments are divided between all intersections, their relatively short length is believed to compensate for the lack of detail in the way rerouters are performed

2. Tool:

- The tool closes streets for traffic according to a uniform safety criterion for a street closure. Different vehicle types like busses have a higher stability threshold in flood waters, but for the sake of safety, they are rerouted as well following the same flood depth criteria.
- It is not clear how precisely the street closure is managed in practice – there are numerous closures, and that would mean a lot of traffic police being involved in the operation. The other option is a system which is partly self-organising, where drivers can identify which flood allows passage and which is too deep. Perhaps the best choice is a system in between – supported by traffic signs in the most critical areas so that drivers would not continue if the water is accumulated on the road ahead. Ideally, traffic police would need to be physically present at locations with high flood velocities in order to ensure street closures are respected.
- In the dynamic simulation, the flood propagation is modelled as flood changes in time segments (time steps of 10 min). The flood situation at the end of the time segment is considered to represent the whole-time segment. This assumption can potentially misrepresent a very quickly developing flash flood. Shorter time steps are expected to overcome that issue. The 10 min timestep portrayed a sufficiently good representation of the flood propagation in Marbella.

3. Resilience assessment:

- The variability of the transport system might not translate directly into reliability, but it can be argued that drivers can adjust with time to changing conditions as long as the changes are gradual.
- Assessing variability and consequently, reliability is here based on multiple scenarios of different traffic demand settings. Ideally, it should be based on traffic model results, rigorously validated with a rich database of measurements
- Number of vehicles in the transport system may not be sufficient to describe the system performance. It certainly lacks any spatial information.

3.7 Conclusions

The chapter presented a novel framework for the integration of flood and transportation models. The methodology was successfully translated into workable ArcGIS/Python tool that unlocked an untouched chapter in both flooding and road transport systems science. It facilitated a dynamic integration of the two models where temporal and spatial dynamics of the flood propagation can be translated directly into network capacity changes in the transport model. In Chapter 4 a static, semi-dynamic and dynamic interpretations of the flood-traffic integration framework are applied to two case studies, and the impacts are assessed accordingly. Chapter 6 focusses on the resilience of the transport system to flooding, and it discusses how three intervention measures improve the overall resilience of the system.

4 APPLICATION OF FRAMEWORK TO CASE STUDY 1: SAINT MARTIN (CARIBBEAN)

4.1 Introduction

Figure 4-1: Saint Martin's location in the Atlantic Ocean

Saint Martin is a Caribbean island that is divided between French and Dutch administration. Saint Martin's transportation system is already experiencing challenges due to a wide variety of reasons, mainly related to fast urbanisation; the particularities of the terrain that limits network connectivity; and inadequate network capacity. On top of the delicate balance of the transportation system, the island is often exposed to hurricanes with immense impact. To assess the consequences of flooding on road transportation, a microscopic traffic model has been integrated with time-varying flood modelling results. Due to the lack of traffic data in Saint Martin, the model simulates randomised traffic demand to test the response of the network during dry and flood situations. Although the reliability of the traffic model may not be best, the traffic model is still able to capture some of the characteristics of the transportation system and the potential flood impact to the critical infrastructure (CI) on the island. This section explains the method of model integration and then discusses the knock-on effect of flooding on the traffic. As a recommendation, a mitigation measure was applied to the transportation model to investigate how this mitigation measure could alleviate the flood impact on the transportation CI in a central zone of Philipsburg.

4.2 Methodology

The rationale is that flood conditions affect the accessibility of particular roads so that vehicles would avoid driving into flooded waters. Therefore, vehicles that are initially passing through a flooded street are forced to choose an alternative route to reach their destinations. Consequently, these vehicles will experience longer travel times to complete their journeys. Because of the dynamic nature of transportation, the knock-on effect of events like that can expand further than the locations of the flooded areas and the duration of flood events. This rationale was applied in the next case study (Marbella) using two different approaches – static and dynamic. The static approach assigns a global duration of all the flooded locations in the city. It is very fast and straightforward, but it bears inherent problems related to the selection of that global flood duration value. The dynamic integration of the flood and the traffic models are more realistic because it captures the flood propagation over time by using time-varying flood maps as the input for the traffic model. The evolution of flooding is represented in the traffic model by closing the inundated streets for traffic. The dynamic integration is achieved by iterating the tool with various flood propagation maps.

The simple static integration is inefficient to represent the flood in the traffic model, because of the significant variation in the spatial distribution of the flood duration (up to 6 hours). The flood model is run for the whole island of Saint Martin including several catchments, which may react differently to a uniformly distributed rainfall. Moreover, the flood model also simulates coastal flooding, which has different drivers and durations from the inland flooding. On the other hand, the long duration of the flood means a lot of simulation effort for a dynamic integration. Under those circumstances, another approach was necessary to integrate the models realistically, without compromising the temporal variation of the flood propagation. By applying a shift in the understanding of the methodology, a semi-dynamic approach has been developed specifically for Saint Martin (Figure 4-1).

Instead of using a series of flood maps to capture the flood propagation, the new approach employs a pre-processing algorithm to analyse the duration of the flooding of each road. The flood duration is determined based on the period of flood water on a road that exceeds the criteria for street closure, assuming a road with flood deeper than 0.3 m is too dangerous for vehicles to pass through and will be closed for traffic (Shand et al., 2011a; Martínez-Gomariz et al., 2017; Smith et al., 2017). That method practically eliminates the concept of shallow flooding that was previously applied to introduce speed reductions on the flooded roads with less than 0.3 m flood depth. The flood duration map gives information about spatially varying flood duration for all flood depths more than 0.3 m. If the dynamic simulation refreshes all rerouters according to its time step, the semi-dynamic provides each road with one rerouter for the time it is flooded.

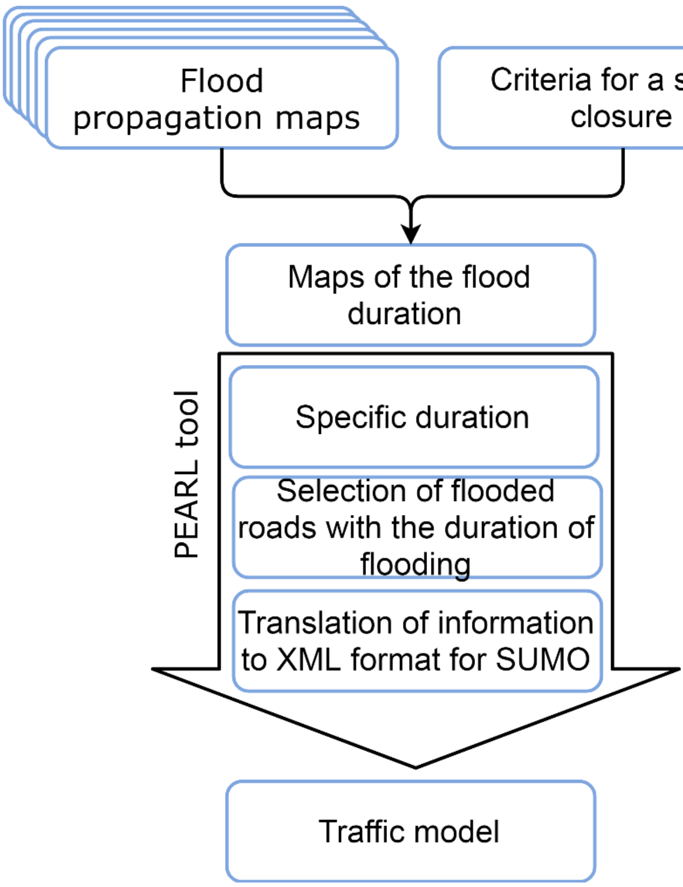


Figure 4-2: Methodology for a semi-dynamic integration of flood and transportation models

The output of the flood duration map is then further classified the following categories: 0 – 10 min; 10 – 30 min; 30 – 60 min; 60 – 90 min; 90 – 120 min; 120 – 150 min; 150 – 180 min; 180 – 210 min; 210 – 240 min; 240 – 270 min; 270 – 300 min; 300 – 330 min; 330 – 350 min. Each category is regarded as a separate flood map and run with the flood-traffic integration tool to identify which streets will be closed for traffic using the relevant flood duration. Although most of the categories have a range of 30 min, the first, the second and the last ones have respectively 10 or 20 min duration. The first distinction was selected to be shorter in order to provide higher resolution to very short-term flooding, whereas the highest value determined the maximum flood duration (350 min). Figure 4-2 depicts the flood duration map, and it differentiates the coastal flooding from inland flooding because the coastal flooding has a maximum duration. The coastal flood has the same colour as the sea, but the flooded locations can be identified if the coastline is observed.

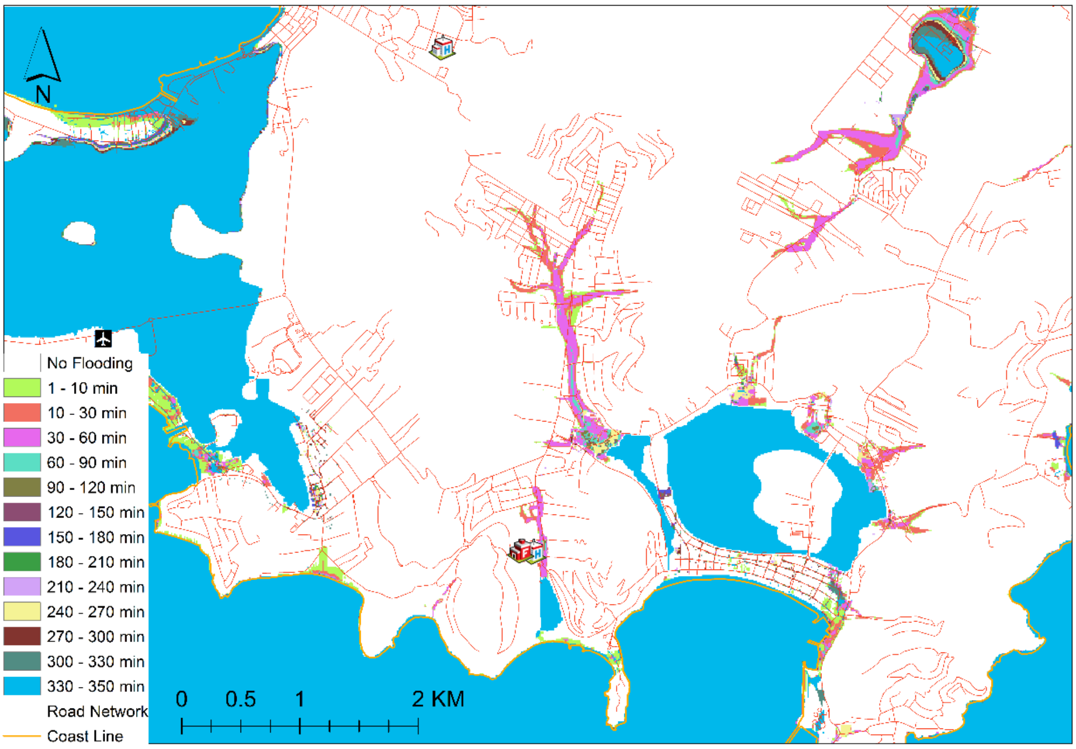


Figure 4-3: Map of the flood duration

As mentioned previously the flood duration determines the period of the street closures in the traffic model. The street closures within one category require a single value which was considered to be the maximum value of the range. This assumption may lead to overrepresenting of the flood durations on the road, but it is also reasonable to expect that a flooded road may not become functional immediately after a flood has receded. This problem can be solved only with a dynamic integration between the flood and transport simulations, which was applied to the case study of Marbella within PEARL.

Another notable drawback is related to the timing of the flood occurrences. The duration of the event does not provide any information when the beginning of the flood and whether the areas with the same flood duration flood simultaneously. An observation of the flood propagation over time indicated that the rainfall-related events tend to start flooding almost simultaneously (with differences in the order of 5 min). Consequently, the assumption is that the flooding also accumulates quickly and so all durations of closures start simultaneously from the beginning of the simulated flood in SUMO.

The flood impact was estimated as a difference between transport conditions during dry weather and flooding conditions. Once the effect has been assessed, a mitigation measure was tested to determine how it potentially could alleviate congestion in critical areas of Philipsburg.

Traffic model set up

A microscopic traffic model was set up to simulate the mobility in the whole island of Saint Martin. The model consisted of two main components: network capacity (supply) and demand models (Figure 4-3). The supply model represented the road network together with the rules to operate it, while the demand simulated the movement of people – when, from where and to where vehicles travel. The road network has been extracted from Open Street Map (OSM) and rigorously inspected and compared to Google Maps data, with special attention given to road classification and assigning correct speed limits. Due to the lack of traffic counts, the traffic demand modelling was based on a random trip generation. The route assignment method employs the shortest path by Dijkstra's algorithm. The randomised traffic simulation may not represent the actual road conditions accurately, but it was still capable of capturing trends and patterns. Most importantly, the microscopic traffic model can simulate the knock-on effects of road closures on the hole transport system. As the flood duration was nearly 6 hours, the traffic simulation was set up to last for 8 hours traffic – one hour before and after the flooding.

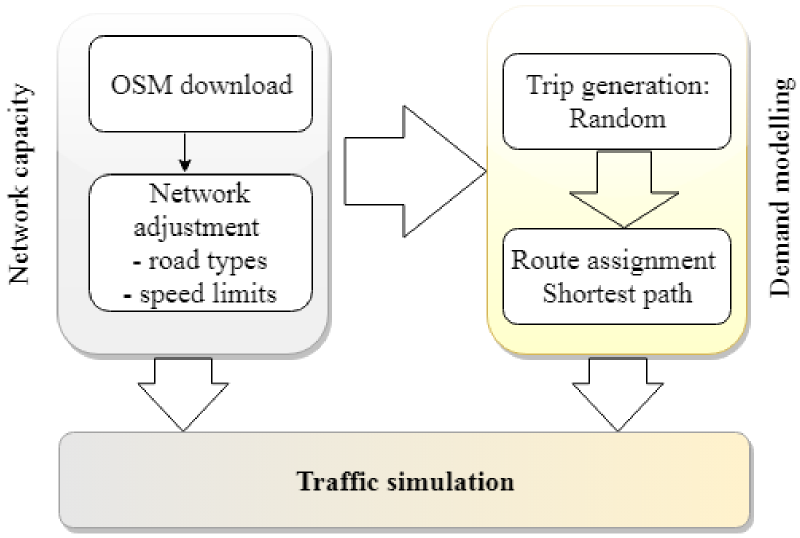


Figure 4-4: Flowchart of the implemented traffic model

4.3 Model results

The traffic model was run for both dry weather conditions and flooded conditions. The flooded conditions were simulated with MIKE Urban with 100 years return period of design rainfall and 0.5 m storm surge, derived from hurricane simulations. It was essential to assess which of the roads suffer the knock-on impact of flooding. Maps for average vehicle speed per road per simulation hour were produced to visualise the speed changes when the two scenarios are compared. Due to the randomness of the simulations, some roads remained unused in the dry weather condition.

Nevertheless, these roads can be used during the flooding conditions by vehicles that were forced to reroute. As these roads were initially emptied, the rerouted vehicles would drive at a speed close to the maximum speed limit. The required output was meant to compare the used roads in both conditions and the not originally used roads were classified as a separate category. Once that assumption was set up, the road velocities were visualised in ArcGIS. Figure 4-4 depicts the speed changes between the flooded and the dry weather conditions between the 2nd and the 3rd hour of traffic simulation. That segment of time was selected because that is the period with the most significant flooding near the hospital and the fire brigade.

The most substantial speed reductions are registered on the main roads that create a ring to connect Phillipsburg, Marigot and the north of the island where the airport of the French part is located (L'Espérance Airport). As the main roads became blocked during the flood event (speed reductions 50 - 87 km/h), the flood impacts have propagated on the territory of the whole island and cannot be confined only to the vicinities of the flooded areas.

Figure 4-6 shows a pie chart of the speed changes in the network which confirms that the flood impact is massive with 45 % of all streets in the network experienced varying delays (speed reduction from 5 – 89 km/h). The speed increase during the flooding conditions is not negligible – 10 % of all roads registers higher speeds than the normal conditions scenario. This can be explained by the routing mechanism used in the traffic model. The routes are based on the shortest path, which may not always be the fastest route to reach a destination and in some cases when flooded; the rerouted vehicles may be prompted to travel on a less crowded road and thus partially alleviate congestion. However, the number of roads that have experienced certain conditions can hardly be representative of the traffic conditions. As seen in Figure 4-6 most roads that have experienced speed increase are short and usually located on the outskirts of the road network.

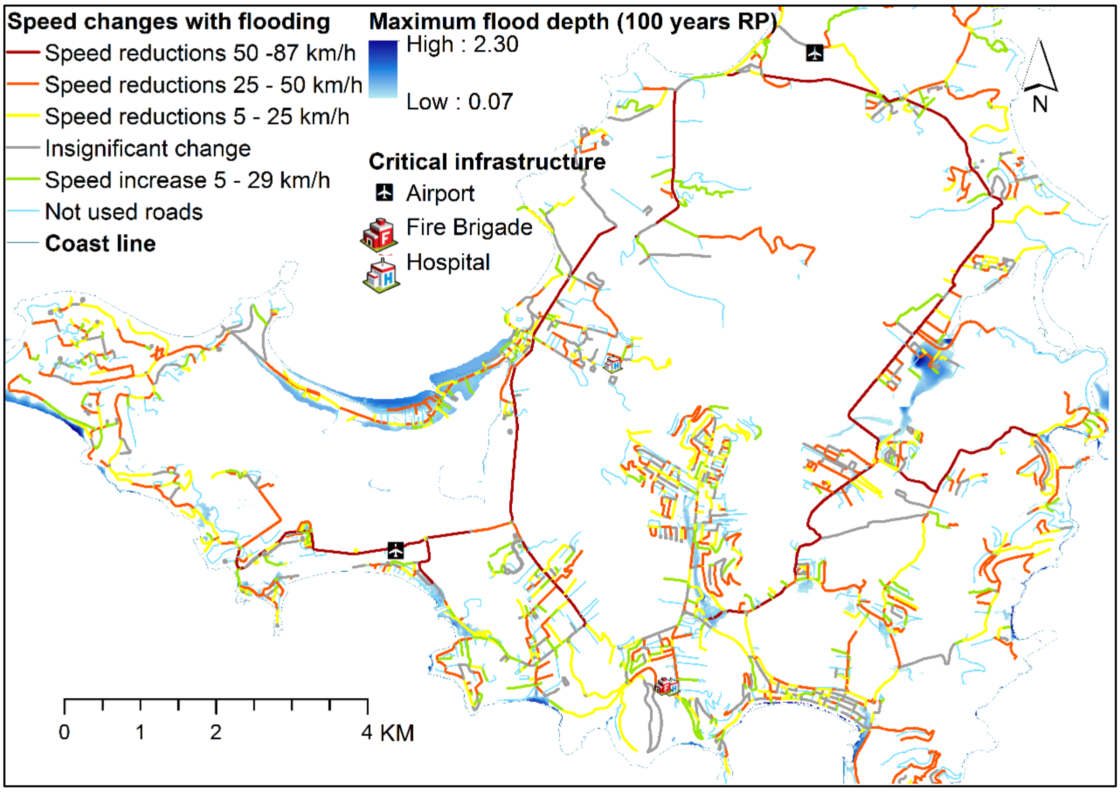


Figure 4-5: Speed changes per road between flood conditions and dry conditions

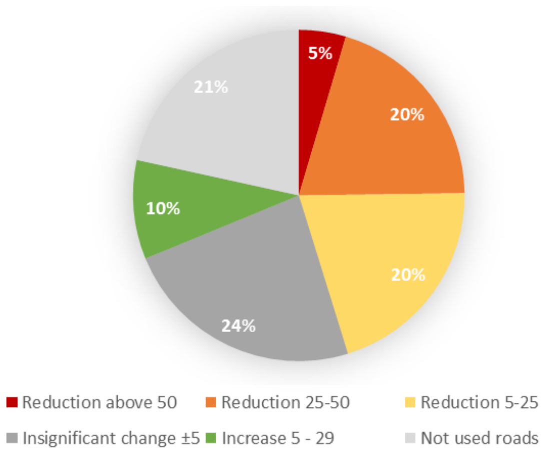


Figure 4-6: Pie chart of the proportion of roads experiencing speed changes in the road network

4.4 Implementation of a mitigation measure

To improve the operation of CIs on the island, a mitigation measure was developed to increase the connectivity of the hospital and the fire brigade, which are located next to each other on a flooded road (Figure 4-6). When that road is flooded, the access to and from both CIs is minimal, and that will paralyse the emergency service and pose a higher risk to human life. Therefore, maintaining safe access to the CIs is essential to minimise the cascading effect caused by transportation disruption. A mitigation measure assumes that the roads leading to the CIs are protected from flooding and consequently the traffic model results were examined

to demonstrate the benefits to the enhanced transport system.

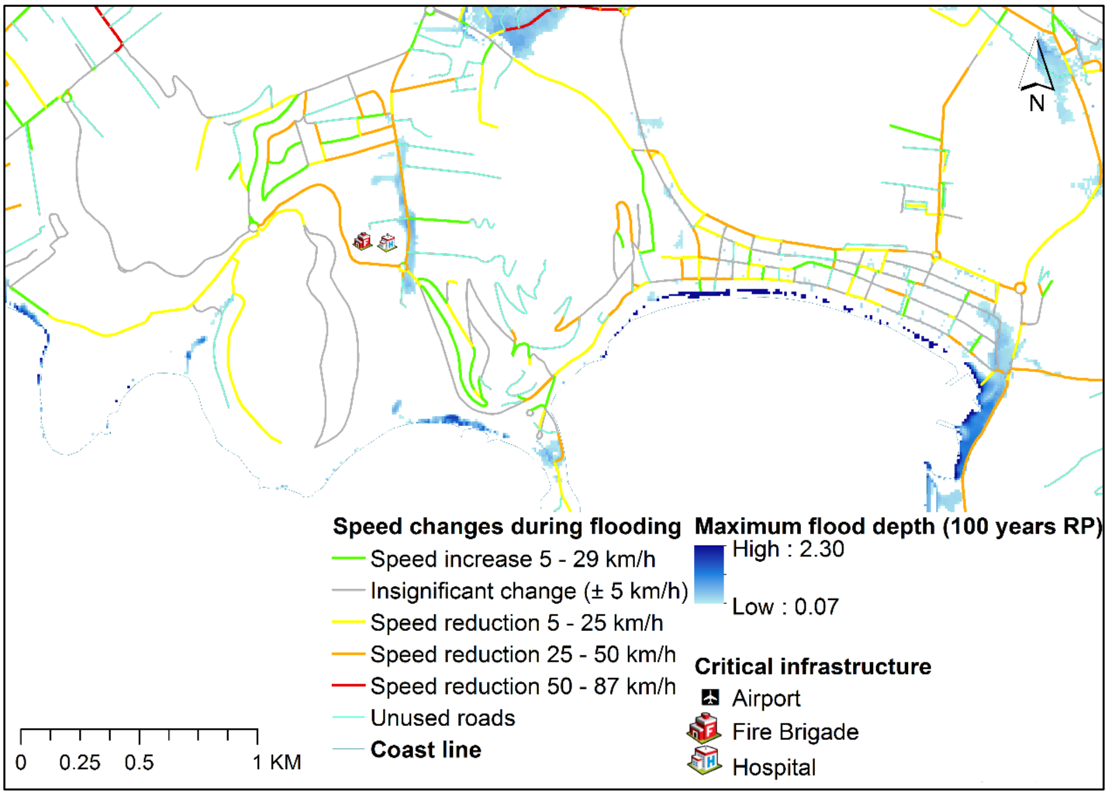


Figure 4-7: Flooded areas around the hospital and the fire brigade

After the mitigation measure was implemented, a comparison was made between the roads speeds in the scenario of a reference flood and the scenario of a flood with a mitigation measure (Figure 4-7). The figure depicts the differences in road speeds between the scenario with and without the mitigation measure during the same flood condition. Therefore, the higher the speed increase on the map, the better the performance of the mitigation measure. The results show a significant increase in the road speeds on the roads connecting the hospital and the fire brigade with the city of Philipsburg to the east and the airport to the west. The flooded roads were blocked for different durations under the normal flood conditions and because of that have maintained high downstream road speed. Once they have been open for use again, the downstream roads after the flood might experience some delays, but overall the connectivity with the critical infrastructure has been significantly improved.

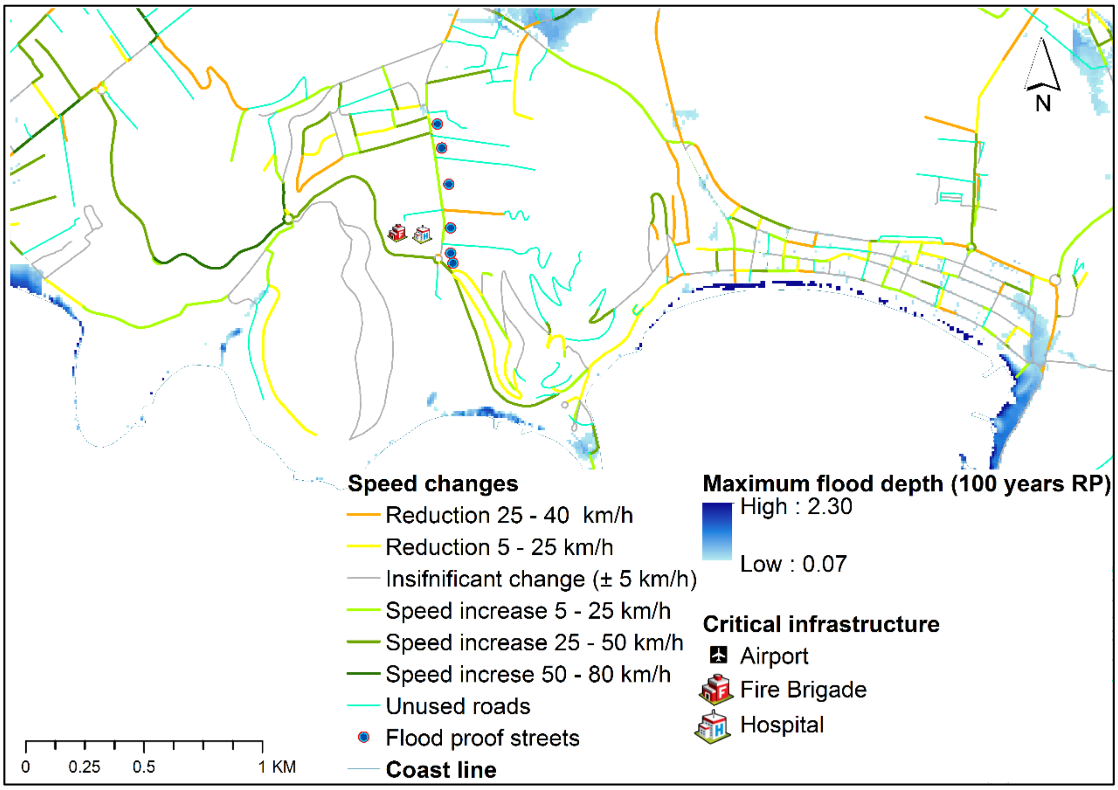


Figure 4-8: Speed changes with the implementation of a mitigation measure

4.5 Conclusions

The proposed novel approach to integrate flood and traffic models was tested in Saint Martin. Even though the traffic model relied on only randomised trips, the model was able to capture some of the characteristics of the traffic system and most importantly the knock-on effect of flooding on the overall network. A single mitigation measure was implemented to alleviate the flooding on the road that prevented access to both the hospital and the fire brigade. When the flooding in that area was eliminated in the traffic model, the connectivity between the city in the east and the airport in the west has been substantially improved.

5 APPLICATION OF FRAMEWORK TO CASE STUDY 2: MARBELLA, SPAIN

5.1 Introduction

Marbella is a medium-size city in the Andalusian region of Spain (Figure 5-1). It is located on the Mediterranean coast to the south and Sierra Blanca piedmont to the north. Sierra Blanca piedmont reaches 1200 m, needing only 5 km stretch to the sea coast. The mountain has vegetation, but rather than having dense forests, it is mainly covered by bushes and scattered trees (observation from Google Earth Pro). The steep slopes and the lack of thick forestation decrease the retention capacity of the region and are prerequisites for flash floods.

Figure 5-1: Case study area of the city of Marbella (Source of big image: Google Earth Pro)

The average annual rainfall amount is 625 mm, but it accumulates mainly in summer and autumn with the potential of forming violent torrential storms. The last such storm was in November 2016 when around 200 mm of precipitation was registered for 24 hours period (PEARL, 2017). All things considered, that rainfall event evolved into a flash flood that led to two casualties – one of them in a vehicle swept away from the flash flood[8].

[8] Source: FloodList website - http://floodlist.com/europe/spain-floods-costa-del-sol-december-2016

Marbella is established as a luxurious touristic destination and many famous people visiting and buying properties. Large areas in Marbella have luxurious mansions, which might register potentially high tangible damage. Simultaneously, the average density of population is high - 1200 people per km^2 (PEARL, 2017) which means that except the luxurious neighbourhoods, other areas are very densely populated.

5.2 Flood model

The flood model results were provided by CetAqua (Spain) as a part of PEARL project collaboration, and the set-up of the flood model is described in PEARL (2017). The flood model is 1D-2D InfoWorks (Innovyze, 2016) DTM resolution of 2m of the central part of Marbella. The model assumed that massive infrastructure like railway and motorways have independent drainage and thus are protected by vertical walls. This practically means that the motorway cannot flood.

The analysis is based on one rain gauge and three water level sensors. The model was calibrated with the information of the flood event in 2016 – measurements and photos form flooded roads (PEARL, 2017). The flood event is simulated with 100 years return period of synthetic rainfall, but it was not clear what extreme value analysis was employed to obtain the extreme rainfall characteristics.

5.3 Preparation of flood results for integration with the traffic model

The static integration employs a maximum flood depth map which is straightforward to apply, but the dynamic integration involved some hurdles. The flood propagation maps were implemented in the flood-traffic integration tool to examine how the flood propagation influences the street closures along with the flooded areas. The flood map results have a 5 minutes resolution, but here, the integration tool was run every 10 minutes (i.e. using every second flood map). Figure 5-2 shows the number of flooded/closed streets over the simulation time of the flood model. It can give an overview of the spatial propagation of the flood – it initiates and develops immediately after the rainfall, it peaks quickly, but after two and a half hours, it remains nearly constant. This behaviour of the model was not expected because it does not include sea level as an external boundary, which can potentially be creating a backwater effect. On the other hand, the terrain is very steep, so it is logical to be able to drain well. The water depths do decrease slightly with time, but the constant number of flooded streets is suspicious. The model performs well when it comes to modelling the channel flow, where the flood subsides 2h and 30 min after the beginning of the simulation.

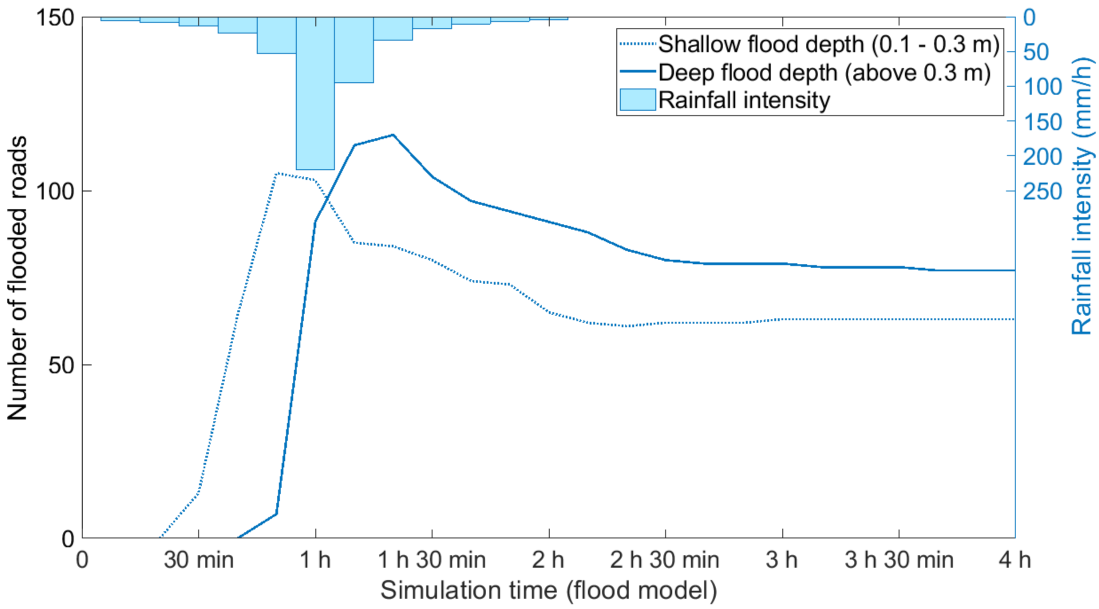


Figure 5-2: Number of flooded street per 10 min interval

As there was no access to the actual flood model set-up, there was no way to find out why the model drains so slowly. CetAqua agreed to run long simulations to investigate the behaviour of the model, and there were locations in the catchment that would keep constant flood depth for nearly 18 hours. Usually, problems like this can be due to insufficient drainage connection that allows the water to return to the drainage. Not having access to anything else than the model results, the only possible intervention was to interfere with the model results. And therefore, was assumed that the insufficient drainage links would be compensated by a depth reduction constant that will remove 2 cm of flood depth every 5 minutes. This was initiated in time step 1h and 40 min of the simulation time so that the first reduction was applied at time step 1h and 50 min and it was 4 cm. The flood reduction was applied uniformly over the flooded area. At the end of the flood simulation time (4 h), the total amount of enforced flood depth reduction was 56 cm.

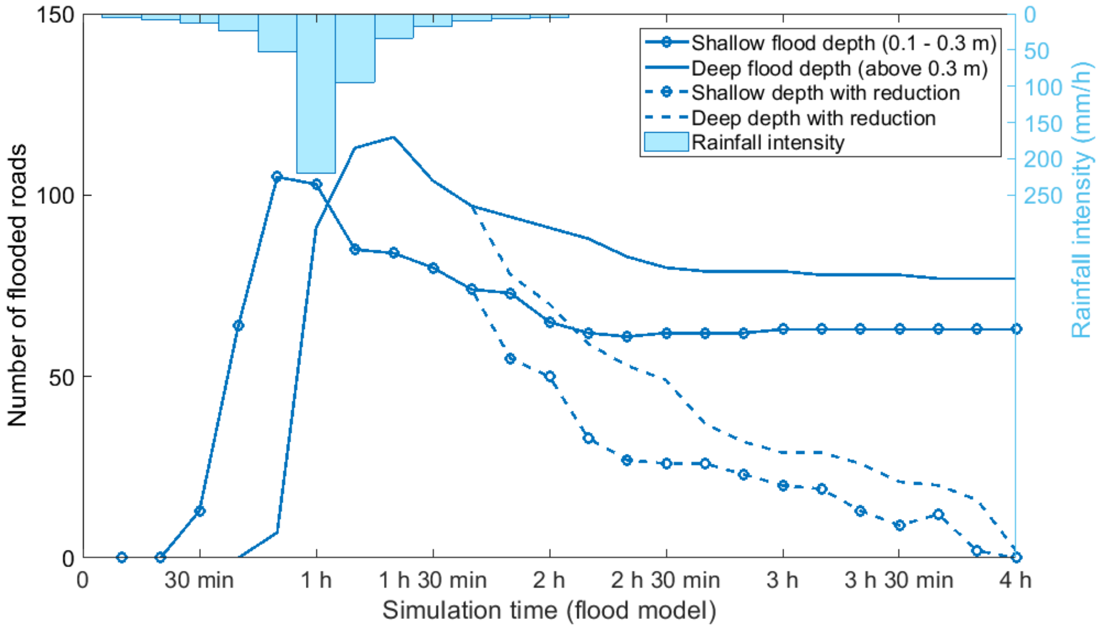


Figure 5-3: Flooded roads with and without flood depth reduction that accounts for insufficient drainage links

Once this reduction was implemented, the updated flood maps were run in the flood-traffic integration tool, and the results are displayed in Figure 5-3. The flood depth reduction constant confined the flood duration for just above 3 hours in total as opposed to the original flood model set up that had locations that will keep constant flood depth for nearly 24 hours.

5.4 Traffic model

Traffic models usually integrate two components: traffic supply and traffic demand. The traffic supply describes the capacity of the infrastructure (road network and the rules to operate the traffic). The traffic demand represents the 'behaviour of consumers of transport services and facilities' (Ben-Akiva and Lerman, 1985) over space and time. Transport modelling describes how these two components interact over time and space.

5.4.1 Traffic supply

The Marbella case study employs a road network downloaded from Open Street Map (OSM) with dimensions 6.3 to 2.5 km. This map is filtered in JOSM to ensure that all streets, rules, permitted speed limits are up to date and correct. After the road network was processed in JOSM, it was essential to establish a robust communication between ArcGIS and SUMO so that they can exchange information about the exact location of the floods. And so, it was confirmed that both platforms must provide identical road networks with corresponding IDs of the streets.

The road network had to be processed to convey the exact locations of the flooded streets from ArcGIS to SUMO. In the downloaded road network from OSM, each street was represented by a single line (corresponding to one ID). This was not suitable for the purposes of the methodology because it could not show which part of the street was flooded. Therefore, all the streets were segregated so that each segment of a street had a unique ID. Thus, the base of the integration between ArcGIS and SUMO was established (more information in Section 3.3 p.64). This segregation of the roads was done in ArcGIS, and then the network is saved as an OSM file again. OSM is used as an interpreter between ArcGIS and SUMO because importing shapefiles in SUMO leads to loss of detail (speed limits, number of lanes, categories of roads).

The traffic lights on the network and their phases were installed after careful observation of the traffic modelling results and few iterations. It was taken into consideration that a traffic light at one place can interfere not only with the traffic upstream and downstream but also at many other locations of the case study area.

Generally, Marbella has a good transportation system, but this system is primarily affected by three factors. Firstly, is the terrain of the city: the city is situated in a very hilly area, and it happens that neighbourhoods would be surrounded by hills and have very few connecting roads to the other parts of the city. Secondly, the city centre is pedestrian, and large areas of the city are not accessible by car. The city centre also floods, which complicates choosing alternative routes. Thirdly, the large number of one-directional roads are limitations, which often impede rerouting, just because drivers may not have an option to make a u-turn before the flooded section of a road.

5.4.2 Traffic demand

The traffic demand models aim at predicting how people will move over time and space in the modelled domain. Generally, demand models are constructed by two main components – the trip generation model and route generation and this section goes into details how these two components were set up in Marbella's traffic model.

5.4.3 Data availability

The research was not supported by any traffic data. As the research is part of the PEARL project, the case studies were limited to the project case studies. In 2015, there was limited but available traffic data on the municipality's web page which was consequently lost with the change of the local government. CetAqua made attempts to restore the lost information, but unfortunately, none of the data was obtained. The available traffic information is on the regional and national level but does not provide any information about traffic within Marbella. There is an only a solid record of daily vehicle use of the motorway passing through Marbella. This record is 74,306 veh/ day, and it is not certain how many of the vehicles are trespassing and how many are travelling within the city. And so, the lack of data is a severe obstacle for the reliability of the acquired results. However, a sufficiently plausible model was set up to test the methodology and assess potential impacts.

The lack of data prevented the natural progression of the model into stages of calibration and validation, and the sensitivity analysis focused on the visual interpretation of the traffic conditions during peak hours in the city. It was observed that if more than 1500 vehicles are running in the city, the transport system starts clogging and the knock-on effect is visible in many locations. There were 125 simulations with different traffic demand set-up and in the first 40 the maximum number of vehicles in morning peak hours rarely dropped under 1750 which was already too demanding for the traffic system.

For validation purposes, the traffic results are visually compared to maps of the transport conditions in Google maps traffic in Section 5.4.7 (p.105).

5.4.4 Trip generation model

The trip definition is central to traffic demand modelling. A trip is defined with beginning time, starting position (origin) and end position (destination). In a microscopic modelling technique, the trips must be computed for each vehicle in the network. Some trips might have additional stops, e.g. if a child is to be taken to school, the school location is added to the trip's definition as a point the driver has to pass by, before reaching their original destination.

To compute the trip distribution in Marbella, an activity-based generation model has been employed. The central presumption of this model is that people travel to satisfy a particular purpose or activity, e.g. going to work, school, shopping, meeting up with friends. The model computes synthetic traffic demand according to demographic statistics for the population of a specific area. The statistical input is both general (for the whole case study domain) and specific (with information about precise locations in the city). The model populates virtual households and residents, and it assigns them jobs (depending on each person's age and employability). The result of the computation is a file that specifies vehicles' origin and destination for the duration of the simulation (24 hours). Additionally, some vehicles need to pass via certain roads to drop off children or family members and the additional stops are also specified in the trips file.

General statistical data

The demographic statistics utilised in the model to set up the activity-based traffic demand are listed in Table 5-1. Most are taken from El Instituto Nacional de Estadística (National Statistics Institute) for 2011[9] and 2015[10], (European Commission, 2011) and (Eurostat, 2014)[11]. The age distribution of the population is from 2015, and the presumption is that the proportional changes are not very significant when compared to 2011. As it is evident, the data is not consistent in the time it was issued or the agency that has collected it. However, there is no

[9] Raw data for demographics in Marbella for 2011 is downloaded from: http://www.ine.es/jaxiT3/Datos.htm?t=10849

[10] Raw data for demographics Marbella for 2015 is downloaded from: http://www.ine.es/jaxi/Datos.htm?path=/t20/e245/p05/a2015/l1/&file=00029001.px

[11] Raw data for number of passenger vehicles in Spain is downloaded from: http://ec.europa.eu/eurostat/web/transport/data/main-tables

significant variation in the data over time, and the references are trustworthy, so it can be assumed all data is homogenous.

Table 5-1: Demographic statistics of the population of Marbella, employed in the activity-based traffic demand model (ActivityGen)

Parameter	***Value***	***Year***	***Source***
Inhabitants	138,662	2011	El Instituto Nacional de Estadística
Households	56800	2011	El Instituto Nacional de Estadística
Unemployment (%)	28.5	2015	El Instituto Nacional de Estadística
Legal working age	18		European Commission (2011)
Retirement age	62		European Commission (2011)
Age demographics:			
Age group 0-14 years (%)	16.6	2015	El Instituto Nacional de Estadística
Age group 15-64 years (%)	69.7	2015	El Instituto Nacional de Estadística
Age group above 65 years (%)	13.7	2015	El Instituto Nacional de Estadística
Car ownership (%)	58	2011/ 2014	El Instituto Nacional de Estadística (2011)/ Eurostat (2014)

Table 5-2: Sensitivity analysis parameters with default values, recommended by the SUMO developers[12]

Calibration parameters	***Value***	***Value Type***	***Proportion***	***Default Value***
Foot distance limit	1500	Float (m)	-	350
Incoming traffic	100	Integer	-	-
Outgoing traffic	50	Integer	-	-
Car preference	0.4	Float [0;1]	-	0.5
Mean time per km in the city	500	Integer (sec)	-	360
Free time activity rate	0.25	Float [0;1]	-	0.15
Uniform random traffic	0.2	Float [0;0.99]	-	0.2
Departure Variation	600	Float (sec)	-	120
Work hours beginning	09:00	Integer(sec)	0.2	-
Work hours beginning	10:00	Integer(sec)	0.1	-
Work hours end	18:00	Integer(sec)	0.2	-
Work hours end	20:00	Integer(sec)	0.1	-

Other parameters, required for the activity-based traffic demand estimation, are not straightforward to acquire and were used as calibration parameters. The parameters are shown in Table 5-2.

- The parameter *foot distance limit* defines the trips that will be performed by foot. Marbella is a medium sized Mediterranean city and a very touristic place. The assumption that people will prefer walking for longer distances is valid because as per (El Instituto Nacional de Estadística, 2016) 19.4% of their work trips are by foot. To determine what the average walking distance would be, the foot distance limit is set to 0, so that no trips will be filtered out. From all of the

[12] http://sumo.dlr.de/wiki/Demand/Activity-based_Demand_Generation

computed trip lengths, the 19.4th percentile was between 1497m and 1504 m (simulated five times). As the differences between the maximum and minimum are not significant, it was accepted that the final distance would be 1500 m. Although this threshold is supposed to limit the trips shorter than 1500 m, in the final results there are still short trips. Around 3% of the overall generated trips are shorter than 1500 m. The reason for this discrepancy is the random trips that consist of 20 % of the total amount of trips

- *'The incoming and outgoing traffic'* is a parameter that is not necessarily required for the setup of the model but is considered to give additional density to selected entry points in the city. Unfortunately, the demand model cannot simulate arriving tourist from the airport, because it assumes that the incoming vehicles are working in the city and it assigns them work positions on a random principle.
- The '*car preference'* is the probability an adult might prefer to travel by car, instead of using public transportation, provided both options are available. This value gives a probabilistic choice when user assignment is computed. The value of 0.5 is recommended initially by the DLR, but 0.4 was used instead so that more people will be using transit. Not all bus lines are incorporated in the model, because some of them are going outside of the modelled domain. To compensate for the missing bus lines, a lower probability of choosing a car was adopted. In that manner, more people that have the option of catching the bus will be encouraged to do so.
- The parameter '*Mean time per km in the city*' represents the average time needed for a vehicle to travel a km in the modelled domain. Its purpose is to determine the time when the cars will leave home depending on the length of their trips and desired time to reach their destination (i.e. beginning of working hours in the morning). The value of that parameter is 600 seconds (nearly twice higher than the default one). It practically prompts drivers to leave home earlier, and it gives them more time to reach their destinations.
- *'Free time activity rate'* is the probability that given household on a given day is going out in the evening. Since Marbella is a touristic city, the value of that parameter is kept higher than the recommended one. That results in a gradual increase of the evening trips.
- The parameter '*uniform random traffic*' is the fraction of the already estimated trips that will be computed uniformly at random through time for a given

network. The randomness is set up to the recommended value of 20 %. It does not interfere a lot with the traffic, but it provides a variation in the spatial distribution of the trips. The randomly generated traffic diversifies the overall traffic, and it can compensate for potential deficiencies in the trip generation model. Such deficiencies may result in minor roads not receiving any traffic because the routes from all combinations from households to employers may not cover all streets in the network.

- *'Departure variation'* is a parameter that attempts to give a human variation in schedules. It is 5 minutes in the simulation, despite the recommended 2 minutes. The idea here was to spread departure time over time so that if there are vehicles with similar route length, starting from the same place, they will leave at relatively different times.

Specific statistical data

Except for the general statistics for the city, the traffic demand requires information on particular locations through the modelled territory. The required input will determine locations where people live and work. The provided streets have a density of population and density of work positions available. Based on that information the scheme generates households on random locations along the specified roads. These households are being populated first with adults per categories: single adult, a couple, retired adult. Depending on the unemployment rate, the inhabitants of working age may become employed or unemployed. The employed people get assigned to an available work position from the list of positions. Next, children are distributed via Poisson distribution as per the mean number of children per household. Children are also assigned to available schools and kindergartens, depending on age and availability. Automobiles are associated with adults depending on the car ownership rate. In this manner, a household can have one, two or no cars available for transportation. At the end of this process, each household has a specific number of inhabitants that have different categories and a specific number of personal automobiles. The adults that do not own a car are given a lift by another household member that drives or are using public transport (if available and the bus stop is not further than the permitted on-foot distance).

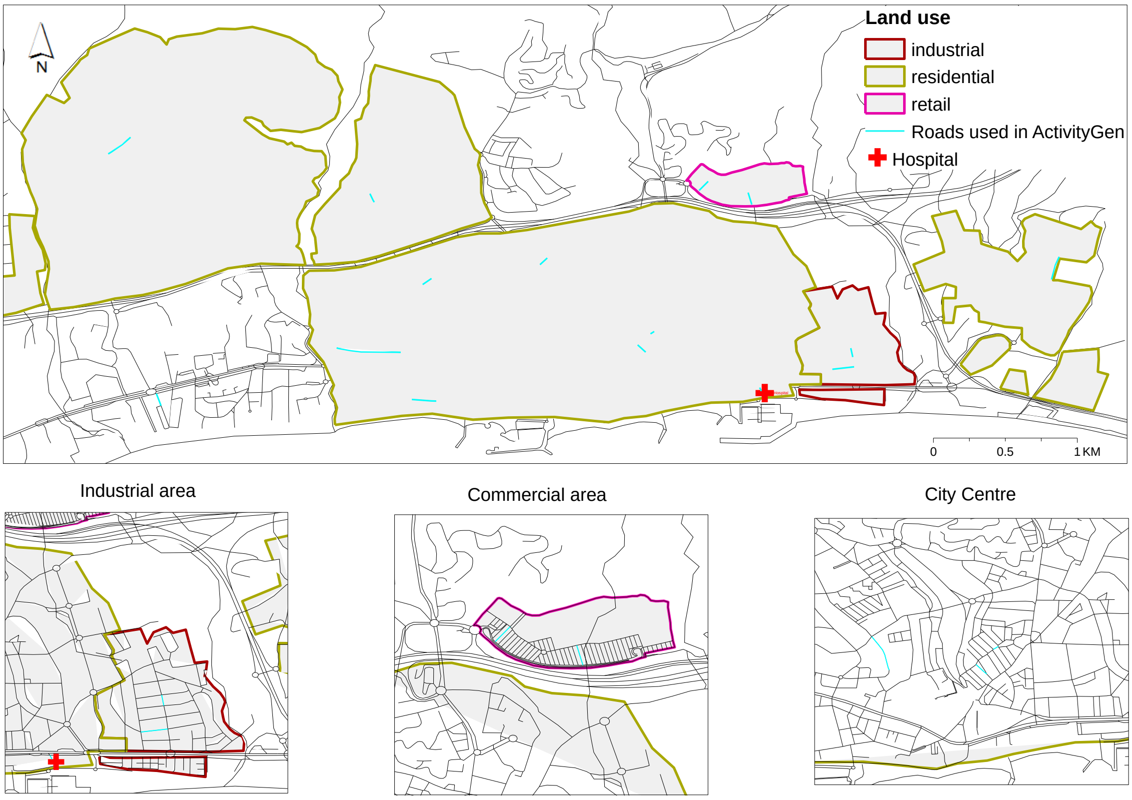


Figure 5-4: Streets selected to present activity per land use in Marbella

Figure 5-4 depicts the locations of the streets selected for trip generation and the various neighbourhoods in Marbella. The industrial part of the city is located in the southeastern part of the town and has no residents. The selection of streets has been made in a way that will provoke vehicles to reach the work positions using different entries to the industrial area. The main hospital is also included in the model, but it is represented as an employer, that attracts employees. It is set up to provide 3.5 % of the working positions, meaning that around 2000 people from different locations of the city are travelling to it. The assumption that people in the hospital work from 9 AM to 6 PM is not very realistic, but its presence in the model could potentially give valuable insight on how trips of the hospital personnel are affected by the flooding. The commercial area is, in fact, a shopping mall and is represented by three streets, that have been chosen in a way that will allow vehicles to enter the commercial area from two different entry roads. The idea was to prevent queueing from one of the entry points of the commercial area. The city centre of Marbella is mainly pedestrian hence these streets are not included in the traffic model. One of the selected streets in the city centre map is close to the ideal centre and is the entrance to a big parking area included in the model. Additionally, the southwestern corner of the city is an area with large hotel complexes, which adds uncertainty to model, because the guests are not travelling daily around the city and most likely not visiting the industrial zone. The traffic to and from the hotels is mainly represented in the traffic model

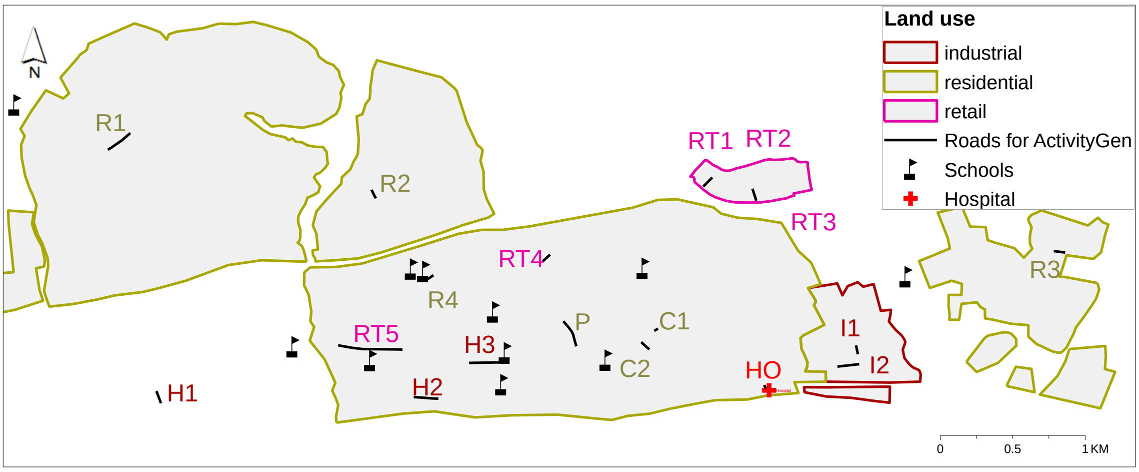


Figure 5-5:Schools and selected roads with their abbreviations

as the movement of the employees of the hotels.

Table 5-3: Details about the selected streets for ActivityGen

Name	*Abbrev.*	*Road's lenght*	*Population density*	*Work Positions density*	*% population*	*% work positions*
Residential 1	R1	164.8	5	1	15.7	3.0
Residential 2	R2	164.6	5	1	15.7	3.0
Residential 3	R3	153.0	5	1	14.6	2.8
Residential 4	R4	66.8	7	1	8.9	1.2
Hospital	HO	19.2	5	10	1.8	3.5
City Parking	P	245.0	3	5	14.0	22.6
City Centre 1	C1	86.5	6	6	9.9	9.6
City Centre 2	C2	44.4	5	5	4.2	4.1
Industrial 1	I1	112.9	0	4	0.0	8.3
Industrial 2	I2	52.5	0	5	0.0	4.8
Commercial 1	RT1	70.7	0	4	0.0	5.2
Commercial 2	RT2	25.0	0	4	0.0	1.8
Commercial 3	RT3	63.2	0	4	0.0	4.7
Commercial 4	RT4	47.7	0	5	0.0	4.4
Commercial 5	RT5	347.5	1	1	6.6	6.4
Hotels 1	H1	90.1	1	3	1.7	5.0
Hotels 2	H2	137.3	1	2	2.6	5.1
Hotels 3	H3	230.9	1	1	4.4	4.3

More detailed information about the selected streets can be found in Table 5-3. Together they show where different fragments of the population or work positions are located. For example, the population is concentrated mainly in the residential areas and the city centre, whereas work positions are more evenly distributed throughout the whole city. The length of the roads is also an important parameter because the households or work positions are allocated on the whole stretch of these roads. Hence, there is a direct connection between the length of the streets and the total number of residents and work positions on that street. The overall number of inhabitants or work positions depends on the density of these on the given road, but the length was always a factor that must not be overlooked.

Street selection criteria:

- To represent a specific area, ideally in the middle of a neighbourhood or where the density of population is highest
- To represent a specific important object (i.e. parking or a hospital)
- To represents a characteristic feature (a hotel complex, shopping mall)
- To be well connected to other parts of the city
- Not to be too short or too long because the distance determines the number of virtual households and work locations
- In the case of the industrial and the retail areas (the shopping mall), the selected multiple roads were intended to encourage the use of different access points to these zones

The schools and kindergartens in Marbella were located on Google Maps and applied in the traffic model with the unique IDs of the streets they are located in. A requirement for the school's input in SUMO is the number of children that can study there. These numbers were assigned after considering the physical size of the school building in Google Earth. If the total number of school positions is much less than the children in the city, many children in the simulation will stay at home. For that reason, 25,000 school positions were set up, assuming that the total number of children (up to 18 years of age) is just above 30,000.

Once the trips are created ActivityGen assigns how the trips will be completed - on foot, using public transport, or by vehicle (personal or shared). At the end of that process, ActivityGen produces a file with starting time, origin and destination of each vehicle. An example of the hourly trip distribution is depicted in Figure 5-6. The late evening traffic presents the busy nightlife of a typical touristic centre in Spain where dinnertime is usually delayed. The randomly generated traffic that accounts for 20 % of the overall traffic established the base of the hourly traffic (similarly to baseflow), and in the beginnings and ends of the working days, the commuter traffic starts accumulating.

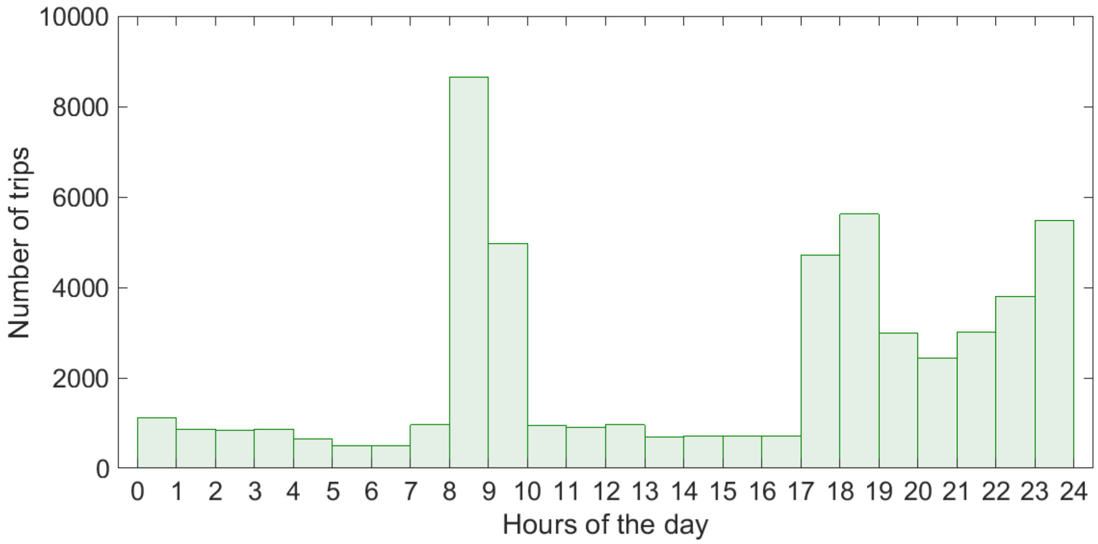


Figure 5-6: Distribution of trips over a 24-hour period

5.4.5 Route Assignment

The route assignment is a process of determining what route each trip is going to undertake, in other words, it is establishing connections between point A and point B for each trip. The initial idea was to keep the route assignment as simple as possible and employ shortest path computation (Dijkstra algorithm) to connect each origin and destination. Using shortest path logic is often unrealistic because it does not account for main roads that can have a larger capacity and consequently being used more often. Because route choice is more often a function of travel time rather than travel distance (Wardrop, 1952), a more comprehensive approach to model the traffic assignment was utilized. The method used is a dynamic user assignment, and it tries to achieve user equilibrium, meaning that it seeks to identify the minimum duration of each trip for each vehicle. On top of that, it is simulating it interactively while modelling the traffic conditions for each set of routes per iteration. Thus, the travel times of vehicles are computed as participants in the travel system, rather than assuming they are travelling in isolation. The main hypothesis in this approach is that drivers have a perfect knowledge of the traffic system, which can be expected for commuter traffic.

To achieve dynamic assignment Gawron (1998) formulated the used model in the following steps:

1. Establish routes assuming an empty network
2. Simulate the motion of the vehicle together with all other vehicles and calculate travel time/travel cost)
3. Assign a probability to each trip depending on the travel time needed to complete the route

These steps are executed on every iteration and the trips with shortest time and highest probabilities are finally selected as the most optimal routes in a user equilibrium model. The number of iterations performed in Marbella was 50 per scenario, and that was applied to 10 different traffic demand scenarios. Figure 5-7 how the number of iterations in the dynamic user assignment process influences the number of vehicles in the network. This approach finds suitable routes very quickly, and even on the 5th iteration, the number of vehicles in the network decreases significantly.

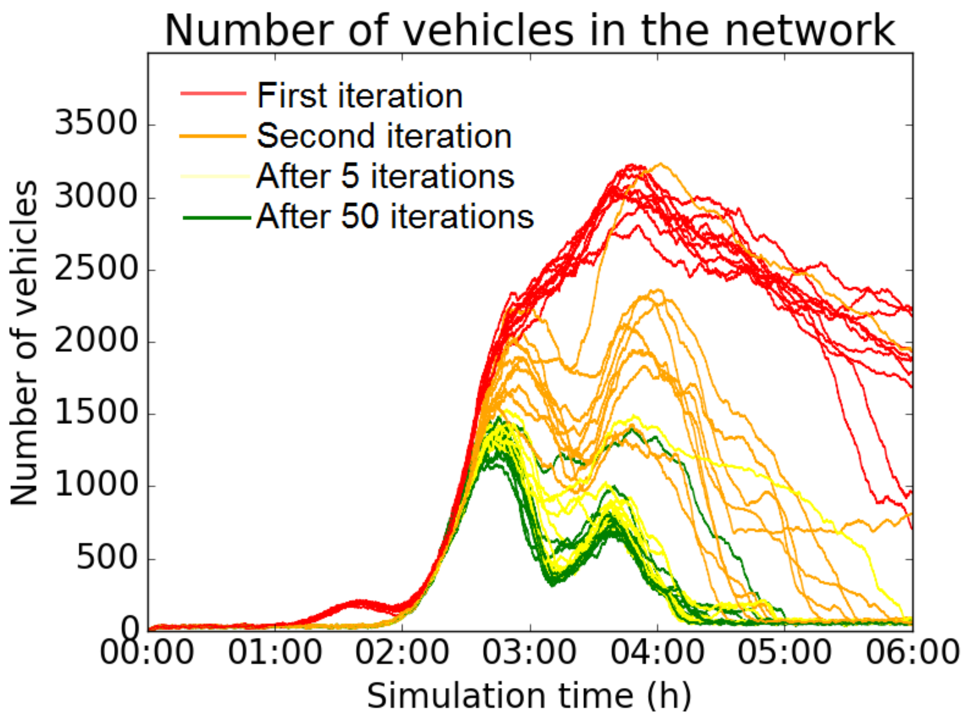


Figure 5-7: Performance of the number of iterations of traffic assignment according to the number of vehicles in the network

5.4.6 Variability of the daily traffic

To address the variability of the traffic system, ActivityGen has been run ten times with the same parameter setting shown in Table 5-1(p. 96), Table 5-2 (p. 96) and Table 5-3 (p. 100). Due to the stochastic nature of ActivityGen, it would generate different trips that respond to the parameter setting – the positions of households and work locations may be the same, but the combinations can differ according to the randomly generated virtual household members. For example, some households may have two cars, and they may use both of them, others might have retired people, that would not go to work, or a family with a child that needs to be taken to one of the kindergartens/schools. Moreover, 20 % of the daily trips are completely randomly generated, so it will always differ among the different simulations.

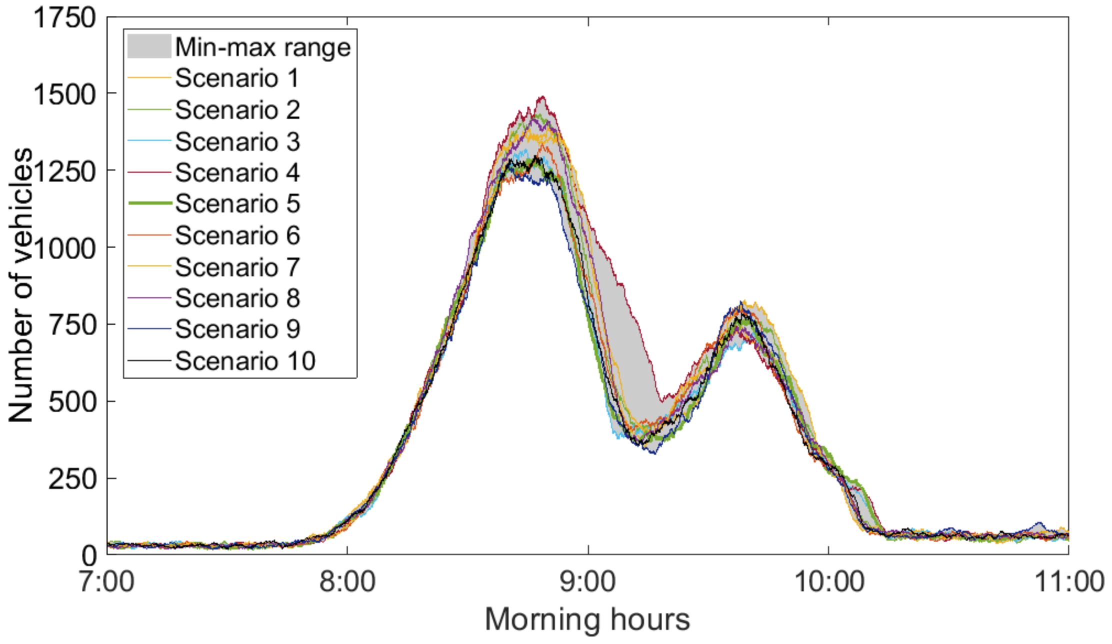


Figure 5-8: Variability of the ten different traffic scenarios

Figure 5-8 depicts the variability among the different ActivityGen scenarios regarding the running vehicles in the network. Most models have similar results, and only one (Scenario 4) is slightly deviating from the rest. If the main traffic peak is considered, the variation is significant, and most lines are evenly distributed between the maximum and the minimum. The difference between the maximum and the minimum reaches around 20 % from the minimum in the first-morning peak.

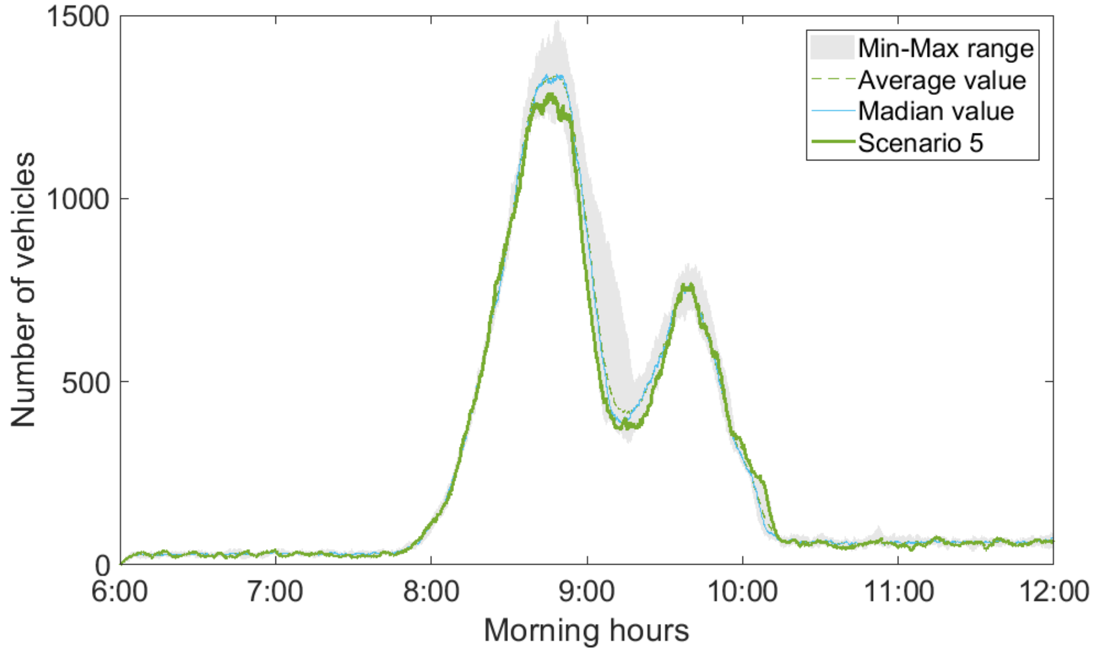


Figure 5-9: Position of Scenario 5 among the variation of traffic scenarios

All of the scenarios will, later on, be integrated with flooding, but one of them was selected to represent the actual flood impact regarding additional travel delays, travelled distance and GHG emissions. Figure 5-9 depicts the variability range together with the mean and median values over the ten scenarios for each time step. None of the scenarios scores consistently near the mean or the median, but Scenario 5 is considered a relatively good representation of the average traffic conditions among the scenarios. The scenario generally scores nearer to the minimum value of the first peak, but it overlaps with the average and median on the second peak. An additional assurance came from the fact that its flooding scenario also scores near the average performance of all flooded scenarios.

5.4.7 Validation

As previously mentioned, due to the lack of traffic data, the model could not be calibrated, but there was an option for validation that could potentially increase the confidence in the model results. The validation of the activity-based model is achieved by visually comparing model results with Google maps traffic data for typical traffic. Google has not disclosed officially how their traffic prediction works or what exactly the used colour coding means. It is very likely that Google Traffic is recording traffic data anonymously and averaging the results for different periods of the day for each section of the road.

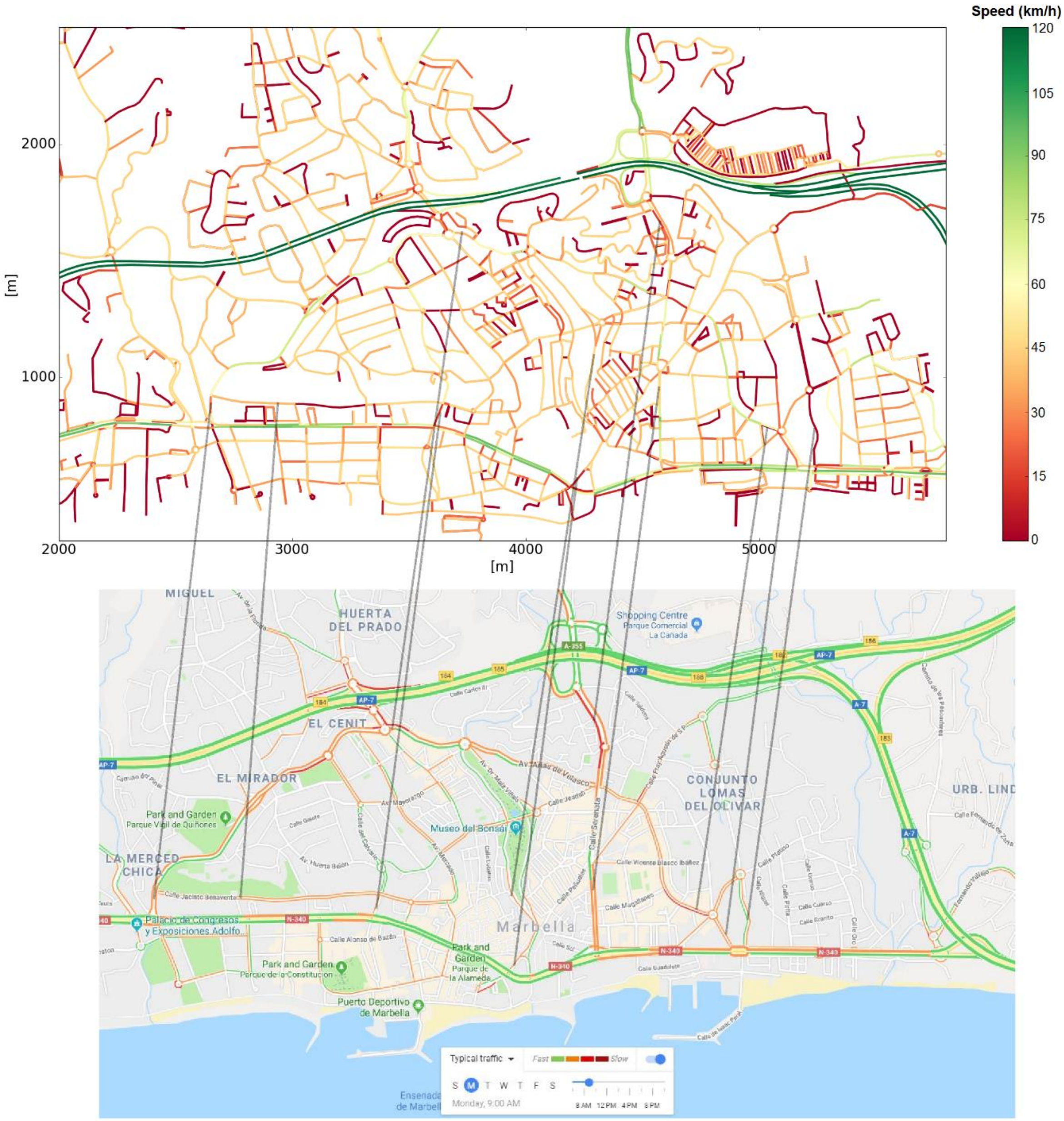


Figure 5-10: Model results for average traffic speeds between 9 and 10 AM (top) and Google Traffic image of typical traffic intensities on a Monday morning at 9 AM (bottom). The lines are connecting the approximately the same locations between the maps

Figure 5-10 shows a comparison between the average modelled traffic conditions between 9 and 10 AM and Google traffic maps for typical traffic on Mondays at 9 AM. The modelled traffic conditions are close to the Google traffic prediction, but most importantly the model has successfully captured traffic trends in the transportation system. The lines on Figure 5-10 connect locations that have distinctive features of the traffic and have been similarly predicted by both the traffic model and Google Traffic. For the different timing of the day, more comparisons can be found in Appendix D (p. 215).

5.4.8 Fuel consumption and emissions model

HBEFA 3 (Handbook of Emission Factors for Road Transport) models the fuel consumption and emissions per vehicle depending on the movement of vehicles and emission maps (Hausberger et al., 2009). These are computed using on a database of emissions of different cars in different driving situations. Figure 5-11 shows an example of an emission map for passenger vehicles with a weight not more than 1760 kg. It is calculated each second, and it estimates the emissions in CO_2, CO, HC, NO_x, PM_x (particle mass). A similar map forecasts the fuel consumption of individually for each vehicle. The HBEFA 3 model has been validated with emission measurements from real vehicles and has high confidence in the results (Hausberger et al., 2009).

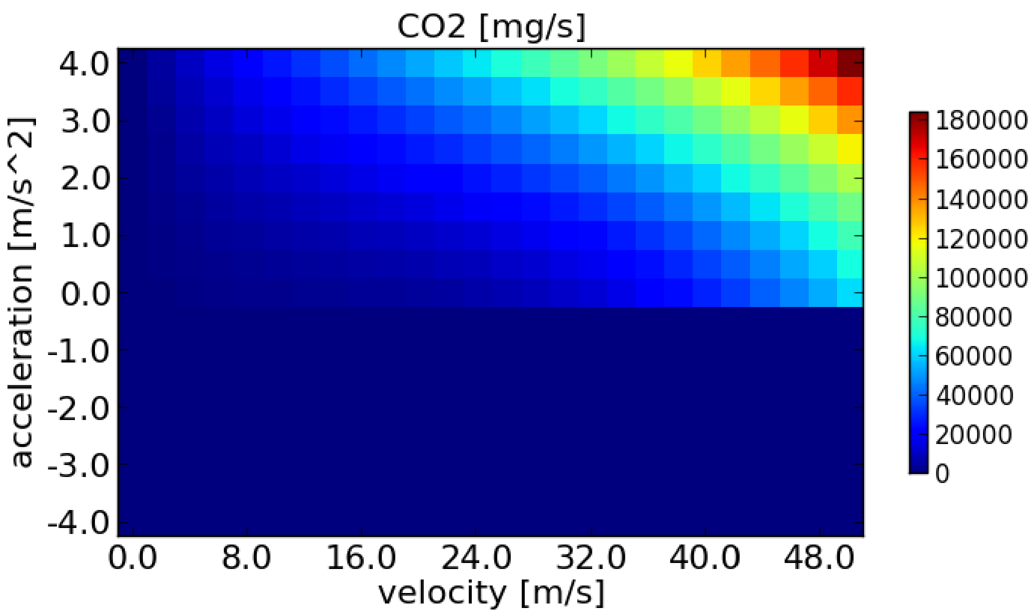


Figure 5-11: CO_2 emission map for passenger cars not exceeding 1760 kg[13]

Eurostat[14] reported that in 2016 in Spain the total share of diesel passenger vehicles was 57 %, so it was assumed that the same proportion is valid for Marbella. Considering the tendency of wealthy people to purchase SUVs, most likely the diesel engine cars' share in Marbella can be above average. However,

[13] Source: http://sumo.dlr.de/wiki/File:P_7_6_CO2.png

[14] Source: http://ec.europa.eu/eurostat/web/products-datasets/-/road_eqs_carmot

the traffic model is consistent with the average data in Spain. All 300 modelled busses are diesel vehicles.

The applied emissions model HBEFA 3 uses emissions data valid before the Volkswagen emissions scandal enfolded in 2015 and its emissions of NO_x are not updated according to the new and more realistic expectations of diesel engine emissions.

5.4.9 Results discussion

The traffic simulation computes the interactions between the traffic supply and the traffic demand. The traffic demand model was set up to represent three days of weekday traffic and the second day was used as a reference for the flood-traffic integration. The reason to do that was that the early morning traffic, that is sometimes before 12 PM, cannot be represented if only one day is to be modelled. As mentioned earlier, ten different traffic scenarios were simulated, using the same setup as the Activity-based model. For the traffic assignment stage of the model, each scenario was run 50 times, and this significantly increases the total time required to complete a simulation. As a result, only the morning traffic was selected to be integrated with the flood model. Even then, the total time to complete the simulation (preparation of files and simulation) extends to 5 hours on a fast-performing laptop. For a whole 24-hour simulation, it takes around 2.5 times longer to complete each of the 500 simulations. There were other reasons to reduce the simulation time, i.e. the physical size of the result files (up to 20 GB per simulation) and the amount of work required to apply this method on a different traffic setting and time of the day. Therefore, the methodology was implemented only to a morning traffic scenario.

The microscopic traffic model produces a lot of results, that can give insight into different characteristics of the traffic model. The primary variable explored in the thesis is the change in the number of running vehicles over time. As each vehicle disappears from the simulation when it completes its route, an increasing number of vehicles in the network indicate the traffic system is getting overloaded. By observing the performance of the traffic model in GUI, it was recognised that once the system has more than 1500, queues start accumulating in many locations in the city and it could take 1-2 hours to unblock the system, so it was naturally supposed that this behaviour could not be occurring daily in a modern European city. However, there is another important variable, that goes hand in hand with the number of running vehicles and this is the number of waiting-to-be-inserted vehicles. The waiting-to-be-inserted vehicles are vehicles that should have started their trip, but the road on which they have to be inserted is busy, and these vehicles are waiting for an opportunity (and physical space on the road) to begin their journeys. Sometimes a model can have a relatively low number of running vehicles, but if the waiting vehicles are too many, the overall performance of the model cannot be right.

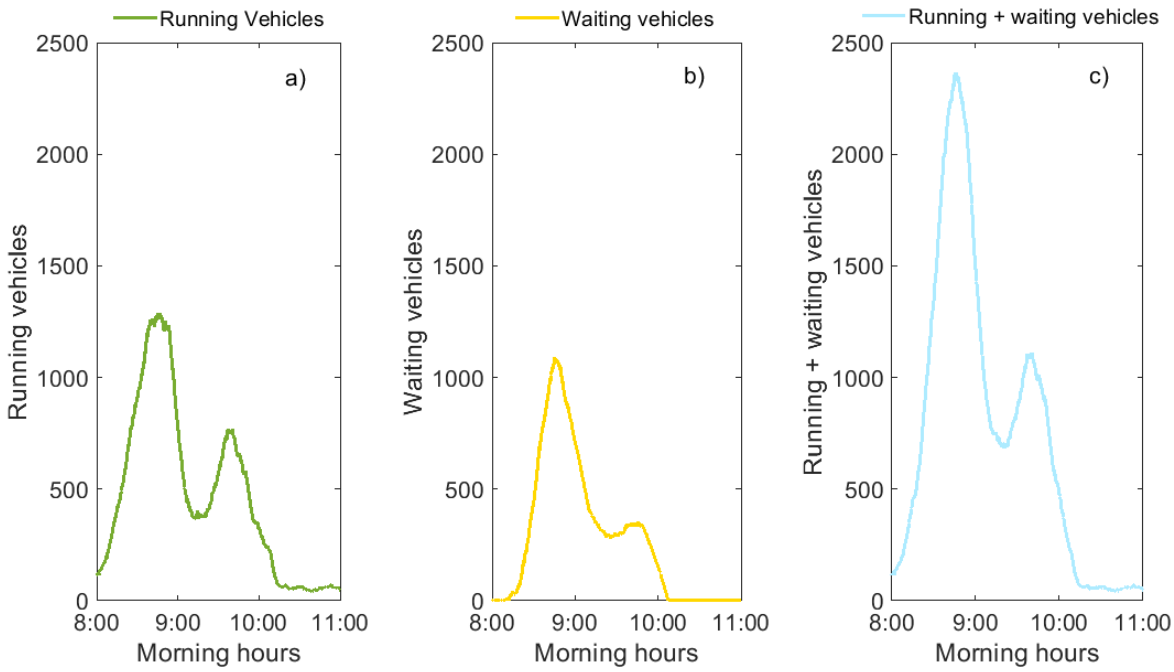


Figure 5-12: Number of vehicles over time for: a) running vehicles, b) waiting vehicles, c) running + waiting vehicles

Figure 5-12 depicts the differences between the vehicles running, waiting or the sum of both. It can be seen that the waiting vehicles are almost as many as the running vehicles but have to be considered that nearly 9,000 vehicles are travelling between 9 and 10 AM. The average waiting time is 139 sec. Figure 5-13 describes the proportional distribution of different statistics in a histogram. There are 15,770 vehicles in total in the network from 6 AM to 12 PM. The histogram of the duration of trips (Figure 5-13 a) shows that the most substantial proportion of trips have a duration between 4 and 6 minutes. This might seem short but has to be considered that the dimensions of the modelled area are 6.3 to 2.5 km. If the histogram of the travel distances is analysed (Figure 5-13 d), the distribution of travelled distances is more evenly spread where around 65% of the trips have distance between 2000 and 6000 m. Although the length of the journey and its duration are correlated, the duration depends on many other factors related to the overall traffic, traffic lights phases, speed limits along the route, other infrastructure like speed bumps etc. Therefore, the distance gives mainly general guidance about the minimum duration of each trip.

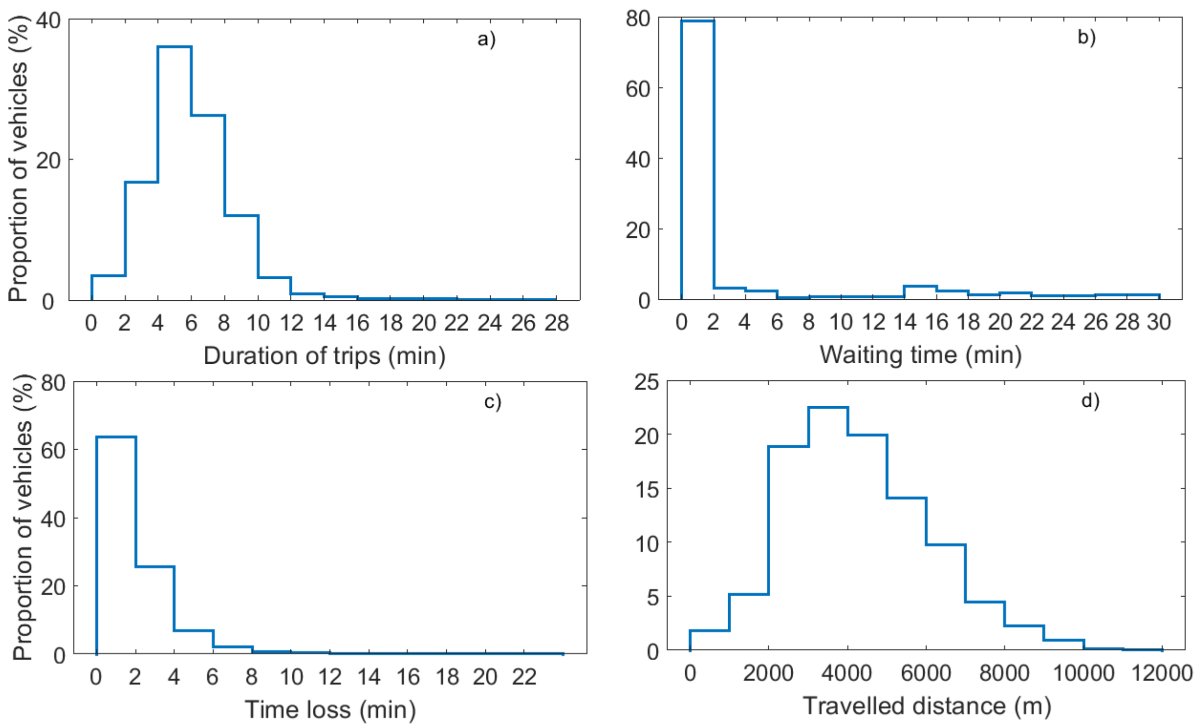


Figure 5-13: Histograms of main statistics for parameters: a) duration of trips, b) waiting to be inserted, c) time loss, d) travelled distance

The number of waiting vehicles is also a good indicator of the performance of a system. Around 80 % of the vehicles either would not wait or wait less than 2 minutes before starting their journeys. The long waiting times at the tail of the curve are an indication that at times the traffic system is struggling to locate space to insert vehicles. The lack of room on the road has its logical explanation within the function of the ActivityGen, which identifies roads that represent a larger area (e.g. a neighbourhood). So, the whole traffic from that area has to initiate their journey form that particular road. As described previously, due to the high mountainous regions literally surrounding some neighbourhoods, there are only a few available roads to connect some neighbourhood to the rest of the city. When these roads are blocked, the rate of inserting vehicles is low, and therefore a queue of waiting vehicles can develop. To overcome this delay and deliver people to their destinations on time, vehicles are prompted to leave their homes earlier. The parameter '*mean time per km in the city'* is set up to a higher value of 500 sec, and it determines the beginning of each trip. Figure 5-13 c) describes the distribution in another variable – time loss and this is the time that was lost due to driving below the speed limit. This parameter cannot be standalone, because it has to be compared to the trip duration. So, if 90 % of the vehicles have time loss of fewer than 6 minutes, that is already longer than the trips of more then 60% of the vehicles. This parameter can give valuable insight when dry and flooded conditions are compared.

5.5 Necessary procedures to ensure smooth integration of the flood and the traffic models

To provide a realistic integration of the flood and traffic models, first, a careful exploration of both models had to be considered. As previously described, the flood model did not consider individual drainage for the motorway, although it is a standard practice for motorways to include such drainage. Figure 5-14 presents the road network overlaid with the maximum flood depth map. The motorway (shown in red colour) does not flood. There is no detailed information about the flood model set up but judging by the way flooding accumulates towards the fringes of the motorway and the orientation of the triangles, it is very likely that the flood model has vertical walls preventing the motorway to get flooded. Furthermore, the flooding next to the motorway is presented by only a few puddles, and it is likely that it could be absorbed by the drainage of the motorway these reasons and uncertainties, it was assumed that the motorway would not flood, and it would remain fully operational. To avoid motorway closures due to the tiny puddles of flooding, the motorway was removed from the ArcGIS environment Thus, the flood-traffic integration tool would avoid forwarding it to SUMO for a closure. If the motorway were flooded in the model, additional

ArcGIS analysis would have been necessary to identify the affected lanes. Currently, due to OSM data standards, the motorway is a single line per direction.

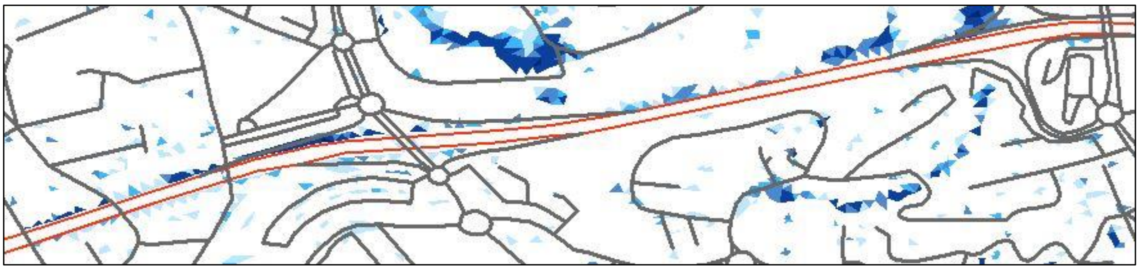


Figure 5-14: Flooding near the motorway (presented with a red line). The flood map is maximum flood depth for rainfall event with 100 years return period

The second adjustment was associated with the bridges crossing the motorway. ArcGIS cannot recognise these bridges automatically due to its 2D representation of reality. And so, it may happen that the flood-traffic integration tool would identify these bridges as flooded and request SUMO to close them. In practice, these bridges do not flood and preventing closures was achieved by simply renaming these bridges. To avoid the bridges to appear flooded to the tool, they have been also filtered out in the ArcGIS environment. Note, that removing the bridges from ArcMap just prevents the tool to close them in the traffic model hence they are fully functional in SUMO.

The third intervention focused on improving transport system performance. This time the SUMO model had to be updated to reflect a reasonable selection of alternative routes. Because the rerouting scheme was never intended for large-scale closures like floods, some vehicles may struggle to find a flood-free route home. The rerouting scheme is designed to assign the shortest route from the closed street to each vehicle specific destinations, and it cannot consider whether any of the newly selected roads are flooded now or in the future. If one of these roads is truly flooded, a new reassignment takes place sometimes going back to the initially flooded road. That results in vehicles going in circles between two flooded roads until one of them is open for traffic. The best solution would be to employ a diversion sign that can lead drivers to use the best possible way to continue their journeys. Unfortunately, this is not implemented at the moment, but the SUMO developers agreed it is an important feature and most probably will be available in the next release. Until then a workaround that is also efficient was developed. To prevent vehicles from driving in circles, first the locations where this occurs were studied, and it was confirmed that all four are associated with the same problem. To avoid cars going back to the same position, an effortless adjustment was applied to the road network. The street just before the second rerouter had its U-turn removed so that vehicles will be forced to continue in a different direction. It required a few iterations, because sometimes the U-turns of the next couple of streets had to be also removed, but eventually it was a very robust workaround, which did not affect the traffic model under dry conditions and ensured vehicles would not circulate between two flooded streets.

5.6 Assumptions

1) Flood model
- The flood model is set up on a quarter of the transport model. With an extreme precipitation event, other parts of the city may be flooded, and the transportation system might experience even more severe shock
- The flood depth reduction constant is plausible for the purposes of his analysis
2) Traffic supply
- While the road types and speed limits are acquired from OSM, the traffic signals and their phases are not known. Main traffic lights were manually set up, and their phases were arbitrarily selected but adjusted if not functioning adequately
3) Activity-based traffic demand model (ActivityGen)
- The selection of centres of households and work positions are realistic
- Time to leave is computed based on the desired arrival time (e.g. beginning of the working day) minus the product of the shortest path and the expected average duration per km in the whole city. The latter parameter may differ significantly in different parts of the city
- Bus lanes are not complete and their frequency is every 10 min
4) Traffic assignment
- Assumes that drivers have a perfect knowledge of the transport system and take objective travel choices
5) Flood – traffic model integration

- The flood development is modelled in the peak morning hours traffic. The selection of the flooding hours was quite arbitrary and therefore a flood development in other morning hours can result in different results.

5.7 Static integration

To address the flood impacts on transportation, first a static flood scenario is considered, and consequently, it will be compared to a dynamic flood scenario. Initially, the tool was run with static flood conditions, using a maximum flood depth map for 100 years of the return period of design rainfall (hyetograph is shown in Figure 5-17). In other words, the flood is represented in the model by only one flood map for a specified duration of time. In an urban setting, the surface flooding is essential for the description of flooding on the road. The most recent integration of the two models by Chang et al. (2010) modelled channel flow discharge necessary to close a bridge. So, it focused on very localised flooding, rather than a whole catchment. Figure 5-15 shows the road network overlaid with the maximum flood depth and illustrates the location of the flooded area in the hearth of the transportation network. The PEARL tool uses that flood map as an input to determine which roads will be closed and which will suffer speed reductions.

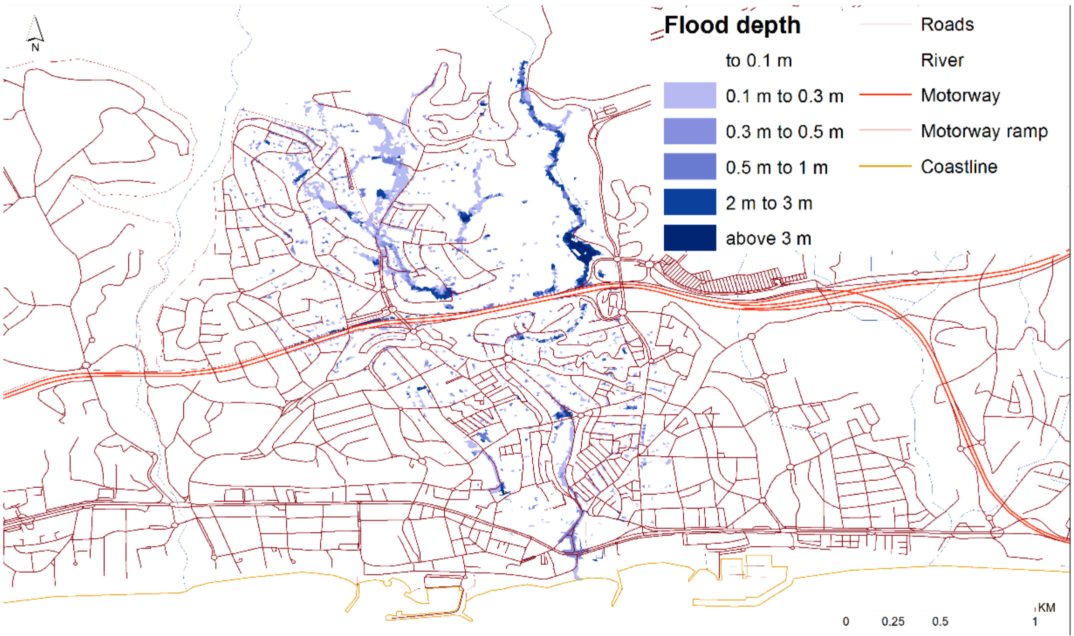


Figure 5-15: Map of the road network in Marbella and the location of the maximum flood depth for the event with 100 years return period

The tool identified 142 roads (5.9% of the total number of roads in the traffic network), as listed in Table 5-4, to be closed for traffic and further 90 roads (3.7 % of the total traffic network) to suffer slower traffic. Considering that the area of the flood model in less than a third of the area of the traffic model, 10% of affected roads is a noticeable figure. However, in traffic, the proportions of flooded streets are not that crucial as the locations and the capacities of these roads. As illustrated in Figure 5-15, the city centre of Marbella is profoundly affected by the flood. Due to the nature of a coastal city, Marbella's traffic network has an oval shape that is additionally pressed by the hilly areas on the North. Therefore, a flood in the city centre may divide the city into two isolated islands and make the whole system inflexible.

Table 5-4: Number and length of streets with deep and shallow flooding. The deep flooding (above 0.3 m) will lead to a street closure, and the shallow flooding (0.1 - 0.3 m) will lead to slower movement of the traffic

	Max flood depth	*Proportion of the whole network*
Number of streets with deep flooding	142	5.9%
Overall length of the streets with a deep flood depth (m)	19,436	8.7%
Number of streets with shallow flood	90	3.7%
Overall length of the streets with a shallow flood depth (m)	8,509	3.8%

Employing static integration means simultaneous closures of all of the flooded streets. Determining the duration of the flood-induced closures in the traffic model is essential on this stage. As a matter of fact, the maximum flood depth map may not co-occur during the flood propagation, and therefore it is challenging to select a representative duration of the event. Moreover, if the selected interval of time is too long, it would overrepresent the maximum flood depth map. On the other hand, if it is too short, the flood event can be underrepresented in time.

The duration of the flood event was derived from information about flood propagation. Figure 5-16 shows that the number of flooded streets increased very rapidly from 8:20 AM, and it peaks between 8:50 and 9:00 AM and then gradually decreased. The maximum number of simultaneously flooded streets was 116, and the duration of the event was derived based on that value. The maximum flood depth represented the most flood extreme conditions which could be described only by the peak. However, the total duration of the flooding is 3 h and 10 min, and it must not be misrepresented. A simple approach was applied to determine the event duration. If the number of flooded streets is more than a certain threshold, that time segment qualifies to represent the flood duration. Two thresholds were applied in the flood model – 50 % and 75 % of the maximum simultaneously flooded streets. With a 50% threshold of flooded streets, the flood duration was 90 min, whereas if the 75% threshold is selected the period of the flood was just 50 min (Figure 5-16). After the end of the flood, the roads that were previously flooded have speed reductions in the traffic model for 30 minutes. This way the binary conditions of flood/no-flood were smoothed out to represent a transition period after the flooded roads are open for traffic.

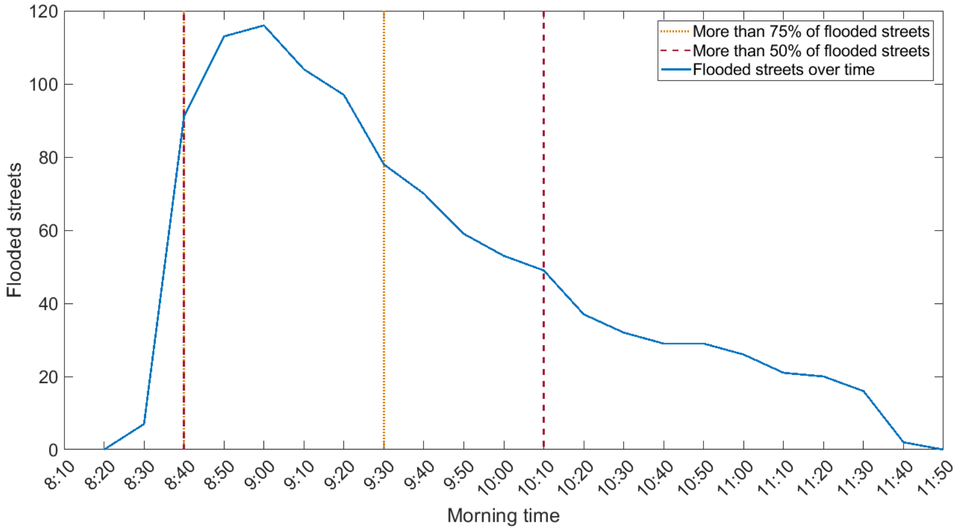


Figure 5-16: Number of flooded streets with a flood depth deeper than 0.3 m and duration and intensity of the rainfall event, integrated into the flood model

To examine how the flood affects the traffic situation, the changing traffic conditions also need to be considered. The modelled traffic conditions vary during the hours of the day. As previously described the traffic demand had two morning peaks – one before 9 AM and another one around 9:30 AM. The flood was set up to begin at 8:30 AM in the transport model and finish at 9:20 AM or 10 AM depending on the flood duration. The longer flood duration covered both traffic demand peaks. Speed limitations of 20 km/h were applied to roads with flood depth 0.1-0.3 m for the duration of the flood. After the flood, all previously flooded roads suffered speed reductions for 30 min.

The traffic conditions were simulated with flood duration of 50 min and with 1h 30 min. Figure 5-17 depicts the differences between the two simulation results, compared to the dry weather traffic scenario. Until 9:20 AM the results of both flooded simulations overlapped. They registered a considerable increase in the number of vehicles before 9 AM and remained relatively constant instead of decreasing. The constant number of vehicles in the network coincides with the drop in traffic demand after 9 AM, and it means that the system is still assimilating the previous surge in vehicles. Both of simulations did not recover between the two demand peaks which means that many vehicles due to start work at 9 AM were still circulating by 9:30 AM. And this is where the two simulations with different flood durations diverge significantly. The number of vehicles in the short flooding simulation remains almost constant for the next 20 minutes after the flooded streets were open for traffic and started decreasing gradually until it returned to normal conditions values at around 11:20 AM.

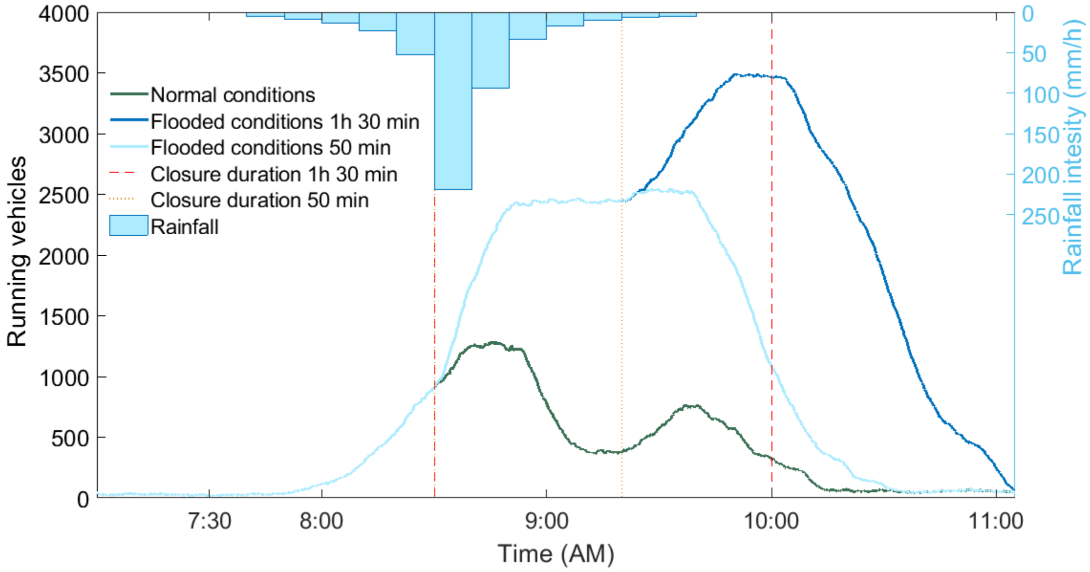


Figure 5-17: Vehicles numbers in normal vs static flood conditions

When the second demand peak started, the long-duration flood simulation was already severely congested, and the number of vehicles continued to increase. Consequently, at 10 AM the number of vehicles in the flooded traffic system was seven times greater than in the normal conditions. Even after the capacity constraints were removed, the number of vehicles remained almost constant for about 5 minutes and started decreasing steadily until it returned back to normal at 11:05 AM. The two simulations with different flood durations exhibited one similarity – in both cases it took the system 1 hour to fully recover after the flooded streets were open for traffic.

Table 5-5 and Table 5-6 present the overall statistic results are defining the traffic conditions for the normal and flooded simulations with durations of 90 min and 50 min. The additional travel distance rose with only 6 to 11%, whereas the overall travel time increased by 250-400%. The sharp increase in trip duration confirms previous studies' observations that transport disruptions in an urban environment are more prominent for travel delays than additional travel distance. The difference between travel time and travel distance increase is sure evidence of thorough gridlock in the whole transport system, and this is valid for both modelled durations of the flood event.

Table 5-5: Overall travel distance comparison

Travelled distance	*Dry conditions*	*Flooded conditions* ***90 min***	*Flooded conditions* ***50 min***
Sum (km)	65,764	73,274	69,597
Absolute difference		7510	3833
Relative increase (%)		111	106

Table 5-6: Overall travel time comparison

Trip duration	*Dry conditions*	*Flooded conditions* ***90 min***	*Flooded conditions* ***50 min***
Sum (hours)	1527	5986	3828
Absolute difference		4459	2301
Relative increase (%)		392	251
Cost of delays (€)		129,311	66,729

Figure 5-18 and Figure 5-19 are maps illustrating the speed differences between the normal and flooded conditions when considering respectively 90 and 50 min of flooding. The speed values are aggregate speeds per road between 9 and 10 AM. There are only mild differences between the two maps and the charts representing the number of affected roads in each category. The two simulations practically produced the same results until 9:20 AM, but there was a serious divergence between the number of vehicles in the second half of the hour. One can argue, that the conditions at 9:20 were already so congested, so there were no options for the central part of the system to become more blocked.

Due to the small difference between the two maps, only Figure 5-18 will be discussed, although most are also valid for Figure 5-19. All major roads in the city registered speed reductions more than 50 km/h (marked with the google maps icon on Figure 5-18). These roads play an important role in connecting different parts of the city, and when blocked, they create long spillback effects. On average, 28% of the roads in the transport system are delayed between 9 and 10 AM, whereas only 4 % of the roads have been closed due to flooding. The differences in these figures also highlight the importance of the knock-on effect when considering traffic disruptions.

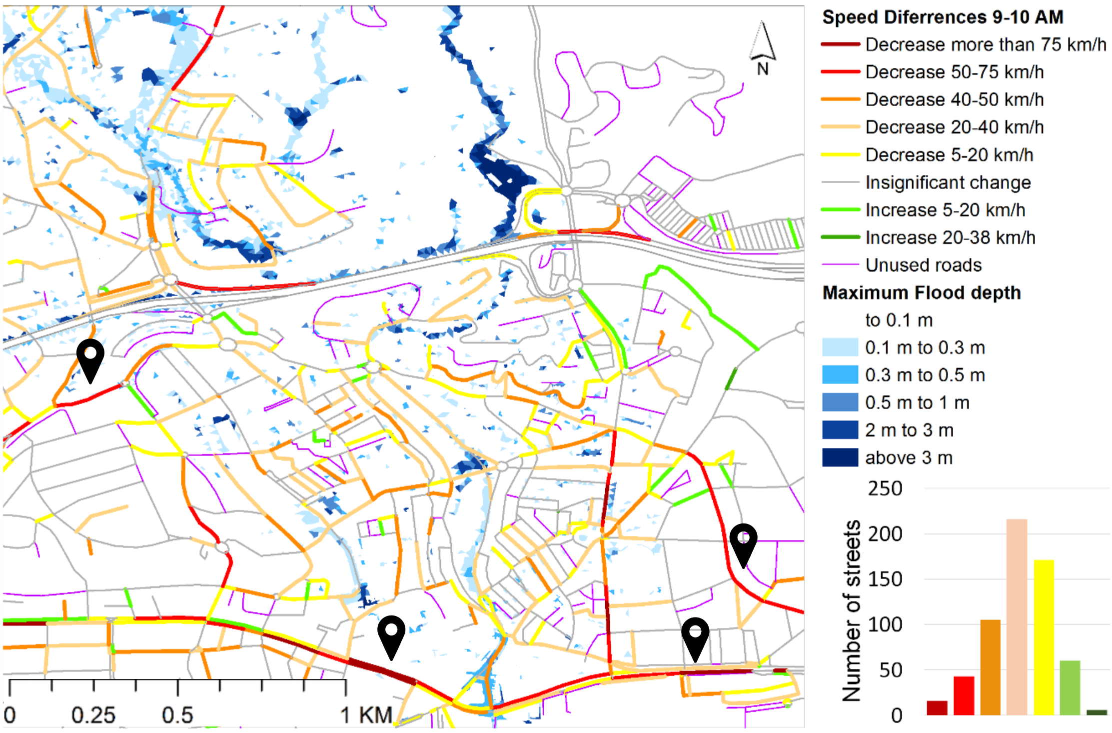


Figure 5-18: Map of speed differences between the normal and the flooded conditions. Flood duration – 90 min

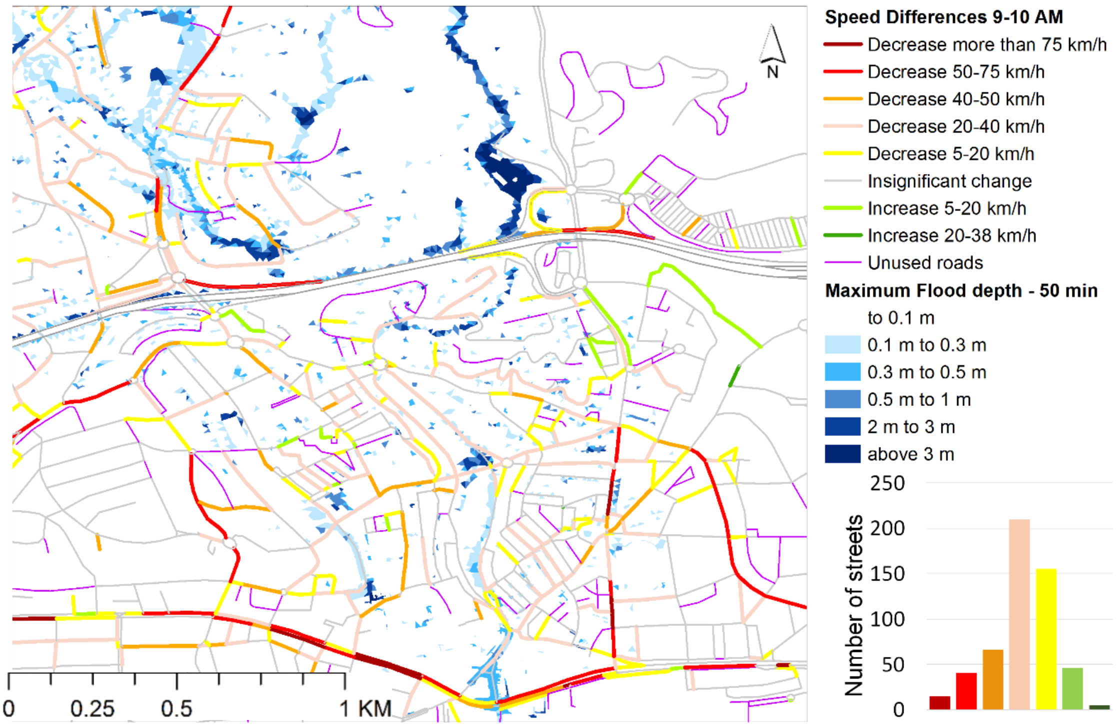


Figure 5-19: Map of speed differences between the normal and the flooded conditions. Flood duration – 50 min

Few roads have been impacted positively by the flooded conditions. These infrequent speed increases are usually a result of the reduced traffic in specific directions after a blocked road. Often a congested road slows down because it cannot continue in a particular direction and the roads in other directions receive less traffic and are nearly empty. This can be observed even in double carriageways because some vehicles do not always use the right lanes and can temporarily block the traffic heading in different directions.

Although there was high confidence in the way the transportation model simulated the flood conditions, there was ambiguity in the way the flood was represented in the system. The main concern is related to identifying the duration of the flood event described by the single flood depth map. This duration is going to be a global parameter for all flooded streets in the transport network. Under those circumstances, all flooded streets are closed with the same fixed closure beginning and end. The use of maximum flood depth maps has become a norm when assessing flood impacts on build environment to determine the worst damage on a property level. When analysing the interactions between two highly dynamic systems, such as flooding and transport, it is necessary to acquire information about the development of the flood. Such information can be depicted in one map only if that flood has a very slow development and prolonged duration (for example, Somerset levels flood 2014 (Thorne, 2014)).

The presented results were based on a relatively arbitrary principle to identify the flood duration – by selecting a time segment which has more than 50 and 75% of the maximum flooded streets. As maximum flood depth is a map of maximums, it is sensible to represent it with the duration of the peak, but there is always the danger of misrepresenting the event. For a transport model, flooding should not be illustrated as a binary problem that can be addressed with a start and stop of a single flood map. And so, one can argue that the discussed results with different closure duration can be equally right or wrong. However, the maps of the speed changes did indicate a certain pattern and potentially pointed out vulnerable locations in the transport network. Previous research integrating flood results and transport models did employ a static flood map to describe the flood event (Suarez et al., 2005; Chang et al., 2010). This PhD thesis argues that this method is not sufficient to represent the flood dynamics in the traffic because the sequence of street closures, corresponding to the flood development, is crucial for the transport model. The next section describes how flooding would impact traffic if a dynamic integration between the flood and the traffic model is implemented.

5.8 Dynamic integration

The dynamic integration of flood and transport models was designed to represent the flood dynamics in the traffic model. With that intention, the traffic model was updated with flood propagation information every 10 min. The total simulated flood duration was 3 hours and 20 min, and so the flood-transportation tool was run 20 times.

Ten different ActivityGen results simulated the uncertainty of the daily traffic variability. All ten traffic scenarios were flooded with the same flood dynamics to examine how slightly different traffic systems react to the same flood event. Figure 5-8 (p. 104) and Figure 5-20 reveal the variability of the morning traffic under normal and flooded conditions. In the dry conditions simulations around 9 AM, all models register a steep slope of descending, meaning that many drivers are already reaching their workplaces. The agreement of the models is clearly expressed as all except one scenario are clustered very close before and shortly after 9 AM. This is not the case for the flooded simulations because the traffic does not ease much after 9 AM and the second peak in demand nearly merges with the first peak. Comparing the figures, the main deduction that can be made is that the flooding inserted a more substantial variability in the transport system, particularly in the second peak of the morning traffic.

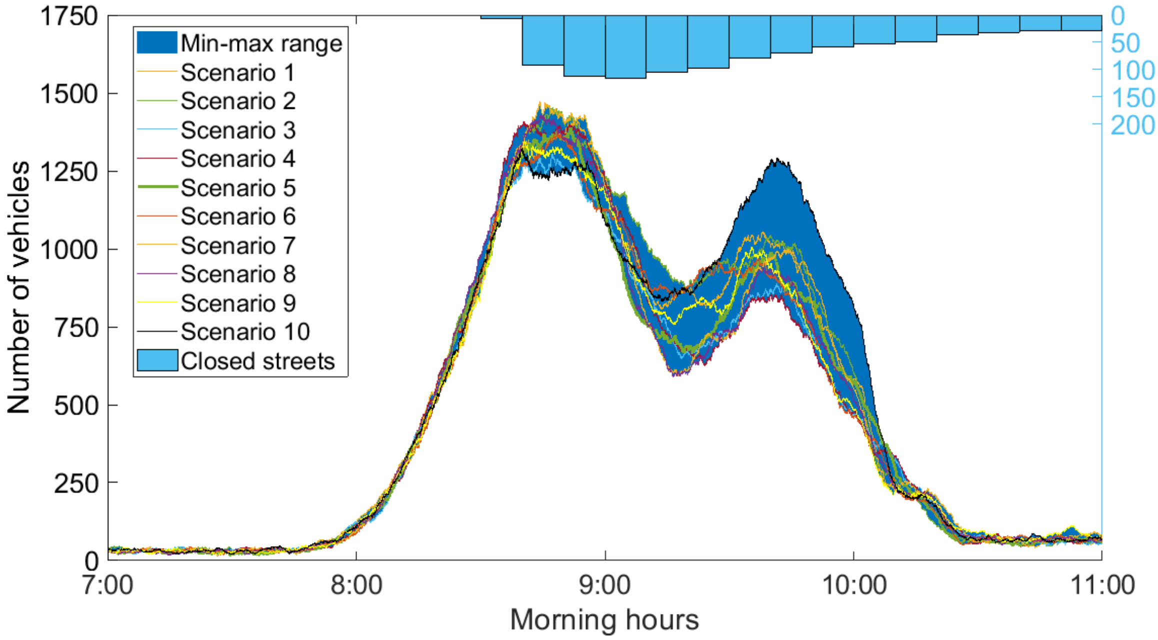


Figure 5-20: Variation of the traffic under flooded conditions. The number of closed streets per 10 min is shown at the top

To observe the differences between the normal and the flooded conditions, the ranges of the scenarios are compared (Figure 5-21). The Scenario Maximum (Subplot a) depicts the range between the maximum of the variability ranges in the normal and in the flooded conditions. While the flooding maximum has considerably more vehicles than the dry maximum after 9 AM, the first-morning traffic peak is slightly lower than the dry conditions one. The Scenario minimum (subplot b) the flooding minimum registers a marginal increase in vehicles compared to the dry one. There are two reasons for that discrepancy:

- The flood starts accumulating from 8:30 AM with only seven streets being flooded until 8:40 AM. The short peak in the dry maximum is registered at around 8:45 when 91 streets were closed, and most were located in the northern part of the city. The argument is that the system has not reacted to the constraints that are localized, and most closures have happened in the previous 5 minutes.

- Another explanation of the small differences in the first peak is that in a congested network, some vehicles cannot start their journeys because there might not be any room on the road and they wait to be inserted.

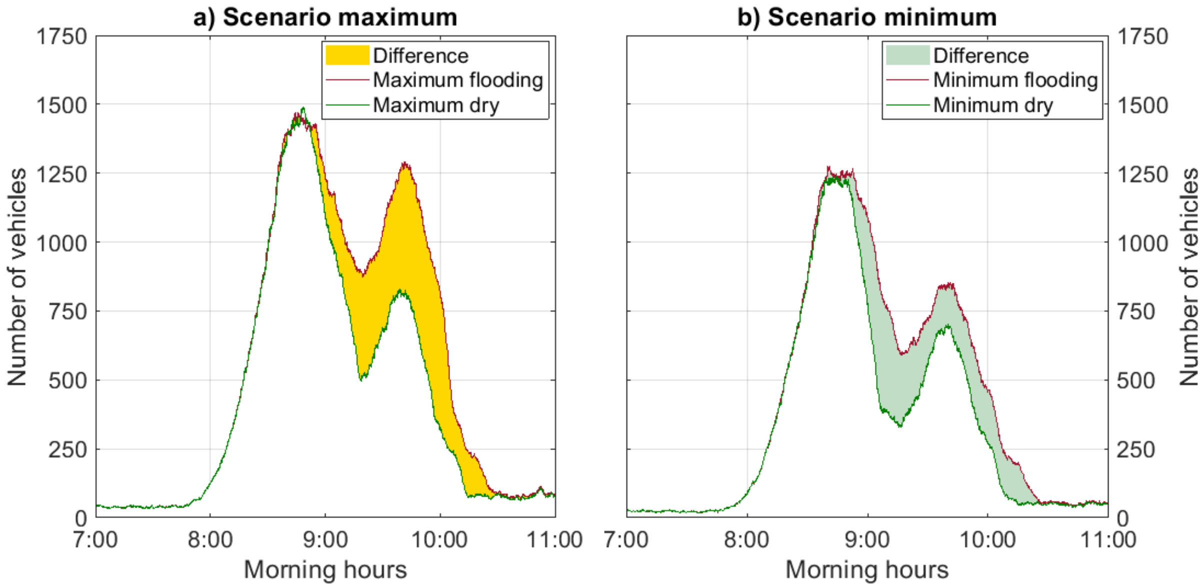


Figure 5-21: Differences between dry and flooding conditions for scenario maximum and scenario minimum

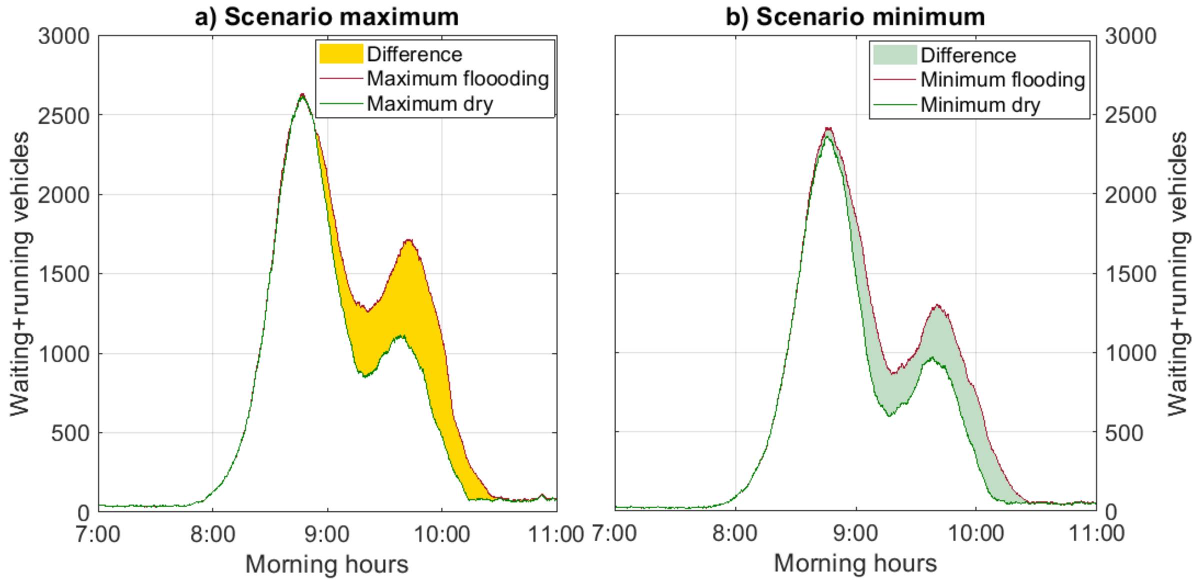


Figure 5-22: Scenario maximum and scenario minimum for the sum of running and waiting for vehicles

To investigate whether the waiting to depart vehicles affect the overall number of vehicles on the network, a similar graph was plotted with the sum of running and waiting vehicles (Figure 5-22). When the waiting vehicles are considered, the flooding conditions register more vehicles in both maximum and minimum scenarios. However, the differences are insignificant and fail to prove that the waiting vehicles can conceal trends in the network. In further discussions, the behaviour of one demand scenario will be discussed in depth.

To examine the actual flood impact on the transportation system the performance of each scenario is discussed. Figure 5-23 shows the absolute difference in vehicles between normal and flooded conditions for each traffic scenario compared to the number of closed streets per 5 minutes. The variation is quite significant, and between 9 and 10 AM, the difference between the traffic scenarios is around 400 vehicles. Subplot a) depicts the variety of all traffic scenarios where the maximum scenario (number 4) and the minimum scenario (number 10) develop differently from the other eight scenarios which tend to follow the same development trend with a single peak just after 9 AM. However, all traffic scenarios are considered as independently plausible scenarios, and the dismissal of any is avoided. To interpret the significant variation and some of the positive values (Scenario 4), the waiting-to-be-inserted vehicles are added to the number of circulating vehicles for each scenario and the absolute difference is calculated between the dry and flood conditions for each traffic scenario (Figure 5-23, subplot b). The variation within the scenarios is significantly reduced if the waiting-to-be-inserted vehicles are included as participating in the transport system. The positive values are seen just before 9 AM in subplot a) has diminished when the waiting vehicles are considered. Furthermore, subplot b) indicates the presence of two peaks of the absolute difference between the dry and flooded conditions. Given these points, the conclusion is that the underlying waiting cars are significant for the overall transportation condition waiting times must be considered as well as travel times when analysing travel delays.

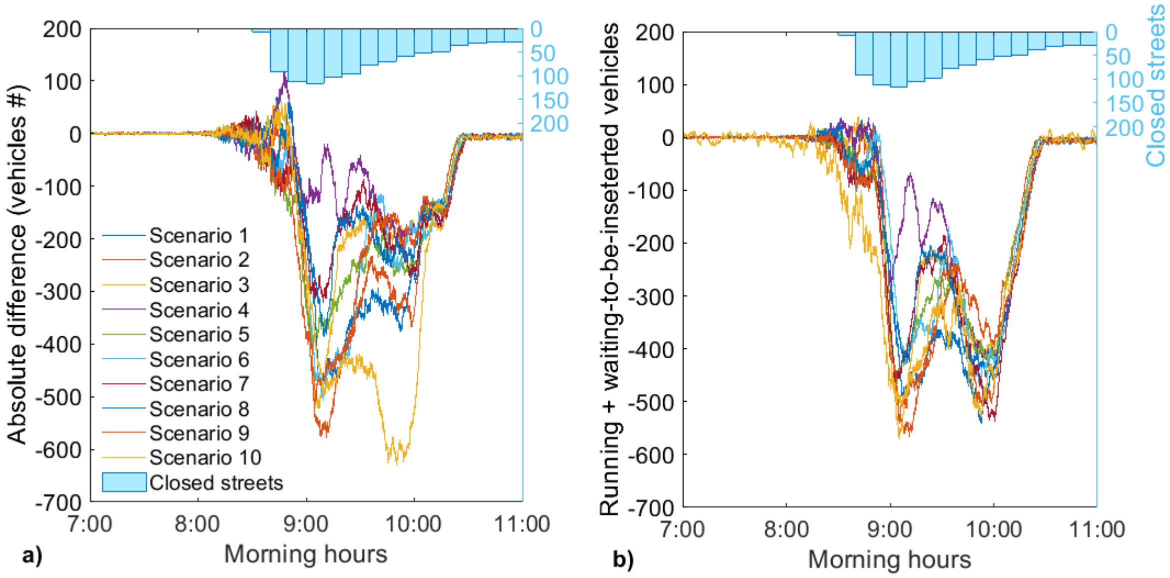


Figure 5-23: Absolute change of the number of vehicles between the dry weather and the flooded conditions (Dry-Flooded): a) running vehicles; b) running vehicles + waiting-to-be-inserted vehicles

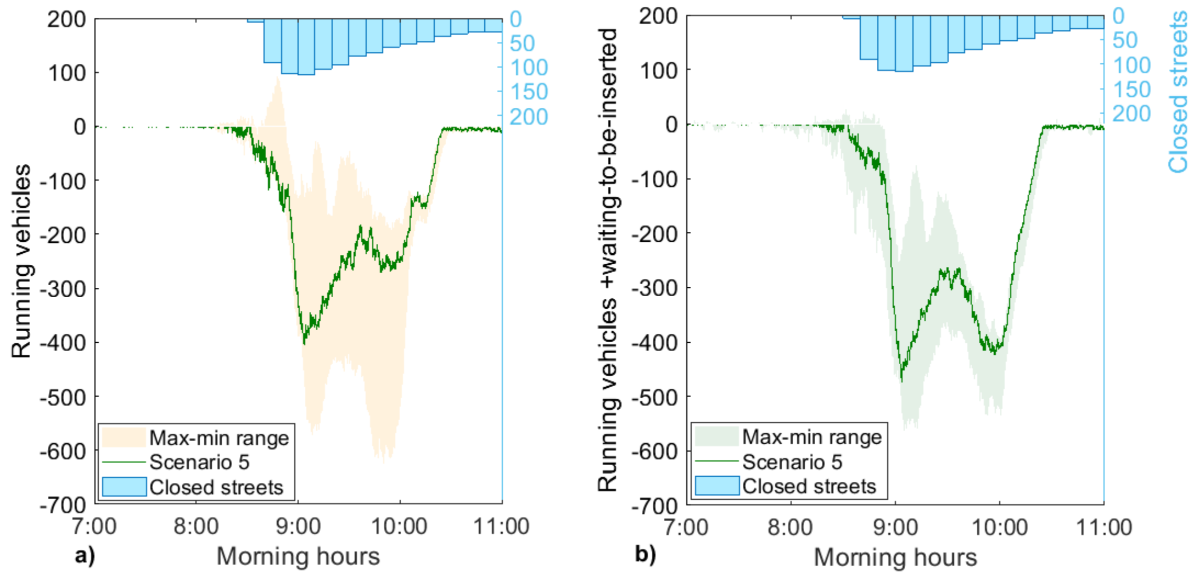


Figure 5-24: Max-min ranges and the position of Scenario 5 within the overall spreads for a) running vehicles and b) running vehicles + waiting-to-be-inserted vehicles

For detailed results discussion, one of the scenarios that consistently scored near the middle of the range was examined in detail. Figure 5-24 depicts how Scenario 5 fits within the maximum-minimum range for running vehicles and the total of running+ waiting-to-be-inserted vehicles.

For comparison purposes, the percentage changes in the number of vehicles are visualised in Figure 5-26 a). As discussed previously, at the beginning of the flood event the transportation system is capable of absorbing the shock induced by the flooding. However, around 9 AM all scenarios except Scenario 4 register 50 - 100 % increase in the volume of vehicles in the network. That is the time when many vehicles reach their work locations in the dry conditions models. Due to the flooding, however, some vehicles are delayed and are still circulating in the transportation network. By 9:30 AM some scenarios in the flooding situation have managed to return closer to the traffic under dry weather conditions, but one of them still registers a 50 % increase in vehicles. The system is showing signs of going back to normal, but then the second peak in demand starts and the transport system is already saturated and unable to accommodate reasonably the incoming vehicles. The uncertainties between the ten different traffic scenarios become greatest between 9:30 and 10:30 when all models register a short peak above 200% increase in vehicles.

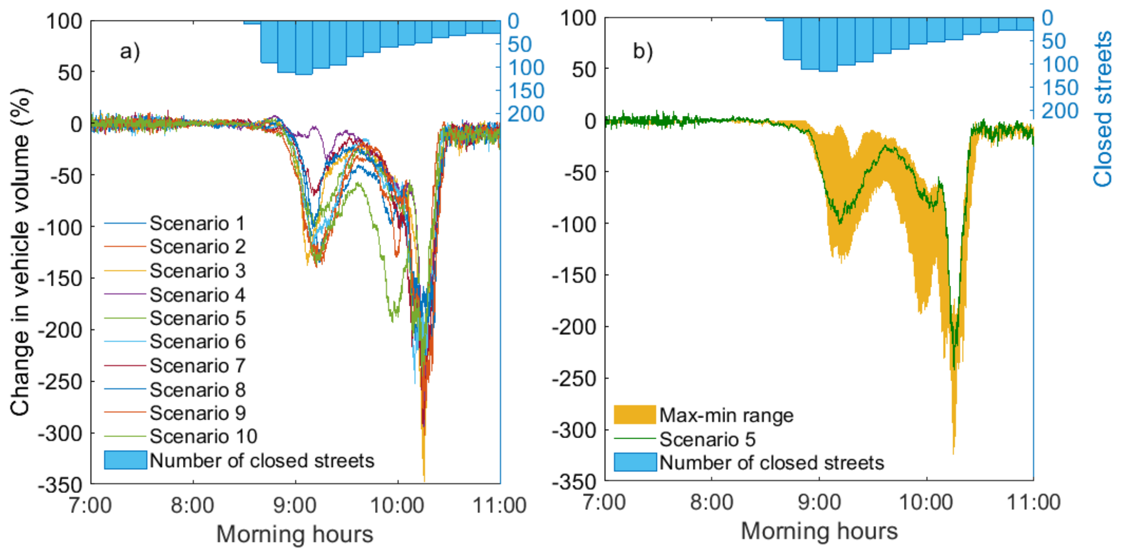


Figure 5-25: Percentage change of vehicle numbers during a flooding: a) percentage changes per scenario b) how Scenario 5 fits into the range of scenario results

Due to the relative comparison, Figure 5-26 cannot provide information when the traffic conditions were the worst, but it unmistakably accentuates the travel delays experienced by vehicles. Each scenario provides a very specific detailed output, and therefore one scenario was selected to fully assess the flood impacts on the transportation system. Figure Figure 5-26 b) shows how the selected Scenario 5 fits in within the existing range of variability among the scenarios. How Scenario 5 fits within percentage change between normal and flooded conditions when both running and waiting-to-be-inserted vehicles are considered, shown in Appendix (p. 217). The particular results of only Scenario 5 will be looked from different angles to describe as accurately as possible what the traffic situation in the network is. First, different components of the impacts will be discussed, and in the end, the overall percentage changes of these components are examined.

The rerouters expressed the direct impact of the flooding in the traffic model so that vehicles passing by a flood would need to choose alternative routes. Therefore, the number of cars that are rerouted can be considered as the initial perturbation in the system. Figure 5-26 presents the change of rerouted vehicles over time. This change is a direct consequence of both the number of street closures and the changes in traffic demand. It should be noted, that the spatial dimension of street closures is also crucial for the number of rerouters. For example, at the beginning of the flooding, around 8:30 AM, the demand is considerable, but the closed streets are localised only in the upper catchment and do not affect many trips. Once the main road is flooded, that consequently leads to an increase in reroutered vehicles. The hourly number of trips distribution can be observed in Figure 5-6 (p. 102), and between 8-9 AM almost twice mode vehicles than between 9-10 AM. However, the flood-affected trips at 9:30 are as many as the affected trips at 8:50 AM. With this in mind, the maximum street closure affects only around 200 vehicles, due to rapid changes in traffic demand in that part of the day. Therefore, the number of closed streets does not translate directly in the number of affected vehicles.

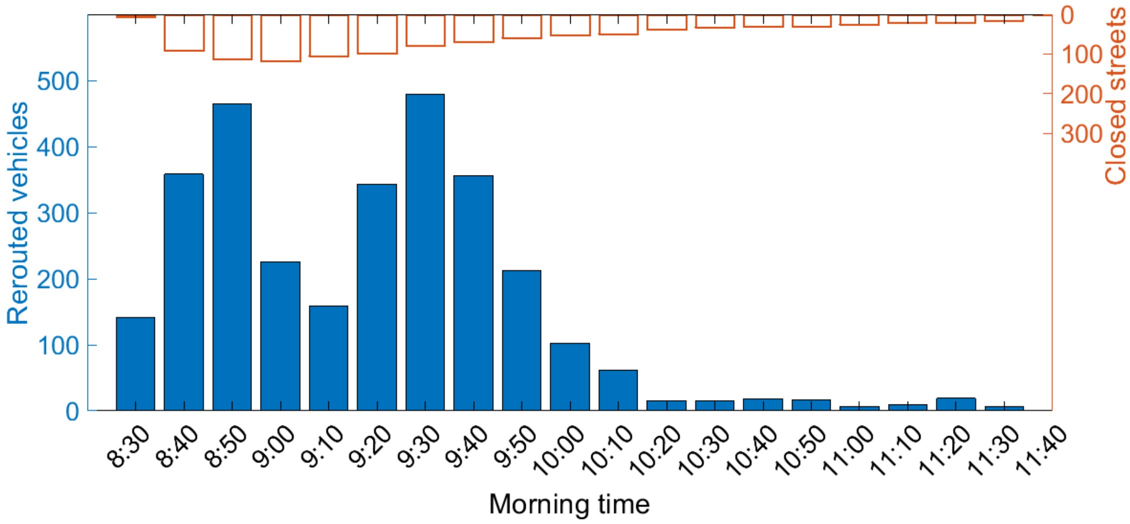


Figure 5-26: The number of closed streets force the rerouted vehicles in a non-linear way due to changes in traffic demand over time

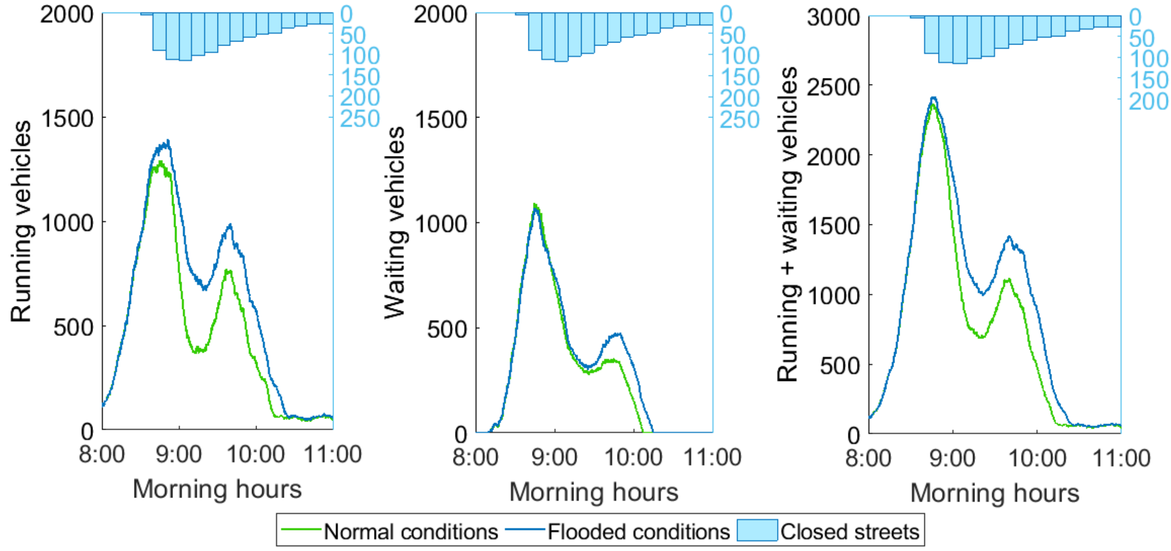


Figure 5-27: Differences between normal and flooded conditions with regards to the number of vehicles running, waiting and a sum of both for the whole network

Figure 5-27 illustrates how the flooded conditions result in a higher number of vehicles running, waiting or a sum of both. Regarding running vehicles, the differences between the two are greatest between 9 and 10 AM when the normal conditions have a rapid decline in the number of vehicles. This decline is slowed down during the flood because the strain on the system forces many vehicles to travel longer to their destinations. Regarding waiting vehicles, scenario 5 is not much affected by the flooded conditions but has to be noted that the flooded areas are not in the proximity to the neighbourhoods where most of the working force is located.

To investigate how the flood propagation impacts the transportation system, few parameters will be examined – travelled distance, travel duration, waiting time, fuel consumption CO_2, NOx, PMx emissions. The differences between the normal conditions and the flooded conditions yield the actual impacts. Average values for the whole simulation and hourly averages are considered to depict both the global consequences and their temporal variation. To assess and compare the hourly traffic, vehicles were selected based on the starting time of their trip in the normal weather conditions. The reasoning behind is that sometimes due to depart delays the same vehicles might start their journeys at different hourly intervals. It is important to clarify that the hourly statistics compare vehicle journeys but may not be fully representative of the actual traffic conditions if the particular time segment. This logic ensures that all vehicles' trips are analyzed and examined from a temporal perspective.

Before proceeding with the actual statistics, it has to be clarified how some of the statistics were estimated. When considering absolute values (i.e. hours, or km), the values for each scenario and time segment are simply summed up. However, this value can be ambiguous, because not all vehicles are suffering from the flooding. Due to the sensitive balance in traffic, the fact that some vehicles are prevented from using a particular road might benefit other vehicles that are travelling downstream the flooded road. In these situations, travelled distance does not change, but the travel duration of some vehicles might be reduced. To compare how the various parameters have altered during the flooding, a percentage change per each vehicle is computed. Many vehicles do not register significant changes, and therefore the changes less than 1% have not been considered in the statistical representation. Moreover, outliers in the extreme 1 % have been removed from the estimation – for example, the most significant trip duration increase is 19,000%, and it is statistically dismissed as not reliable. To conclude, the statistical analysis starts from general with all data considered and become more specific with some of the values removed.

5.8.1 Travel distance

The travelled distance is the most commonly discussed impact of an interrupted transport system because it does not require a traffic model and can be assessed based on assumptions about the road network. In a dense urban environment, the additional travel distance may not be very significant because many alternatives might be available. However, flooding might lead up to multiple closures in the same area, that can potentially fragment a network and make reroutes longer. As previously described, Marbella's road network has several particularities that potentially increase its vulnerability to road closures (See 5.4.1, p. 92). Table 5-7 shows the main statistics with regards to the travelled distance in the morning hourly time segments. If we compare the proportion of rerouted vehicles to the proportion of vehicles that have longer routes, it can be observed that rerouting does not necessarily mean travelling longer distances. Between 10 and 11 AM half of the rerouted vehicles registered longer routes. As the route selection was based on travel time rather than distance, it is possible that some vehicles might reduce their travel distance after a change in their route. Another reason could be that if a vehicle is stuck in a traffic jam, by the time, it reaches the flooded road, the road could be open for traffic again.

Table 5-7: Flood impact on travelled distance

Travelled Distance	*8-9 AM*	*9-10 AM*	*10-11 AM*	*11-12 AM*	*Overall*
Number of vehicles	*7345*	*5238*	*963*	*890*	*14434*
Normal (km)	32347.6	22945.5	3495.1	3117.6	61903.4
Flooded conditions (km)	34055.8	24339.9	3543.2	3150.9	65087.4
Difference (km)	1708.2	13944.5	48.1	33.3	3184.0
Change (%)	5.3	6.1	1.4	1.1	5.1
Vehicles with longer routes %	11.6	19.6	10.0	5.5	14.0
Rerouted vehicles (%)	14.1	34.2	20.2	5.8	21.3

There is another reason for the discrepancy between the rerouted vehicles and the ones travelling longer distances and it is related to the way the rerouting mechanism works. If there are no available options to reroute (i.e., no turns on a section of the road), vehicles that are supposed to reroute merely disregard the rerouters and continue on the blocked road. Locations of this behaviour were identified and manually corrected. It is possible disregarding rerouters could occur somewhere else during the simulation, but it is not likely to alter statistics significantly. The overall change in route length is only 5.1 % of the total travelled distance during normal conditions, considering that 14% of the vehicles travelled longer distances than their planned routes during the normal conditions.

5.8.2 Travel time

There are many aspects of travel delays that must be addressed to understand the differences between the two simulations. A critical element to consider is how to define a delay. The most straightforward answer would be that a delay is registered whenever the flooded simulation has a longer trip than the normal one. However, it is sensible to set up a threshold that defines under what circumstances a trip is delayed. There are two approaches to assessing delays with a threshold – with a constant value unit or with a proportionate value. As Marbella is a small city with short distances and durations of most trips, the proportionate threshold was deemed more appropriate. The discussed statistics consider delays of 1 %, 5%, 10%, 20% and 50 % of the original travel time under normal conditions (Table 5-8). The 50 % increase in travel time is not proposed as a threshold, but as a statistic that describes the system.

Table 5-8: Flood Impact on travel time

Travelled Time	*8-9 AM*	*9-10 AM*	*10-11 AM*	*11-12 AM*	*Overall*
Number of vehicles	*7345*	*5238*	*963*	*890*	*14434*
Normal (h)	829.0	491.0	73.7	59.9	1456.6
Flooded conditions (h)	1068.1	582.2	80.9	65.0	1851.3
Difference (h)	239.1	91.2	7.1	5.1	394.7
Change in duration (%)	28.8	29.0	9.7	8.6	27.1
Proportion of vehicles with ***1 %*** *delay*	55.8	71.2	67.7	64.4	62.7
Average Delay/Journey time (%)	44.1	35.9	16.3	14.3	35.4
No change vehicles (%)	15.4	12.2	21.9	24.5	15.2
Proportion of vehicles with ***5 %*** *delay*	40.9	58.0	47.0	42.8	47.7
Average Delay/Journey time (%)	84.7	58.1	25.3	22.6	65.6
No change vehicles (%)	43.4	34.5	49.8	55.5	41.4
Proportion of vehicles with ***10 %*** *delay*	32.0	48.6	35.7	29.9	38.1
Average Delay/Journey time (%)	106.4	67.9	30.9	29.2	80.1
No change vehicles (%)	48.6	47.8	61.9	69.7	55.6
Proportion of vehicles with ***20 %*** *delay*	21.2	33.5	19.7	14.9	25.6
Average Delay/Journey time (%)	153.0	91.8	44.3	41.3	113.5
No change vehicles (%)	75.5	65.0	78.9	84.7	72.4
Proportion of vehicles with ***50 %*** *delay*	9.7	12.7	5.0	3.4	10.0
Average Delay/Journey time (%)	299.6	191.2	85.0	78.5	238.4

Depending on the selected threshold for a delay the proportions of delayed vehicles differ, but all keep the same tendency to register the most significant proportion of delayed vehicles between 9 and 10 AM – ranging from 50-70% (1%-10% duration increase threshold). That threshold also determines the average delay of the affected vehicles as a percentage change of individual original trip duration. Naturally, with a higher threshold, the average delay increases significantly. If 1% trip duration increase is used as a threshold, the average trip increase is 35%, but if the threshold is 10%, the average trip increase is 80%.

Similarly, if a 20% increase in trip duration is considered, 25 % of the vehicles will experience a two-fold increase in travel time. The overall results register 10% of vehicles with delays of more than 50% of their original route duration, and on average these vehicles suffer 300% travel time increase.

The overall trip duration difference between the normal and flooded conditions is 27 %, and this is estimated as the difference between the sum of all the trips in both simulations. It is important to underline that although most vehicles suffer from traffic delays, some travel quicker than usual. Roads immediately after the road closure have reduced traffic volumes, and vehicles travel faster. Summing all trips in a system may not be the most appropriate approach, because early trips cannot compensate for individual journey delays. In fact, some authors (HEATCO, 2006) argue that traffic delays, as well as time gains, can equally be regarded as a loss of business time.

The hourly changes in trip duration between the dry and the flooded conditions are plotted as histograms in Figure 5-28. The percentage change of trip duration of each journey is assessed and then plotted as a histogram with normalised probability on the y-axis. The hourly variation of each time segment is compared to the average change in trip duration for the whole simulation. The histograms are using a trimmed dataset which disregards the most extreme 1% and the vehicles that experienced no change. The histograms for all segments are asymmetric and long-tailed, reaching up 400% increase in trip duration. Some vehicles reduced travel time, but the reductions were not more than 30 % of their reference trip duration. As the flood starts developing after 8:40 AM, not many trips experienced delays, but the most extreme delays were registered in that time segment. With time more vehicles are rerouted, and the knock-on effect on the system became more severe. From 9-10 AM longer delays are registered more often, and there were fewer shorter delays. When the flood started receding – from 10 AM onwards, the proportion of trips with short time increase started raising significantly (more than 40% of vehicles). Similarly, in these time segments, the tails of the distributions are shorter.

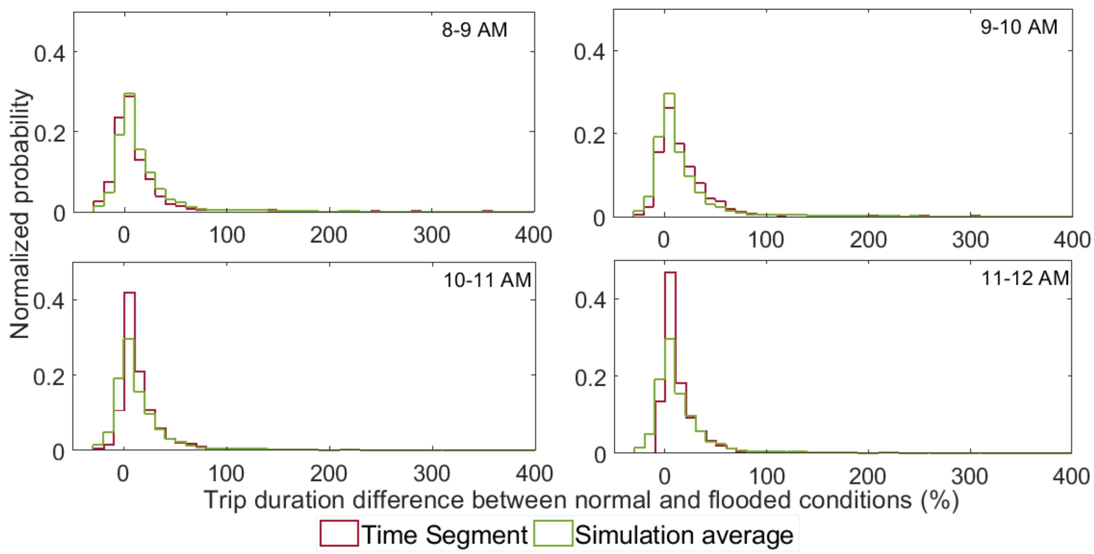


Figure 5-28: Histogram of the percentage change in travel time between normal and flooded conditions. The histogram bin is 10%

As previously discussed, the comparison of travel times was achieved according to their starting time in normal conditions, which may not be strictly the same during the flooding situation. However, by comparing what happened to individual vehicles, it can be concluded that: 1) the distribution of vehicles at the beginning of the flood had long tail meaning that many vehicles were suffering delays longer than 100% original trip duration; 2) after 10 AM the system started to return to normal and the histogram spread became more symmetric; 3) travel time reductions may have happened often, but the actual increase was not significant.

5.8.3 Depart delay

Depart delay is the waiting time before vehicles are inserted in the network and is an indicator of the system performance and must be discussed when analysing of travel times and delays. The normal conditions simulations already accumulated a significant number of waiting for vehicles during peak hours, which increased by 11% during the flooded conditions (Table 5-9). The depart delay is influenced by general traffic conditions on the street where cars are inserted. The rerouters do not work when vehicles are being inserted, and vehicles get inserted to closed roads anyway. The increase in delays of departure confirms that the flooding was exacerbating the knock-on effects on depart delays. With the receding flood and the reduction in traffic demand, the delays are automatically reduced, and between 9 and 10 AM, the flooded conditions even register reductions in waiting time. As this reduction is likely to be spread among many vehicles in the network, it is likely to be connected to the opening of closed roads and clearing way for new insertions.

Table 5-9: Flood impact on waiting time

Waiting time	*8-9 AM*	*9-10 AM*	*10-11 AM*	*11-12 AM*	*Overall*
Normal (h)	311.0	491.0	35.7	0.0	837.7
Flooded conditions (h)	316.1	582.2	32.5	0.0	930.8
Difference (h)	5.1	91.2	-3.3	0.0	93.1
Change (%)	1.7	18.6	-9.1	0.0	11.1
Vehicles with longer waiting time (%)	11.5	10.1	0.8	0.0	9.6
Vehicles with increase in depart delay and travel time (%)	6.1	7.9	0.8	0.0	6.1
Average delay for the above case%	168.8	410.6	256.1		285.1

Only 6.1 % of the vehicles experienced both depart delay increase and travel delay increase due to the flooding, these vehicles experienced overall in journey time increase of 285 %. And the average journey time increase reaches 400% between 9 and 10 AM. It is important to note that the average delay is calculated only for the cases that have both increased in waiting time and in travel time. Their sum computes as a percentage change of their respective sum during the normal conditions. Accordingly, between 10-11 AM there is a reduction in travel time, but a considerable increase in journey time.

5.8.4 Fuel consumptions and greenhouse gas emissions

Congestion can have a negative impact on the air quality and efficiency of fuel consumption. To assess these parameters, the HBEFA 3 emissions model computes fuel consumption and emissions based on the movement of each vehicle in the network. The values were evaluated on hourly segments for the whole transportation network. The flood impact on the transport system was again estimated as the difference between normal and flooded conditions (Table 5-10). The maximum change for all parameters was registered between 10 and 11 AM where it records a 40 % increase in the CO2 and NOx emissions.

Table 5-10: Flood impact on fuel consumption and greenhouse emissions as a difference between the normal and the flooded conditions

	Fuel (%)	*CO_2 (%)*	*PM_x (%)*	*NO_x (%)*
8 to 9 AM	1.3	1.0	1.3	1.4
9 to 10 AM	17.6	17.1	17.6	19.2
10 to 11 AM	20.5	43.7	20.5	38.2
11 to 12 AM	3.0	1.3	3.0	1.8
Overall	9.1	10.1	9.1	10.7
Absolute difference	63.4 l	1.7 kg	0.02 kg	4.8 kg

At first glance, the results disagree with the previously discussed statistics, as the maximum for travel distance, travel time and depart delay was consistently the time segment between 9 and 10 AM. This variation comes from the different nature of the output files, which necessitate a slightly different approach for assessing statistics. The travel distance, time and delay were evaluated previously per vehicle, according to their starting time in the simulation of normal conditions. It considers the whole trip, but it categorises the trip according to the time segment of its beginning. And so, many of the delayed vehicles could be travelling in a different time segment than the one they have initially begun. Rather than comparing vehicles, the emissions model estimates the total emissions per second in the simulation and therefore in expresses more sensibly the dynamics of the system.

Figure 5-29 compares the average hourly change in the most characteristic parameters of the system. Regardless of the threshold for the delay, the percentage of delayed vehicles is not only the most distinctive flood impact but also remains relatively constant over time. Even between 11-12 AM, when the flood is receding, and many roads are open for traffic, around 30-60 % of the vehicles are still delayed. The number of rerouted vehicles and respectively the extra travelled distance is highest between 9-10 AM, but the knock-on effect on the whole system sustains the negative impacts to continue evolving in the next time segment with fuel consumption, CO_2 and NO_x registering maximums between 10-11 AM.

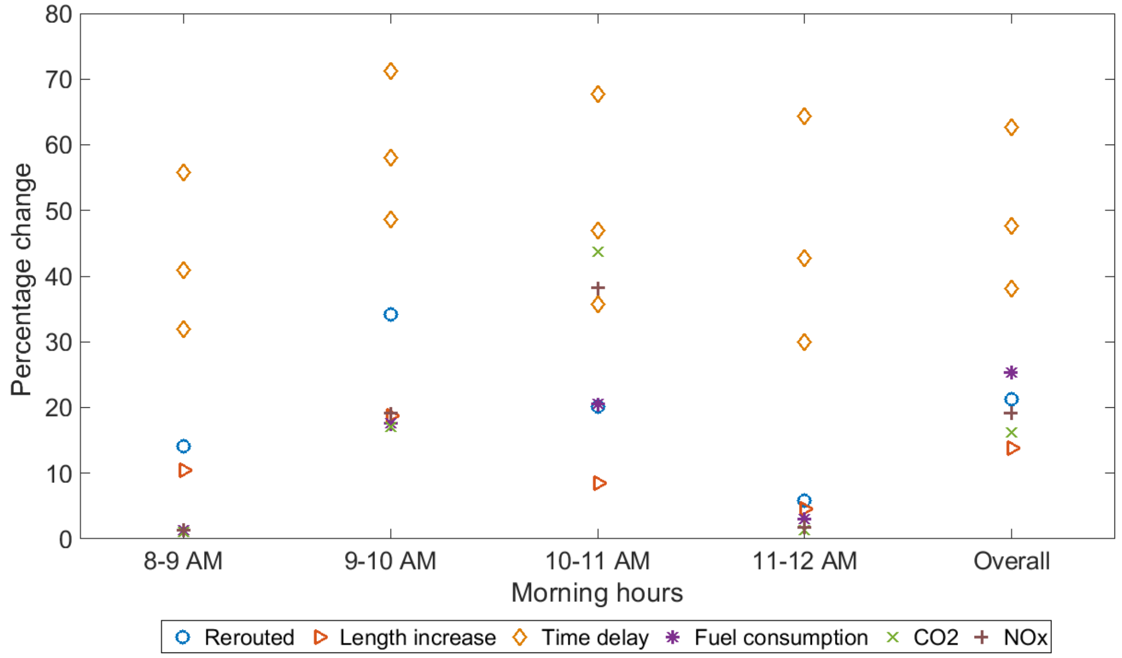


Figure 5-29: Average hourly percentage changes between normal and flooded conditions for different parameters. The various thresholds of time delay (1%,5% and 10%) are shown with a diamond

5.8.5 Flood impacts on trips to and from the hospital

The hospital in Marbella is not located in the flooded areas (Figure 5-30), but it is accessed through one of the main roads that flood less than a kilometre away from the hospital. If vehicles are approaching the hospital from the western part of the city, they might need to undergo complicated detours to reach the hospital. The hospital is incorporated in the traffic model as an employer and is attracting twice as many trips as it is releasing. The total number of trips going to and from the hospital is 499, which is 3.5 % of the total number of trips during the simulation. The vehicles travelling to and from the hospital are not emergency vehicles, because the transport model could not differentiate special access conditions on closed streets. Therefore, instead of modelling ambulances, the model simulates trips to the hospital from personnel or patients. The indirect effect of the flooding on these trips can assist in assessing the change in accessibility of the hospital during flooding.

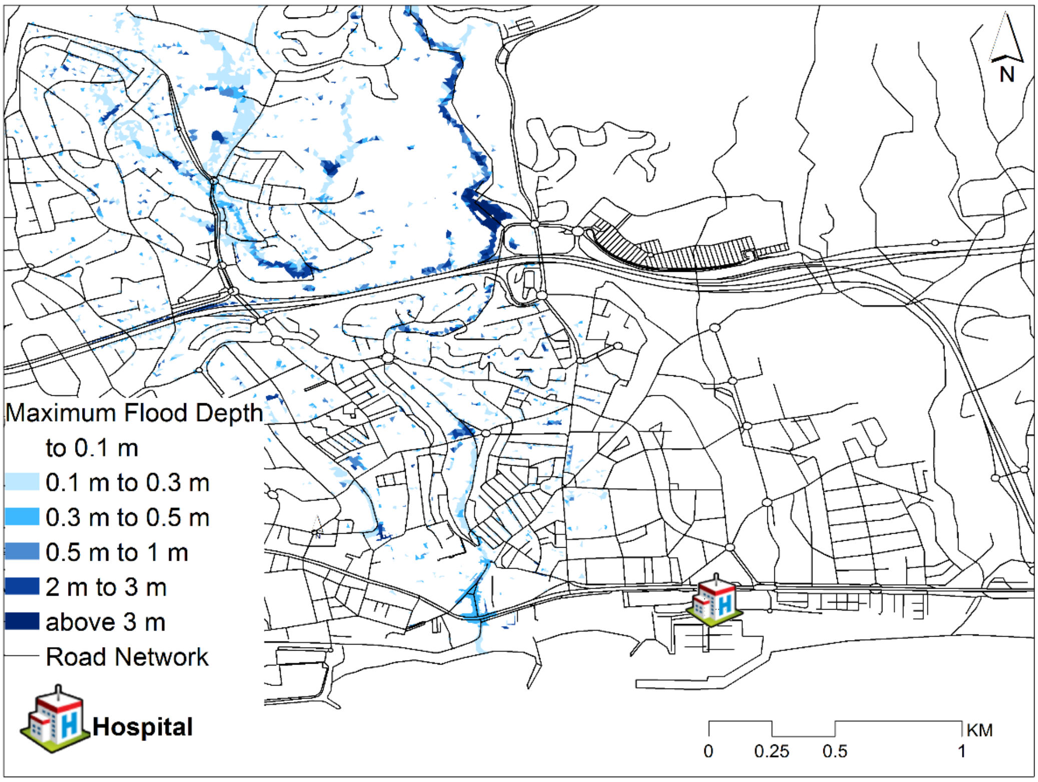


Figure 5-30: Location of the hospital and the flooded areas in the city

Table 5-11 presents the average values of base parameters for the hospital trips and the overall simulation, and the impact of flooding on the trips to the hospital is more severe than on average in every aspect. More than 50% of the trips to and from the hospital have been rerouted which is significantly higher than the 21 % for the whole simulation. Most likely the higher proportion of vehicles being rerouted is due to the hospitals' accessibility being impeded from the flood. Having a low increase in travelled distance and a significant increase in travel time is a piece of sure evidence for the presence of severe congestion in the system. The major knock-on effects on the system indicated that even not flooded CI should be considered in flood analysis, as their services may be indirectly impacted by the flood conditions. The trip duration increase is the increase in the sum of the duration of the trips to the hospital and requires further investigation into the distribution of trip delays.

Table 5-11: Comparison between average parameters of the vehicles going to and from the hospital and simulation averages. The percentage changes are computed per vehicle under normal and flooded conditions

	Hospital (to and from)	*Simulation average*
Rerouted Vehicles (%)	53.9	21.3
Trip Length Increase (%)	5.9	5.1
Trip Duration Increase (%)	57.3	27.1
Depart Delay Increase (%)	11.6	11.1

Table 5-12 shows how different thresholds of delay can interpret the situation in the traffic model. Regardless of the threshold, the trips of there is a slightly greater probability of a trip to the hospital to be delayed than any other trip. But when it comes to discussing the average delays, there are substantial discrepancies. The average delay for 1%, 5% and 10% is twice longer for hospital trips than the average for the simulation. Nearly 17% of all hospital trips suffered delays greater than 50% of their usual trip duration, and if their trip delay is averaged, it turns out that these 17% vehicles suffer trip delays of nearly 400 % (in other words, have increased their travel time five-fold). Generalizing, the results indicate that there is around a 50 % chance that a vehicle will encounter doubled travel times. This situation is detrimental for both patients and staff going to the hospital during a disaster event and can potentially have drastic consequences on the effectiveness of the emergency services.

Table 5-12: Proportion of delayed vehicles and their respective average delay according to different thresholds defining the delay

Threshold	*Proportion of affected vehicles*		*Average delay duration*	
	Hospital	*Simulation average*	*Hospital*	*Simulation average*
1%	62.9	62.7	114.1	50.5
5%	49.9	47.7	143.1	65.6
10%	42.3	38.1	167.7	80.1
50%	16.8	10.0	387.3	238.4

5.8.6 Monetisation of flood impacts on traffic

This thesis evaluates in monetary terms traffic delays and additional fuel consumption. Different approaches to monetize traffic delays were discussed in Section 2.7.3 (p. 52) and the most suitable for the case study was selected. HEATCO (2006) assessed the value of travel time is saving for each EU country and even recommended an inflation rate for future application. The reference value for Spain in 2002 is € 25.95 per hour, and with 0.7% of inflation rate per year in 2018, the price is € 29.01 per hour. As previously discussed the definition of delays is essential to estimate how many hours of delay are registered in the system.

The total hours of travel delay do not differ significantly with different thresholds of trip delay with values varying between 395 and 426 hours (Table 5-13). The depart delay is a constant value that was added to calculate the total hours of delay in the system. The monetary value of wasted time per hour is later multiplied to produce the total cost of delays ranging between € 14,152 and € 15,235.

Table 5-13: Monetizing cost of delays according to different delay thresholds

	Threshold value			
	None	1 %	5%	10%
Total travel delay (h)	394.7	432.1	426.2	415.9
Depart delay (h)	93.1	93.1	93.1	93.1
Sum trip delay + depart delay (h)	487.8	525.2	519.3	509.0
Cost of delays (€)	14,152	15,235	15,066	14,765

This financial loss is marginal compared to the direct tangible damage, that was estimated to be 1,987,323 € in expected annual damage (PEARL, 2017). The additional fuel consumption is only 62 litres which is negligible in monetary terms.

5.8.7 Road speed changes due to the flooding

Except for the statistics of the vehicles experience during the flood, the spatial variation of the flood impacts is critical for the understanding and management of the transport system. To achieve this, the traffic conditions on each street were aggregated for hourly intervals of time. As the primary goal of this chapter was to identify and quantify the differences between the normal and the flooded conditions, the presented maps show the speed differences between the above two. The speed decrease means that for a particular road in the flooding conditions traffic is slower than for the same road in the standard conditions.

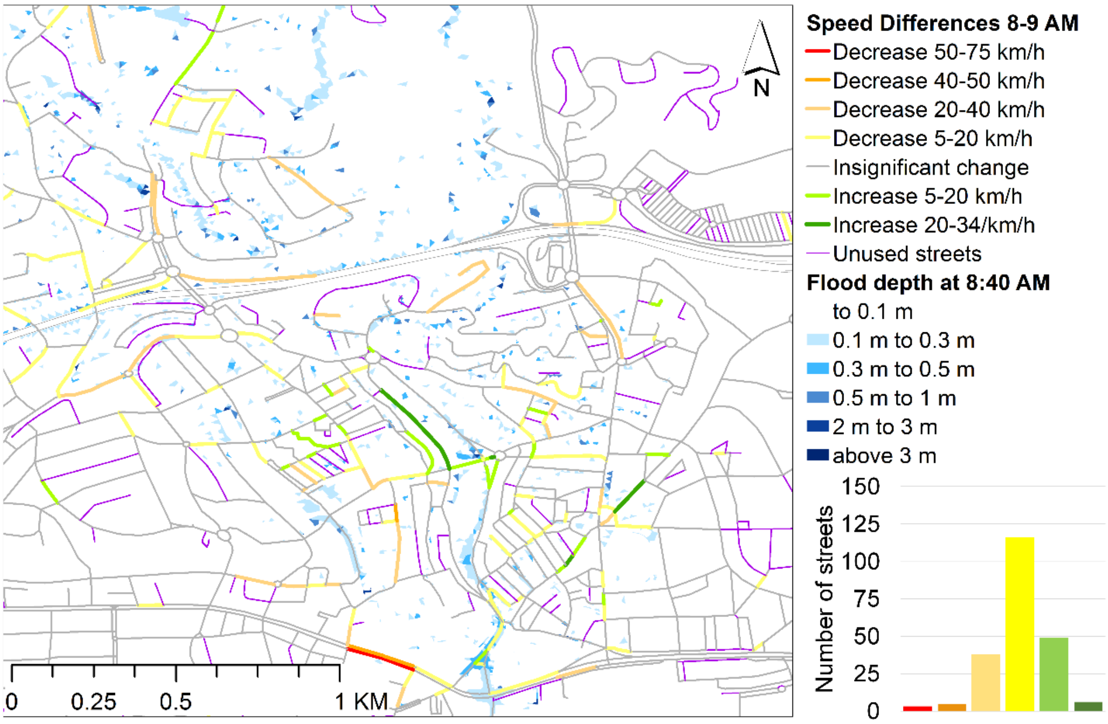


Figure 5-31, Figure 5-32, Figure 5-33 and Figure 5-34 depict the hourly average speed changes during flooded conditions for the time segments 8-9 AM, 9-10 AM, 10-11 AM. They were overlayed with flood maps, that illustrate the flood conditions in these segments. The flooding started accumulating at 8:40 PM and it developed very quickly so that only 10 minutes later it has already reached the coast and flooded areas in the city centre (Figure 5-26 p. 127 shows the number of closed streets over time).

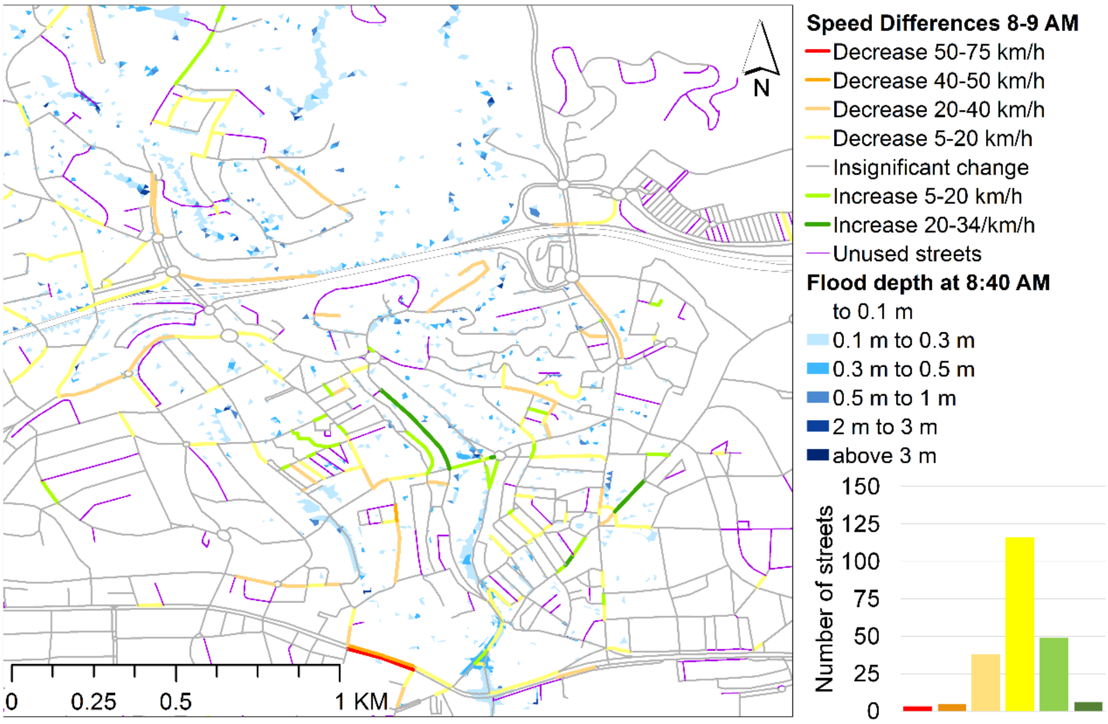


Figure 5-31: Speed differences between the normal and flooded conditions in the time segment 8-9 AM. The colour coding of the bars corresponds to the colour grading of the speed changes

At 9 AM the great number of streets is closed and from then on the flood starts receding gradually. Only 20 minutes are flooded between 8 and 9 AM, and the aggregated speed values are averages over the whole hour of traffic. The differences between the speeds in the normal and flooded conditions are starting to build up

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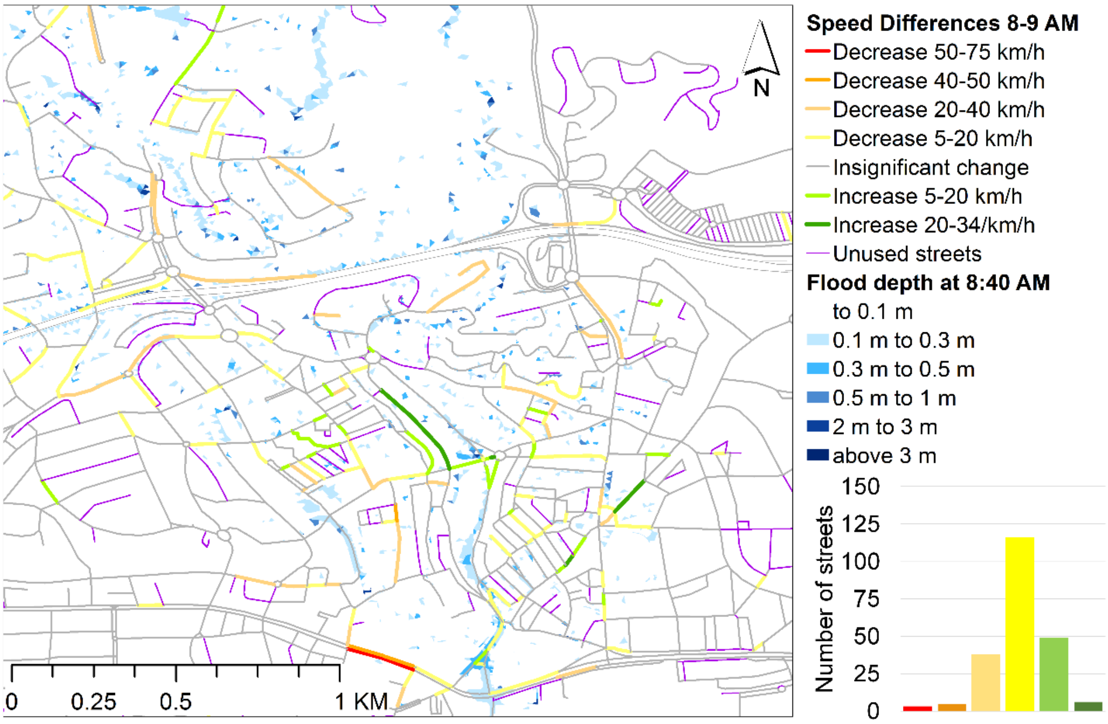


Figure 5-31). Av. Ramón y Cajal starts jamming in both directions with speed reductions of 70 and 45 km/h. The majority of streets with changes receive a speed decrease between 20 and 50 km/h. Some of them are flooded or leading to a flooded area; many are connecting the north-west neighbourhood to the central city. Some roads, however, receive an increase in the average speed, and most of them are located downstream of a flooded area, that prevents some traffic to enter them. Thus vehicles coming from other than the flooded direction register speed increase.

Figure 5-32 shows the speed differences between the normal and flooded conditions between 9-10 AM, when the most significant number of closed streets is recorded – between 116 and 70. With the development of the flood over time, more streets become slower. Between 9 and 10 AM 12 roads had speed decreases of over 50 km/h. The most badly affected streets were sections of Av. Ramón y Cajal, even though it becomes dry from 9:40 AM. Other roads with delays are heading to the motorway or upstream a flood with little options for rerouting. During this time segment, most roads in the city centre are already experiencing delays and their spatial distribution is evenly spread. The roads that have faster average speeds are usually roads, used to move away from the city centre and go to the neighbourhoods. It is also possible that with rerouting some vehicles might select alternative roads that may be a better fit for the circumstances. It is important to note that the dynamic traffic assignment

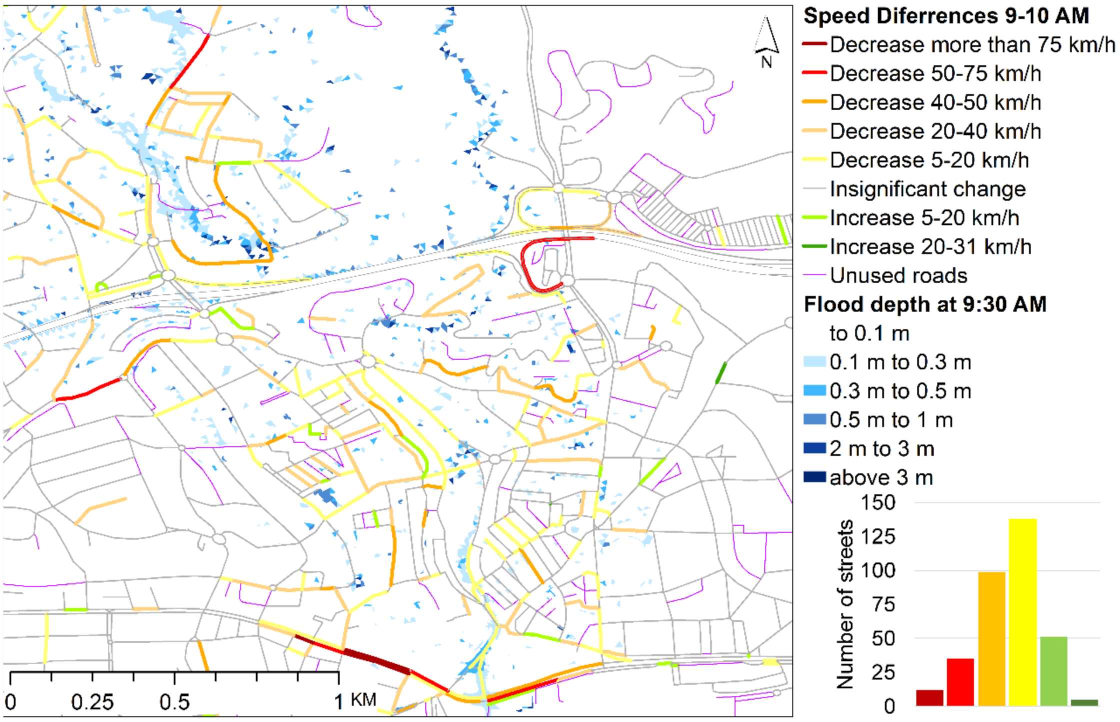


Figure 5-32: Speed differences between the normal and flooded conditions in time segment 9-10 AM The colour coding of the bars corresponds to the colour grading of the speed changes

optimises vehicle routes as participants in the transport system and once the network capacity is altered some routes may not be adequate for the newly established travel conditions.

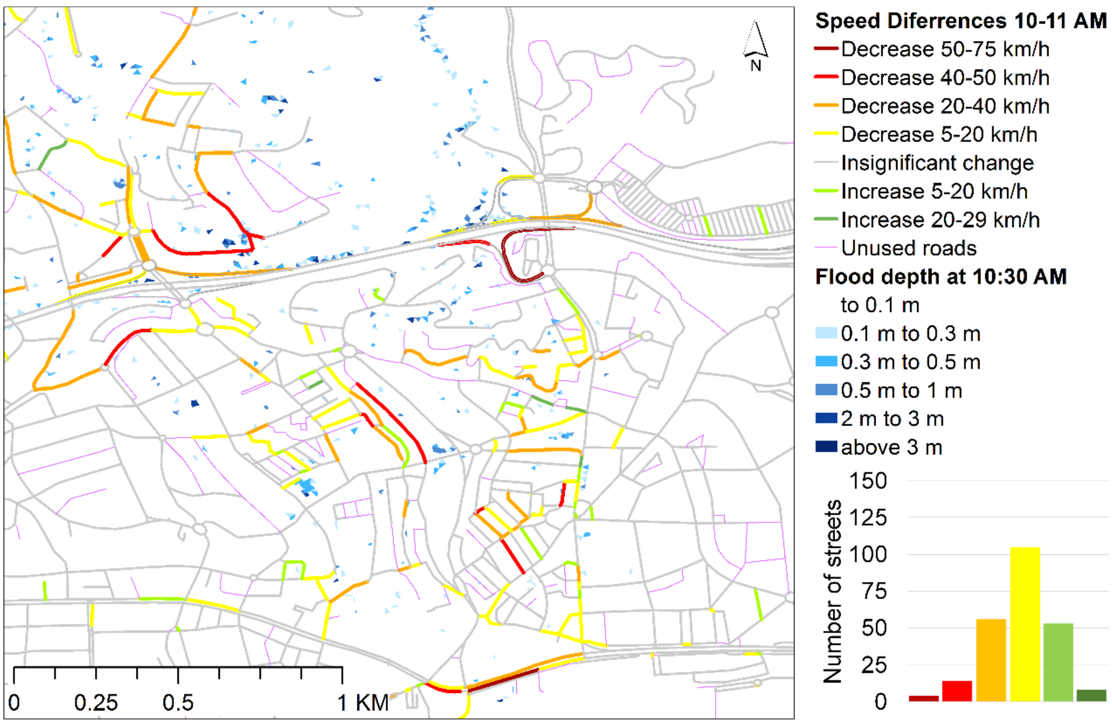


Figure 5-33: Speed differences between the normal and flooded conditions in the time segment 10-11 AM. The colour coding of the bars corresponds to the colour grading of the speed changes

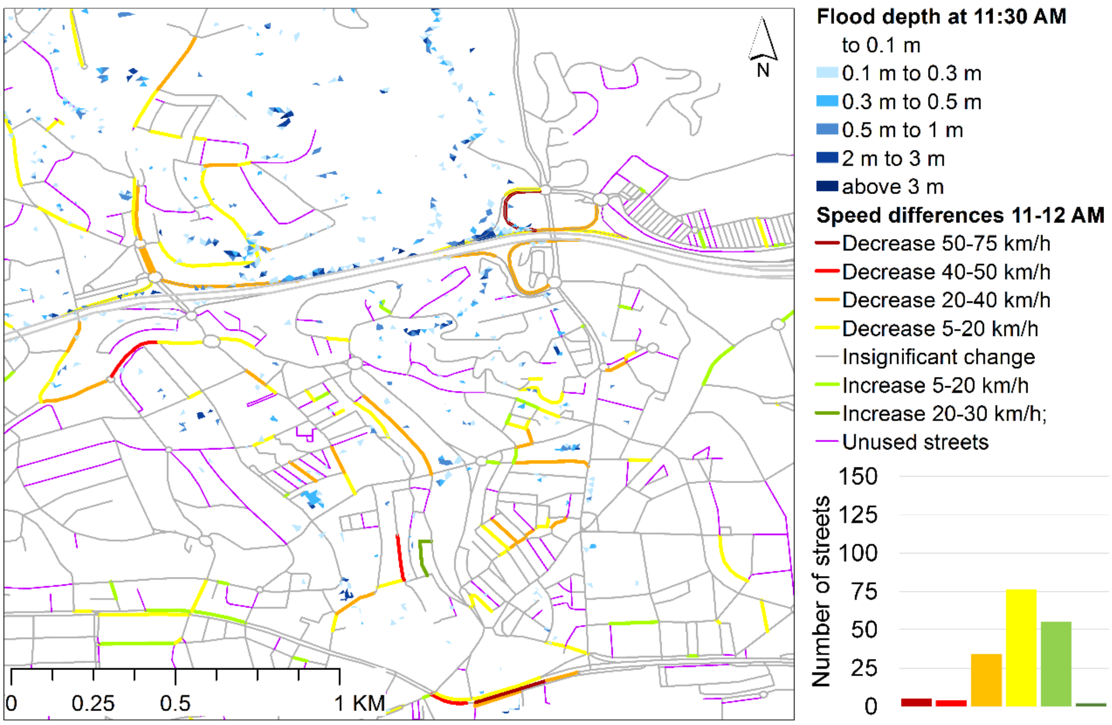


Figure 5-34: Speed differences between the normal and flooded conditions in the time segment 11-12 AM. The colour coding of the bars corresponds to the colour grading of the speed changes

Figure 5-33 shows the flood-induced speed differences in the aggregated traffic conditions between 10-11 AM. The flood extent at 10:30 is already significantly reduced with only 29 streets closed. Due to the changing traffic demands, fewer vehicles are rerouted, and traffic should be returning to normal. However, this is not the case, because the knock-on effects of the previous time segments are still propagating. The congestion is no longer localised, but it is spreading to roads, connecting the city centre with its neighbourhoods. The signs of a gradual improvement are visible in the reduction of the number of streets with slower traffic, while the number of roads with faster traffic is the same as in the previous time segment.

This section demonstrated that the spatial impacts of the flooded transportation system are not strictly associated with the locations of the flooding. The knock-on effects of the restrictions in the network capacity resonate through the whole system, and they continue to evolve even after the system perturbation has seized. It is generally arduous to predict where the congestion will accumulate but several locations received consistently slower traffic throughout the simulation time.

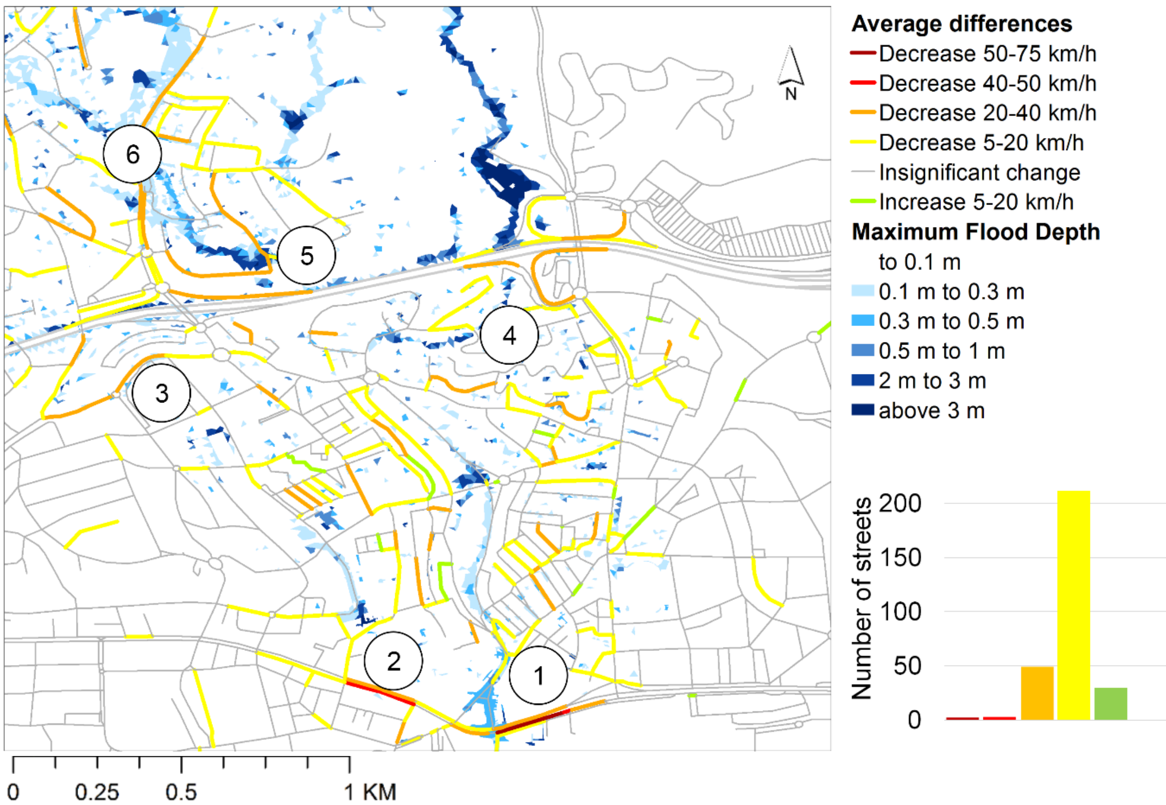


Figure 5-35: Average speed changes between normal and flooded conditions

Figure 5-35 is a map of the average speed differences between the normal and the flooded conditions and indicates the locations of roads that consistently received a speed reduction for the period of 8-12 AM. These locations were marked with numbers 1-6 on the map, and it can be argued that these were the most vulnerable parts of the transport network. Numbers one and two were both associated with Av. Ramón y Cajal, and they appeared before and after the flooded roads. It is important to note that the street was closed due to flooding for only 30 minutes, but it affects the 4 hours of traffic with road segments being reduced with 40-75 km/h. Location 3 registers slow traffic under normal circumstances according to Google Maps Traffic (Figure 5-10, p. 106) during flooding conditions the traffic problems there are exacerbated for an extended period. The road was flooded for only 10 minutes between 8:40 and 9:50 AM and it is more likely the traffic delays to be associated mainly with the knock-on effects on the whole system rather than the localised flooding. Locations 4 and 5 are both motorway ramps/sliproads from or to the motorway. Although the motorway shows no significant delays throughout the simulation, the sliproads to and from it have constant speed reductions. The speed decreases on location 6 are entirely related to the flooding that passes through that area. The flooded road is the best way to reach the rest of the city from that isolated by hills neighbourhood. The flood fragments parts of the network from the rest of the Marbella for 40 continuous minutes, and this is the most dangerous situation for the residents.

5.8.8 Conclusions

The flooded conditions cause severe disruptions to the transportation system. Several findings were discussed while analysing the speed changes in the road network. First, the locations of closed streets cannot be directly associated with areas of traffic disruptions. The knock-on effect of the capacity reductions is overarching in both time and space. For example, the most badly affected street was flooded for 10 - 30 min[15], but the average speeds on different sections were reduced with 50-75 km/h for 4 hours. Another street, which is generally busy during normal conditions is flooded for only 10 minutes, but it is congested for almost the whole time of the flooded simulation. Several sliproads that do not flood had consistently slower traffic through the whole 4 hours of traffic simulation under flooded conditions. Another example of the knock-on effects on the entire system is the traffic conditions between 10-11 AM when the flooding significantly receded, but the slower traffic has resonated throughout the entire system, and

[15] In one direction is flooded only for 10 min and in the other – for 30 min

the streets with speed reductions have a seemingly even spatial distribution. Second, some roads will inevitably become faster in a situation of disruption. While some roads receive significantly higher traffic volumes, others, usually located immediately after closures, would have fewer vehicles. If these roads have one-way traffic, the latter can be even exacerbated. Third, even though it is difficult to predict where the system will struggle mostly, the results allow the identification of vulnerable locations that have experienced consistent speed reductions over time.

The number of rerouted vehicles can be translated into some vehicles that travel extended distances, and that can be defined as a direct consequence of the flood. If the road network had unlimited capacity to accommodate the additional demand, only the direct impacts would manifest the flood impacts on traffic. This representation of reality is arguably not sufficient to describe the complex processes in transportation. As the number of delayed vehicles is two to three times more than the number of vehicles travelling longer distances, it gives additional confidence that the knock-on effects are essential for the assessment of the flood impacts on transportation.

Thousands of drivers suffer delays during the 3 hours flood event. Depending on the delay threshold (1% to 10%), 38-62% of the vehicles suffer travel delays amounting to delays 35-80% of vehicles' original travel time. The greenhouse gas emissions during the flood event can increase by 40% per hour for CO_2 and NO_x.

The trips to the hospital are more than average likely to be rerouted and delayed. Results indicate that 17% of the hospital trips experienced an average five-fold increase in travel time, even though the nearest flooded area is around 750 m away from the hospital. The long hospital delays are a good example of how indirect impacts can propagate in many levels in an urban environment.

The monetisation of these intangible impacts indicated they did not appear to be costly compared to other types of flood damage. Nevertheless, that does not rule this research out as unimportant, because it highlights potential problems that sometimes can be addressed only with contingency planning. When considering intangible impacts, there are many aspects of the transport system that has to be focused on. For example, how to monetise a delayed trip of a doctor to the hospital, an ambulance struggling to reach emergencies on time, or the notion of frustration that the thousands of delayed drivers may experience. As these impacts may have substantial consequences but are hard to monetise, the thesis continues with the investigation of how the system performance can be improved with interventions that are not necessarily expensive to apply.

6 RESILIENCE OF THE TRAFFIC SYSTEM AND APPLICATION OF INTERVENTION MESURES

As discussed in the literature review, resilience is a complex term that expresses the ability of a system to adapt and transform during a shock to minimise negative consequences. This thesis evaluates the resilience of the transport system towards flooding as a performance-based method. This section discusses how the resilience of the transport system can be improved by implementing three different interventions that tackle the problem from different perspectives. One of the interventions aims at the network capacity at a critical point, another one focuses on reducing traffic demand, and the third one is purely operation and applied smart traffic control to overcome specific road closures. These interventions are implemented in the traffic model, and the resilience of the new system is assessed and compared to the original flooded traffic conditions.

6.1 Resilience of the current system to flooding

An essential part of the resilience assessment in this thesis is differentiating resilience from reliability. The reliability was presented as a range of daily variation of the traffic, and if the system performance goes beyond that range, the conditions are exceptional, and the system’s resilience is assessed. As described in the Framework of research (3.5. Resilience assessment, p. 73), resilience is evaluated by estimating three independent parameters - duration, magnitude and severity. The duration of the event is the time it takes the system to return back to the bounds of reliability. The magnitude is the maximum registered vehicles outside the reliability bounds.

The concept of resilience assessment was constructed in Section 3.5 (p. 73), but when real data is applied, it evolves to Figure 6-1 (p. 148148). Here the comparison is made to the dry (normal) conditions scenario which is represented with a flat line of zero changes. The reliability bounds are subtracted from the dry weather scenario to describe what differences from this scenario can be considered the normal variability of the system. These bounds in Figure 3-7 (p. 76) are presented with straight lines but the computed reliability range varies significantly over time and hence, in Figure 6-1 the reliability bounds fluctuate significantly over time. The negative sign means worse performance than the baseline scenario. For example, the flooded scenario accumulates more vehicles because they are delayed due to the capacity constraints, and it registers larger negative values in Figure 6-1 a). The sharp decline of the flooded scenario just before 9 AM is within the reliability bounds and according to the definition, this is not yet problematic. Around 9 AM the flooded scenario performance goes beyond the reliability bounds, and this is when the system performance starts operating under exceptional conditions. Until the system performance returns to the reliability bounds, the system's resilience is being recorded. Naturally, the performance during resilience is the difference between the number of vehicles operating in exceptional conditions and the number of vehicles in the minimum of the reliability range.

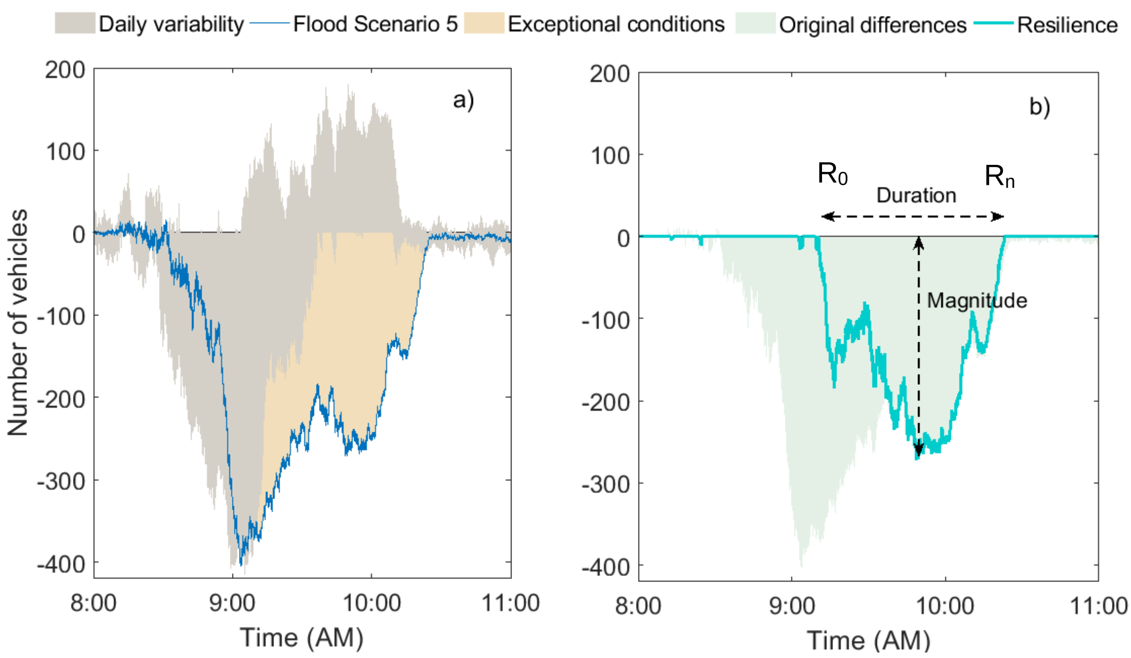


Figure 6-1: Resilience assessment outside the daily variability: a) Difference in number of vehicles in the dry and flooded conditions and reliability bounds; b) resilience overlaid with the original differences in the number of vehicles

The measured indicators of resilience are duration, magnitude and the integral of both. The duration is the absolute time the system goes beyond the reliability bounds (R_0) until the system returns to normal (R_n). The magnitude is the maximum difference between their number of vehicles in a flooded scenario and the reliability band. The area under the x-axes and above the resilience curve is expressed as the Sev_n (severity of a scenario) and represents the integral of the changes in vehicles from time R_0 until R_n.

$$Sev_n = \left| \int_{Ro}^{Rn} f(t) \partial t \right| \tag{6-1}$$

The time that was needed for the system to return to normal conditions was 4,950 sec (83 min) with a magnitude of 272 and severity 705,970 as absolute values.

6.2 Assessment of the effectiveness of mitigation measures

After the performance of the transport system during flooding was analysed, the same method can be applied to assess the performance of a flooded system with intervention measures. Three intervention measures are implemented in the transport model to analyse the changes in transport model performance. Rather than providing an exhaustive list of possible interventions, this section investigates in detail how three traffic management measures could potentially alleviate the negative consequences of flooding on road transport. The classification of intervention scenarios is closely aligned with the framework of the intervention by Butler et al. (2017) (Figure 6-2).

Figure 6-2: Interventions framework (Butler et al., 2017)

Mitigation measures aim at reducing the hazard probability and magnitude (Rose, 2004) and an example of such intervention can assume that a vital area of the transportation network is safe from flooding. However, this thesis aimed at focusing on measures that are relatively inexpensive, but realistic and therefore the implemented measures aimed at improving overall resilience, rather than reducing the hazard's intensities. *Adaptation measures* "address the link between system and impact" (Butler et al., 2017) and concentrate on the operational side of the system while in stress. As an example of an adaptation measure, a demand reduction is introduced so that the system will have more capacity to absorb negative impacts. *Coping capacity* is widely defined as the preparedness to use available resources to reduce the severity of the consequences (Samuels, 2009). To introduce a coping capacity mechanism in the transportation system a smart technology is implemented in the design of traffic signals in one of the affected areas. Another coping capacity mechanism is applied to increase the redundancy of a specific area where a pedestrian street could be open for traffic in cases of emergencies.

6.2.1 System design – smart technology

The system design intervention focuses on inserting smart technology to manage the transport system better. After discussing the spatial distribution of the congestion, one particular road was identified to receive speed reductions of 50-75 km/h for each hourly segment of the simulation. Av. Ramón y Cajal is a major road in the city and together with the motorway are the only ways to cross the city horizontally. It's a dual carriageway, mostly separated by an island of vegetation. The flood started at 8:50 AM and one of the carriageways was flooded for only 10 min, whereas the other direction was closed for 20 minutes.

Figure 6-3: Location of Av. Ramón y Cajal in Marbella. Snapshot from Google Maps

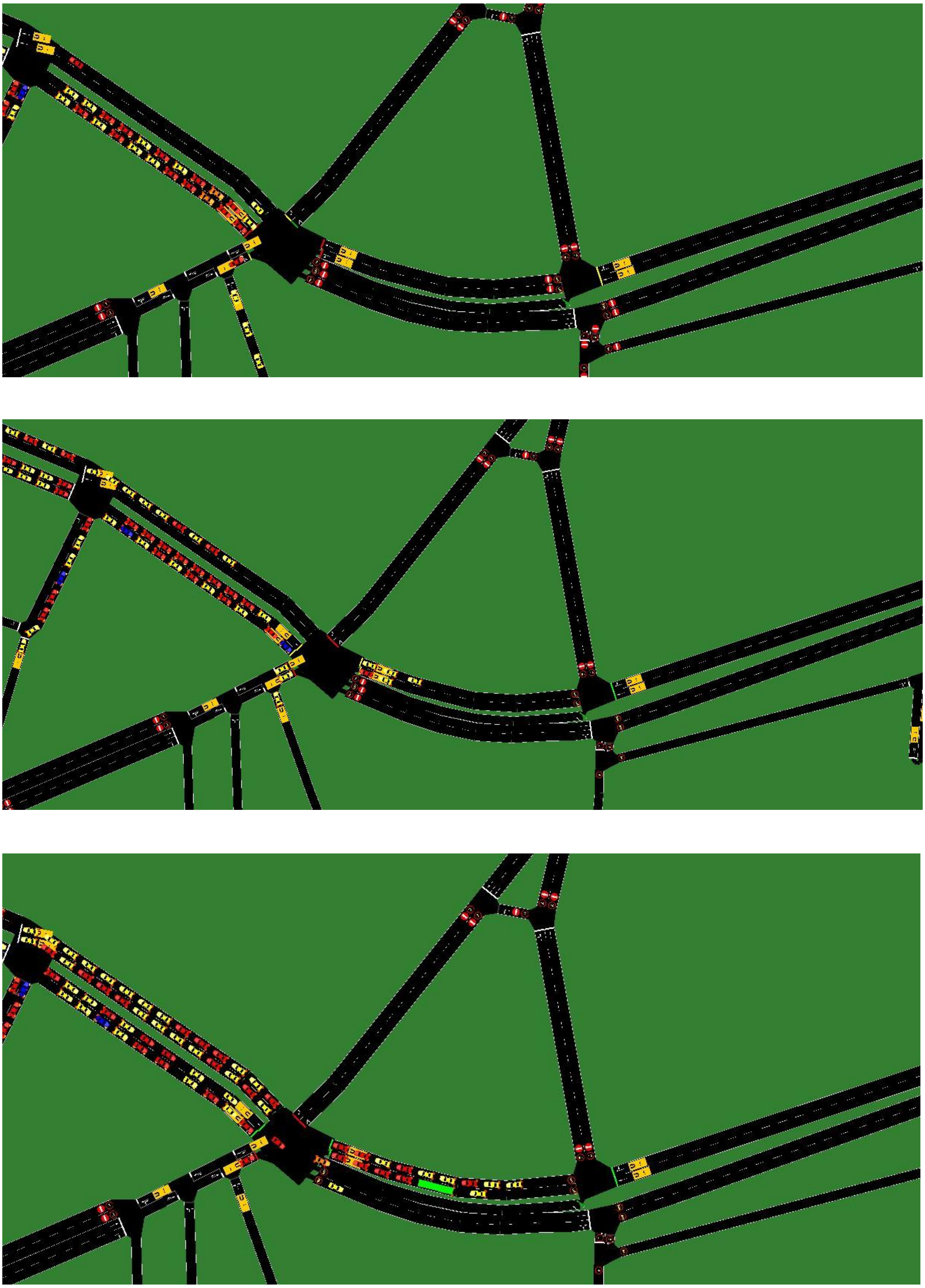
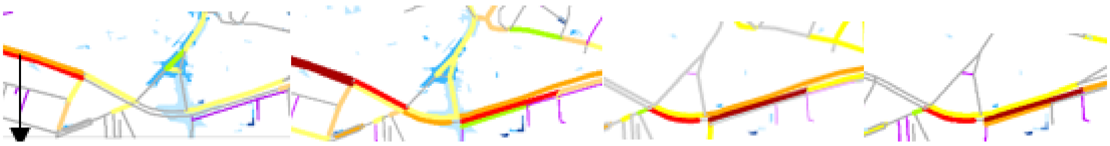


Figure 6-4: Av. Ramón y Cajal as modelled during the flood. The top image is from 8:50 to 9:00 AM (both directions closed). Middle image - 9:00 and 9:10 AM (eastwards direction is closed for traffic). Bottom image – after 9:10 AM both directions are open for traffic. Sumo screenshot without a scale.

Figure 6-4 depicts the modelled traffic in the three different time segments. Between 8:50 AM and 9:00 AM both directions were closed, and possible reroutes were very long. Note that U-turns are not allowed on the main road but many vehicles would turn right and make a U-turn on the small street. Between 9:00 and 9:10 AM only the eastwards direction was closed, and vehicles started accumulating quickly downstream the open road. After 9:10 AM both directions were available for traffic but with speed reductions of 20 km/h until the flood fully receded. Figure 6-5 shows the speed differences between the normal and the flooded conditions for each hour segment along Av. Ramón y Cajal. The flood map at 9:30 AM shows flooding but it is less than the threshold for a street closure (0.3 m), and therefore the roads were open, but with speed reductions of 20 km/h. The direction that remained flooded for 10 min longer is travelling eastwards (it is the lower of the two lines). This direction shows to have been more severely affected by the flood both during and after the flood has receded.



8-9 AM	9-10 AM	10-11 AM	11-12 AM
Flood map 8:40 AM	Flood map 9:30 AM	Flood map 10:30 AM	Flood map 11:30 AM

Figure 6-5: Aggregated over each simulation hour speed differences between normal and flooded conditions. ArcGIS screenshots without a scale.

As one of the dual carriageway directions was not flooded, with the use of a smart traffic light it is possible to rearrange this road from dual carriageway in one way into single carriageway in two directions. This intervention measure 1 (IM1) is intended to balance the number of vehicles passing through that area in both directions. The street closure is next to the city centre, which is mainly pedestrian and that leads to long reroutes. By opening the road in both directions though with limited capacity, the traffic can be readjusted so that neither direction would suffer. To achieve this, a modification to the model was applied, making sure that everything else in the model remains unchanged. The diversion was simulated by adding a new lane to the closed road and closing for traffic one of the lanes on the road open for traffic. Given that vehicles' routes are strictly established, they do not travel on the newly created lane, until a rerouter prompts them to select a new route.

This intervention resulted in more vehicles during the morning peak compared to the flooded conditions without intervention (Figure 6-6). It turned out that the direction that remained open in the original flooding had denser traffic and reducing the capacity slowed down significantly the traffic. To further complicate the situation, the downstream streets are suffering due to other closures in the city and a queue is accumulating towards the road with reduced capacity. So, the slowed down vehicles ended up in another congestion, that many of them could partially avoid in the original flooded conditions. However, the positive effect of the intervention starts paying off after 9 AM, when more vehicles have completed their routes. The delayed gains of the intervention can arguably cancel out the immediate negative effects of it.

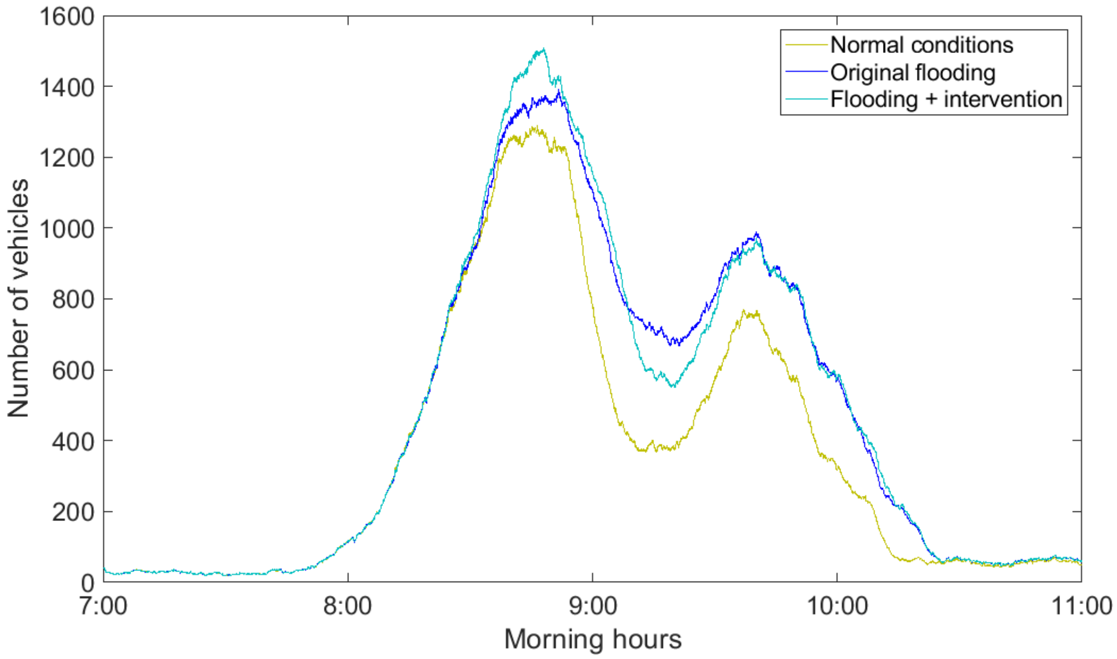


Figure 6-6: Number of vehicles under normal conditions, flooding and flooding with IM1

If the resilience assessment method is applied though, the IM1 system performance is only marginally improved, compared to the original flooding performance. Figure 6-7 a) depicts how the differences between dry and wet conditions were compared with the established daily variability ranges to distinguish resilience from reliability. During the first peak hour, IM1 simulation registered a very sharp increase in vehicles but the ability of the system to recover better contributed to the higher overall resilience of the system. The rationale was that the system would be in a better position to absorb the next surge in traffic demand while still suffering the same capacity constraints due to the flood. In fact, around 9:10 AM the system returns back shortly to normality within the reliability range (Figure 6-7 b). However, the initial gain in the system could not prevent the system form experiencing heavy traffic later during the second traffic peak. The IM1 scenarios registered a higher maximum (magnitude) that the initial flooding simulation (Figure 6-7 c). Comparing the resilience indicators also confirmed that IM3 had a neutral impact on the system performance (Table 6-1). The duration and the magnitude of the event are both slightly higher than in the normal flooding conditions, respectively 1.7% and 4.7%. However, the total area under exceptional circumstances was reduced with 12 % which compensates the overall impact on the system performance to neutral or slightly positive. These results provoke a fundamental theoretical question – are any of the resilience indicators more significant than the others and whether this is a matter of case to case discussion.

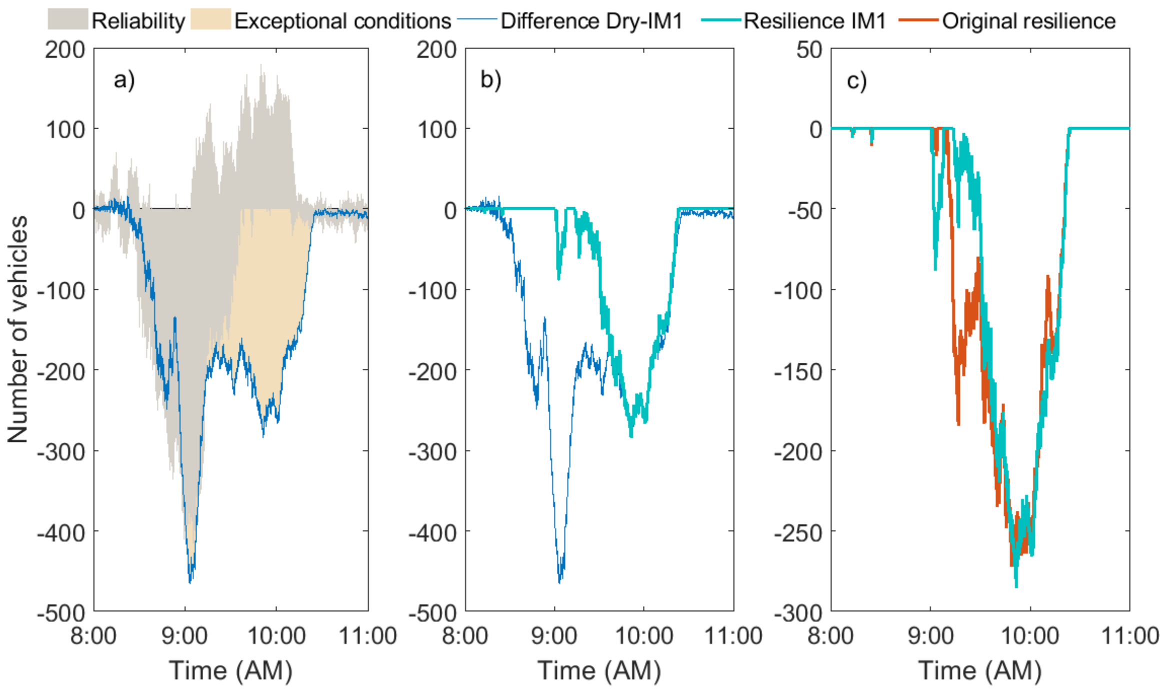


Figure 6-7: Resilience assessment of system performance with applied IM1: design enhancement

Table 6-1: Resilience assessment results: IM1

	Duration *(sec)*	*Magnitude (absolute number vehicles)*	*Severity* *(Vehicles*second)*
Original flood	4950	272	705, 970
IM1 flood	5034	285	620,185

IM1 aimed at balancing the flow of vehicles in both directions on one of the busiest roads in Marbella by applying a smart technology that can regulate traffic. This operational measure is versatile and beneficial for the everyday traffic conditions on one of the busiest roads in the city. Due to the overall low monetary value of the flood impacts on the transport system, the motivation was to identify a measure, that is not expensive and could have a multipurpose in improving system performance. Overall, the measure had only an incremental influence on system performance. Regardless of the positive expectations, this intervention enhances the resilience of the network only marginally. It is partially related to the short duration of the interference (only 10 min). Another reason is the local traffic conditions at that time that led to a considerable number of trapped vehicles in the direction that was initially open for traffic in the original flooded traffic conditions. Consequently, the magnitude and the duration of the event were slightly higher than the traffic conditions without IM1. The integral of vehicles over the duration of exceptional circumstances showed a 12% decrease and confirmed a positive outcome on the overall system performance. Judging from Figure 6-6 (p.153) the system with IM1 was more reactive which not only meant a higher first peak but also did it involve a faster recovery – around 9:20 AM there were about 150 vehicles less than in the original flooded conditions.

6.2.2 Operational – demand management

The applied operational mitigation measure manages demand by informing businesses and residents for the upcoming flood event. Investigating human behaviour during flooding is not a new topic and it is generally expected that effectively functioning warnings reduce the exposed people to the hazards. For example, Dawson et al. (2011) evaluated the potential of flood incident management to reduce vulnerability by dynamically integrating a flood and an agent-based model (ABM). The rationale in this thesis is that once the businesses and households in the most affected by the flood are warned about the approaching flood, a certain proportion of the trips, travelling to and from these locations, will be cancelled. Such strategies are not uncommon in the USA with the 'Reverse 911' as part of the Integrated Public Alert and Warning System (IPAWS) developed by FEMA (FEMA, 2015). Figure 6-8 depicts the general method for implementing the mitigation measure into the traffic model. The most affected roads are identified using the maximum flood depth map for 100 years return period. To identify these roads, two criteria had to be fulfilled: based on flood depth (deeper than 0.3 m) and length of the flooded section of the road (longer than 4m). In this manner, flood puddles are filtered out from the flood danger zones. The streets with flood length less than 4 meters are still closed for driving for the appropriate duration, but the residents and businesses located there are not contacted to reduce demand prior to and during the flood. Once the roads at risk are singled out, all trips that start or end on these roads are selected. A total amount of 2395 trips are defined as potentially at risk due to having either their origin or destination in the flooded areas. This is 15.1 % of the overall number of trips during the simulation. The analysed trip reduction proportions were 30%, 40% and 50%, which is respectively 4.5%, 6%, 7.5% of the total number of trips during the simulation.

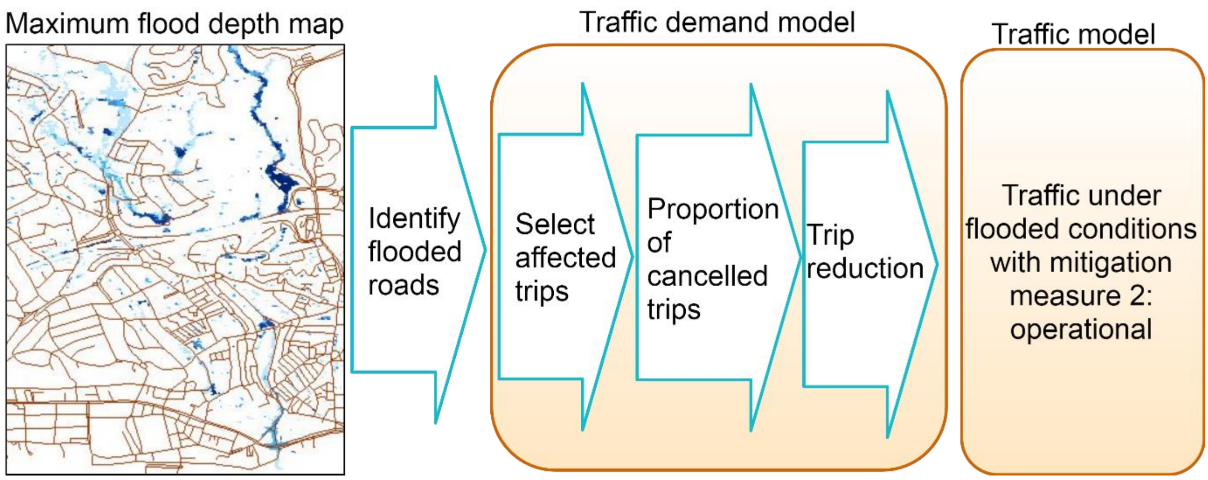


Figure 6-8: Rationale of operational mitigation measure

The trips that are not going to be realised are selected randomly and deleted from the XML file providing routes to the SUMO simulation. The random nature of that method is addressed by considering five different reduction scenarios are for each of the reduction proportions. Although this is not an exhaustive method to represent plausible scenarios, the results show considerable agreement within each demand reduction group.

The results from the fifteen traffic demand reduction scenarios are plotted in Figure 6-9. The performance of the applied demand reductions is compared to the range between the dry and the original flooded conditions. The 30% reduction in affected trips yields only 4.5% of the total number of trips but it contributes to a significant reduction in the vehicles in the first morning peak, and it performs even better than the scenario under normal traffic conditions. Afterwards, between 9-11 AM the randomly generated five reduction scenarios register in the middle of the range between normal and flooded conditions. This approach required a lot of assumptions, but it provides valuable insight into possible alleviating scenarios for transport authorities. By reducing the number of trips, the number of exposed people is also reduced which may result in fewer flood-related victims.

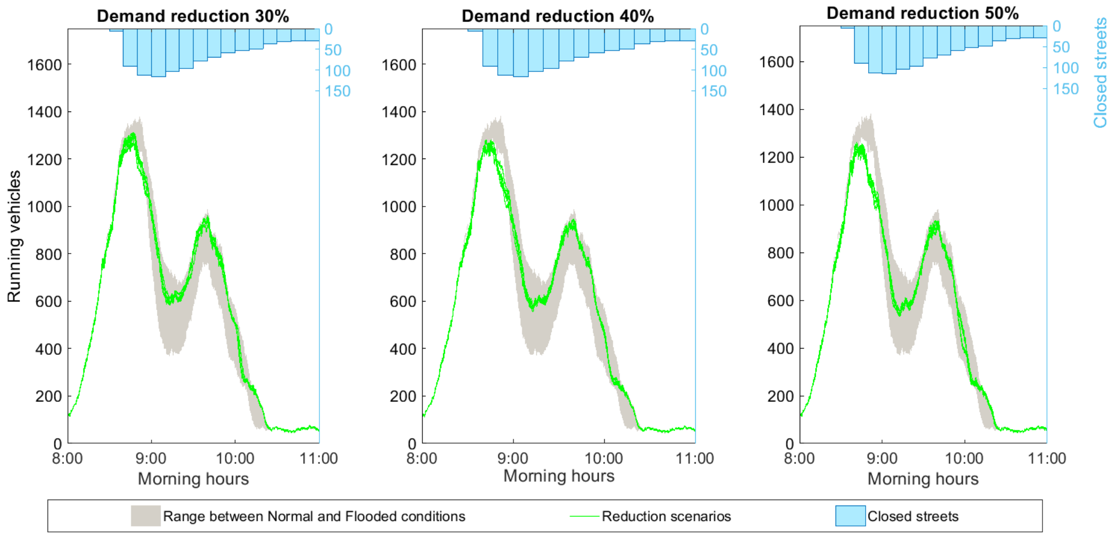


Figure 6-9: Effectiveness of the mitigation measure with demand reduction of 30%, 40% and 50% of trips with flooded origin or destination

The reduced number of vehicles during the peak hour register as a positive performance when compared to the dry weather traffic conditions (Figure 6-10). As resilience is defined by the difference in performance between the exceptional and standard conditions, the methodology of resilience assessment does not recognise positive performance as a gain to its resilience. However, the positive performance is a good initial condition for a system that is suffering from capacity restrains and contributes towards reducing resilience duration. It is worth mentioning that almost all reduction scenarios resulted in an early return to normal conditions at around 10 AM. Afterwards, the system registered a new peak in vehicles which is near the performance of the baseline flood scenario. The number of vehicles waiting to be inserted was high in the IM2 scenarios, and releasing them is the most apparent reason for the peak at 10:30 AM. Most likely these are the vehicles ought to arrive in their working positions by 10 AM and were delayed. However, it is not entirely clear why IM2 scenarios consistently accumulated waiting vehicles.

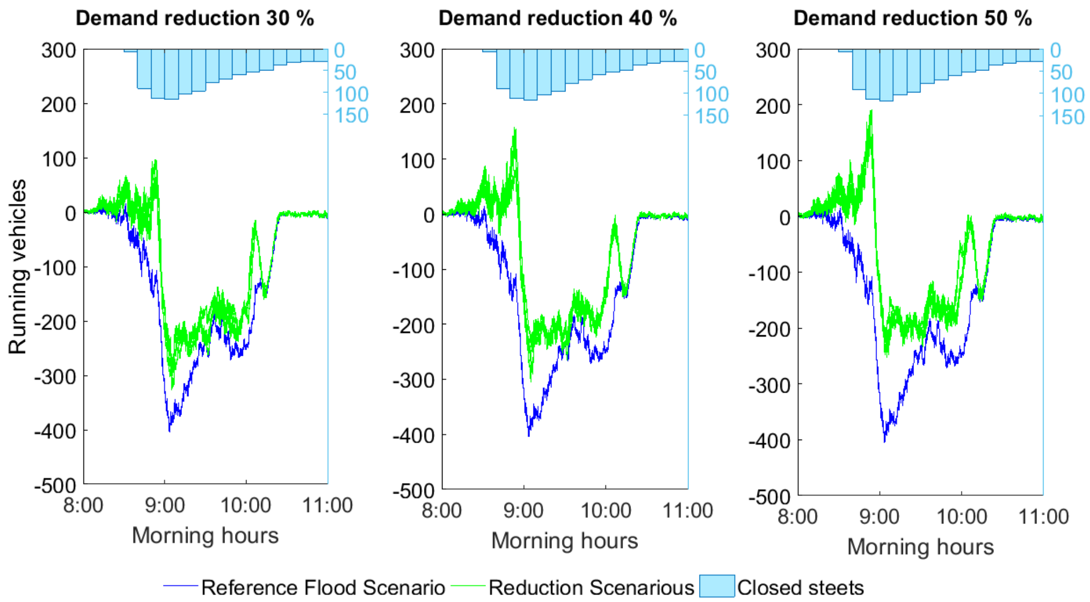


Figure 6-10: Difference between dry weather traffic conditions and wet conditions with and without IM2

All demand reduction scenarios indicated a significant improvement in the system performance under IM2. Figure 6-11 visualises the system performance under exceptional conditions, and although there was a variation among the results, it is evident that this strategy was more successful than IM1 in both reducing the duration and the magnitude of the flood impact on the transport system. The considerable variation within the 30% reduction scenarios contributes towards a higher uncertainty in the effectiveness of that measure. The other two reduction schemes of 40 % and 50 % demand reduction, however, were less ambiguous and resulted in substantial resilience improvements.

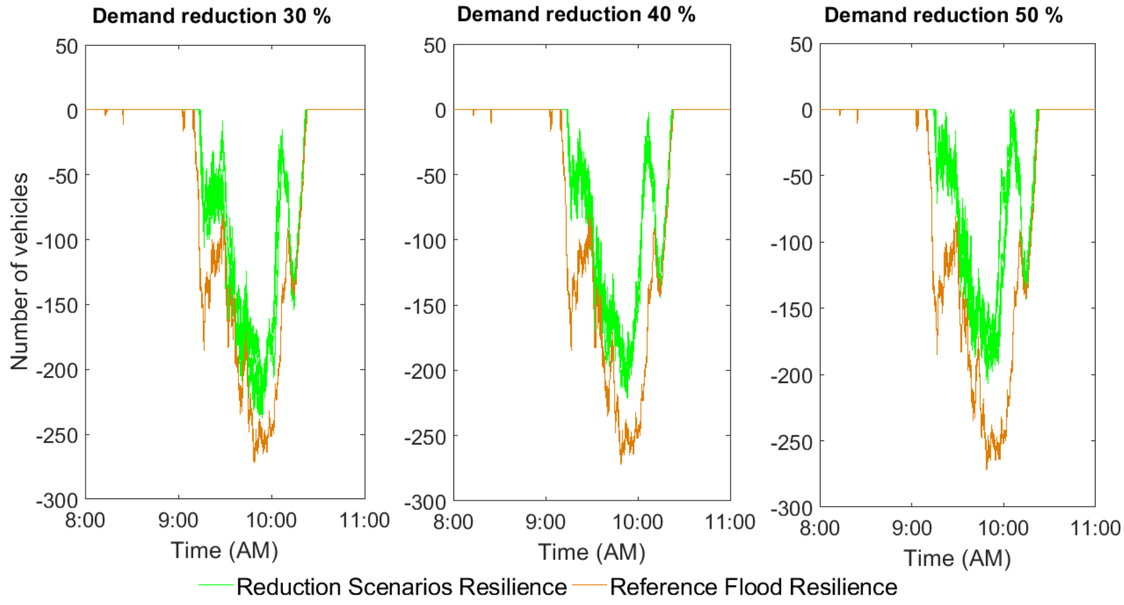


Figure 6-11: Resilience of the flooded system with IM2 - different levels of demand reduction

Table 6-2: Resilience assessment results: IM2

	Duration (*seconds*)	*Magnitude* (*absolute number vehicles*)	*Severity* (*Vehicles*seconds*)
Original flood	4950	272	705, 970
IM2 flood ranges			
30% reduction	[3302, 4400]	[199,291]	[399,228, 605,304]
40% reduction	[3276, 3340]	[191,224]	[382,430, 427,451]
50% reduction	[2848, 3277]	[168,180]	[246,680, 359,654]

Table 6-2 shows the resilience indicators of the flooded system with applied IM2. The results are present as ranges between the minimum and the maximum values among the scenarios in each demand reduction category. The 30 % reduction in affected trips resulted in 11 – 13 % decrease in duration, 13 – 19 % reduction in magnitude and 28 – 34 % cutback in severity. When 40 % of the affected trips are cancelled, the event duration was reduced by 13 - 14 %, the magnitude by 19 – 24 % and severity by 35 – 40 %. If a 50 % cancellation of affected trips was applied, the duration was cut down to 14-17 %, the magnitude – 24-31 % and the severity was reduced with 44 – 48%.

There is no doubt about the effectiveness of this measure, but a question could raise its implementation and its potential losses. Nearly 2400 trips were identified as starting or ending on a flooded street, and these people have to be contacted before the beginning of the working day. Businesses located on a flooded road may be contacted in advance to inform that there is a probability of flooding on their street and to be asked to consider in advance whether the business is flexible and can afford employees working from home. If companies have previously agreed to commit and have developed contingency plans, their reaction time can potentially be speedy. As far as starting a trip from a flooded road is concerned, people may already be obstructed and forced to cancel their journeys even without being contacted. However, this measure requires planning in advance and perhaps a lot of workforces contacting companies and households. The press could also be involved, but that includes higher accountability in a case of false alarm. The second point is related to the economic loss to businesses that have allowed their employees to spend the day home. If these businesses are flooded, it is likely that they may not be able to work due to lack of electricity or internet, or even physical damage to infrastructure, so it is expected that the company would lose the production anyways. It is worth reminding that the primary motivation for the municipality, companies and residents is to reduce the people exposed to flooding and consequently to limit potential fatalities.

6.2.3 Planning – redundancy increase

The third intervention measure aims at enhancing the system resilience by introducing excess capacity and back-up routes in a vulnerable part of the transport network. Additional system redundancy is provided only during flooding in one particularly vulnerable area which receives heavy traffic and is exposed to flooding as well. The most vulnerable locations of the transport network were identified in Section 5.8.7 (p. 139). The road speed changes were estimated as the difference between the hourly average speed of each road between the flooded and the normal conditions. On this basis, several locations with consistently slowed down traffic were identified (Figure 5-35 p.143). Av. Ramón y Cajal was the most adversely affected, and it was already discussed in IM2 where smart technology is implemented to alleviate balance the differences in traffic in both directions. The intention for this intervention measure 3 (IM3) was to concentrate on a different location and test a strategy to increase the redundancy of the surrounding area.

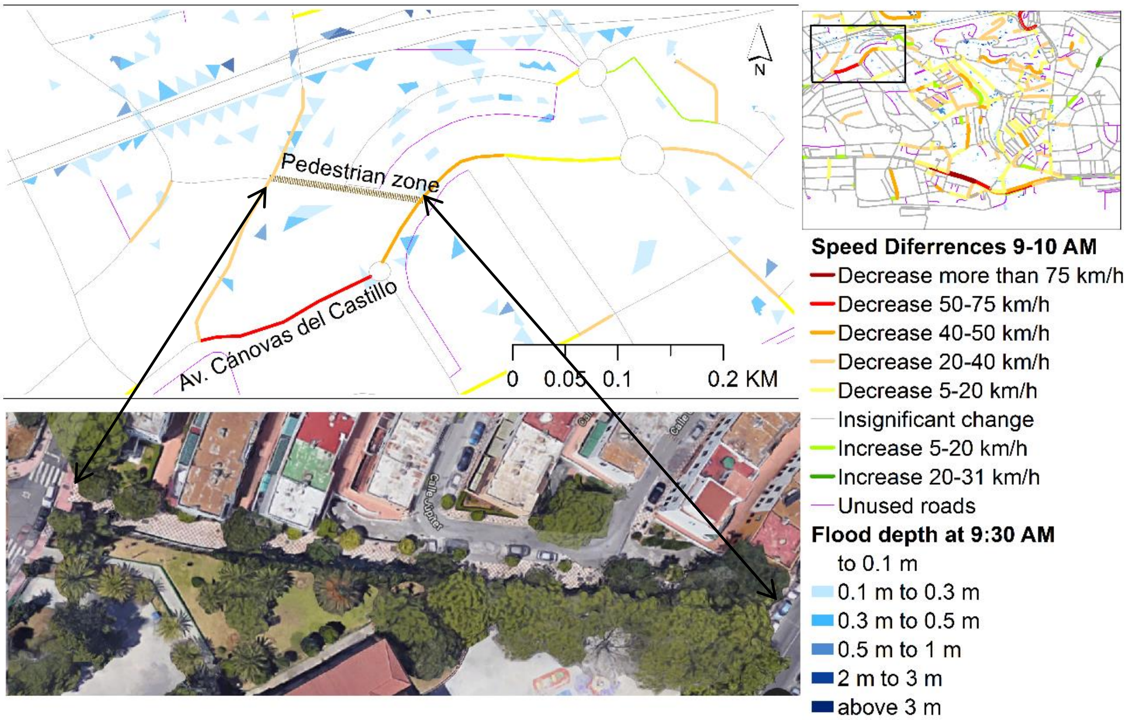


Figure 6-12: Map of the considered area for IM3 application. The bottom image from Google Earth shows the existing pedestrian zone

Figure 6-12 is a map of the area chosen for redundancy enhancement within IM3. This area lies between the city centre and the motorway. Several bridges connect the northern neighbourhood to the area to the city centre. Hence, in the morning many vehicles travel from the northern neighbourhoods going south to the city centre and the industrial zone (Figure 5-4). The top map shows the zoomed area and the street in red (Av. Cánovas del Castillo) is part of a ring of arterial roads in Marbella. In Section 5.4.7 (p.105) this road was identified as one of the vulnerable roads while discussing the performance of normal conditions compared to the visual data from Google Traffic. And so, even in normal conditions, this street is congested, and the situation exacerbates significantly with flooding. Av. Cánovas del Castillo was flooded for only 10 min between 8:40 and 8:50 AM but it was heavily impacted by the knock-on effects on the overall system and its average speed between 9 and 10 AM is with 51 km/h lower than the one under normal conditions.

After a visual inspection of the modelled traffic, it was observed that most vehicles passing through that road are coming from the northern bridge and continue in an eastern direction towards the city centre. To achieve this, they create a large U-turn and must join the traffic of an already congested road. The traffic network was carefully examined for future relief plan that can alleviate the congestion. It turned out a pedestrian zone that area can potentially bypass the big U-turn and some of the flooded roads. The bottom image of Figure 6-12 shows the width of the pedestrian zone allows single lane traffic in one direction. The pedestrian street can be open for transportation as a backup in the time of the flood. Currently, the pedestrian zone is isolated from the traffic by either stairs or traffic posts (Figure 6-13). IM3 assumes that these obstacles are replaced with flexible traffic posts that can allow the use of the pedestrian zone in emergency situations.

Figure 6-13: Both entrances of the pedestrian zone. Source of the images: Google Maps Street View, 2018[16]

The IM3 is applied in the traffic model as one directional connection between the two nearly parallel roads. Unfortunately, the absolute location of the pedestrian street was not possible to be kept. Such interaction necessitated changes in the names of the edges because one of the edges had to be divided into two to allow a connection with the newly created road (Figure 6-14 a). As previously

[16]https://www.google.co.uk/maps/@36.5176446,-4.8938191,3a,75y,93.53h,67.52t/data=!3m6!1e1!3m4!1sOx5wLPKThB4no-sYFlWFVA!2e0!7i13312!8i6656
https://www.google.co.uk/maps/@36.5174642,-4.8921961,3a,75y,316.16h,95.17t/data=!3m6!1e1!3m4!1sy2FhK5mpepFr2cwXKgAtXA!2e0!7i13312!8i6656

discussed, the vehicle's routes follow a specific sequence of edges and if a new edge is introduced cars cannot continue their journeys, and the simulation would fail. The emergency road was connected to the nearest junction, which happened to be on a roundabout (Figure 6-14 b) and thus an edge division was avoided. It is recognised that connection to a roundabout might contribute to better connectivity with the rest of the network, but there were no other alternatives to implementing IM3. The intended direction of the one-way traffic is going eastwards following the predominant traffic direction in the area during morning hours. The emergency road is used only by the vehicles that are rerouted during the flooded conditions.

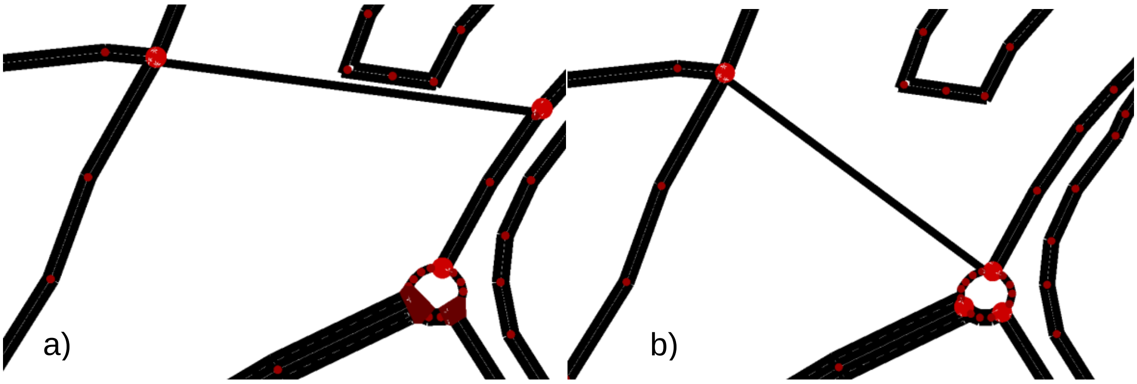


Figure 6-14: IM3 application in the model: a) layout in reality; b) design in the model

The flooded conditions with IM3 were simulated, and the obtained results were calculated according to the methodology defining the resilience of the system. Figure 6-15 shows the steps of identifying the resilience of the new system under IM3. Figure 6-15 a) follows that performance of the system within the reliability range and once exceeded it shades out the performance of the system under exceptional conditions. As previously discussed, this is necessary to discern normal from exceptional conditions to identify resilience from the sheer difference between dry and wet conditions (Figure 6-15 b). Figure 6-15 c) depicts the resilience of the original flooded conditions and the resilience of the flooded conditions with IM3. Although it had an overall positive influence, the intervention did not succeed in achieving significant performance improvement. The resilience indicators can be seen in Table 6-3 were all indicators registered a slight improvement up to 6 %. Figure 6-16 aid in understanding better how IM3 has impacted the number of vehicles in the system. IM3 succeeded in decreasing the total number of cars in the first morning peak, but this gain was not registered in the resilience assessment because both original and IM3 flooded conditions are close to the reliability bounds. Therefore, the resilience results were slightly deflated compared to the absolute values of the number of vehicles in the network.

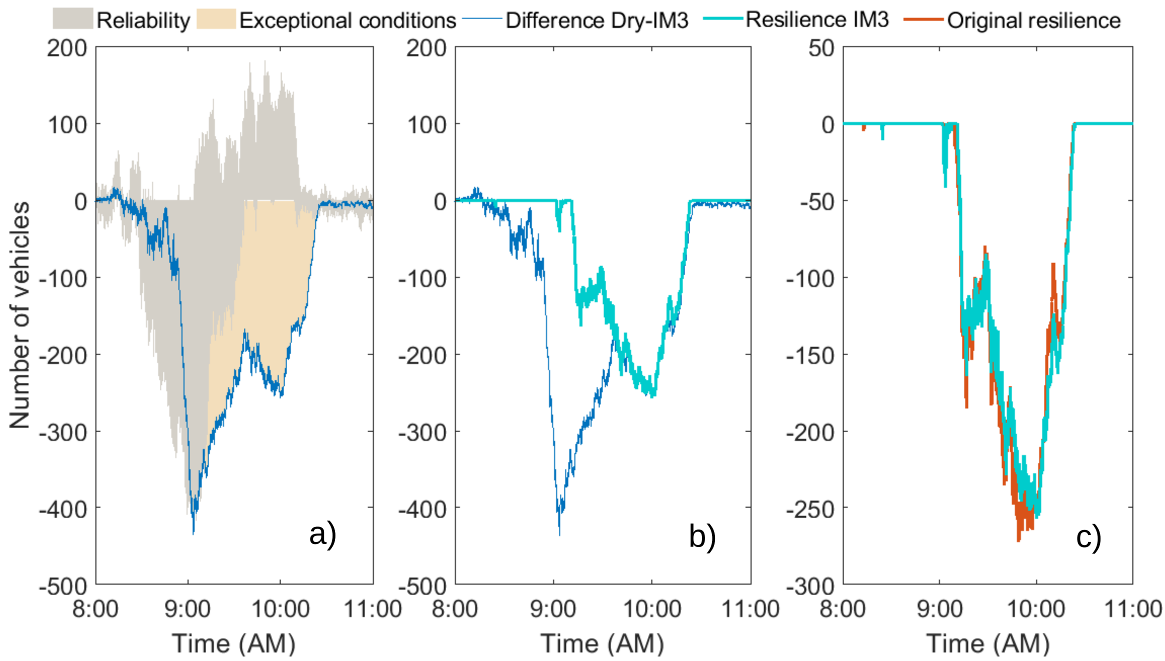


Figure 6-15: Calculating resilience of the transport system with IM3: a) distinguishing reliability from exceptional conditions; b) resilience compared to the difference in the number of vehicles in dry and flooded IM3 conditions; c) comparison between the system original resilience and the new resilience under IM3

Table 6-3: Resilience indicators IM3

	Duration (*seconds*)	*Magnitude (absolute number vehicles)*	*Severity* (*Vehicles*seconds*)
Original flood	4950	272	705, 970
MM3 flood	4914	257	692, 234

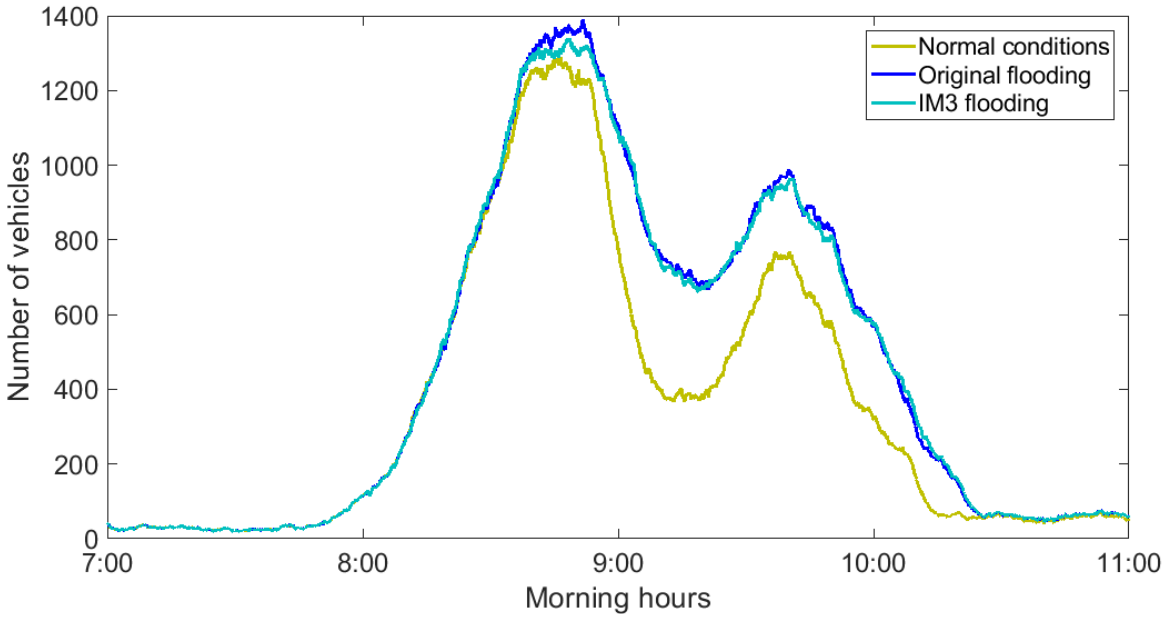


Figure 6-16: Number of vehicles change over time in normal, original flooded IM3 flooded conditions

IM3 aimed at improving the system redundancy by introducing an F route to shorten often used route on a busy road in Marbella. Only the rerouted vehicles in the network could take advantage of the alternative road, and the position of that road had to be slightly altered due to modelling requirements. The final resilience indicators showed a moderate performance increase (duration 1%, magnitude 6% and area 2%). It is important to underline that this intervention can potentially cost nothing except a few traffic signs and it involves only one out of 2402 roads in the network. Hence, this measure should not be disregarded as an only marginal improvement.

6.3 Conclusions

This chapter described how the developed methodology for resilience assessment was applied in the city of Marbella. Three intervention measures were tested to evaluate their influence on the overall resilience of the transport system towards flooding. Each intervention measure aimed at a different property of the system, namely its design (IM1), operation (IM2) and redundancy (IM3). The tested intervention measures focused on a low-cost improvement of the transport system performance. The best performing measure was operational which applied a proportion of demand reduction to the trips starting and ending at the most affected locations. A decrease of 30 % of the affected trips (4.5 % of the total trips) resulted in reductions of up to 13% of duration, 19% of magnitude and 34% of the integral area under resilience. The other two demand reduction proportions yielded even better results (Table 6-4). The shortcoming of the proposed measure is that it may be difficult to coordinate, and it might suffer the same dilemmas as any flood warning (false alarms).

Table 6-4: Percentage changes of resilience indicators. Positive values are improvement and negative are decline in performance

	Duration	*Magnitude*	*Severity*
IM1	-2	-5	12
IM2 reduction:			
30%	10-13	13-19	28-34
40%	13-14	19-24	35-40
50%	14-17	24-31	44-48
IM3	1	6	2

The other two measures had an incremental positive effect on system performance. Considering that both involved a single link change in the whole flooded transportation network for a short time, the performance was satisfactory. These network enhancements were applied to the most vulnerable locations in the transport system and were based on expert knowledge about the system behaviour. However, overcoming more than a hundred capacity restraints with only a single road change, even if it is of the highest importance, proved to be a sensitive task.

The application of intervention measures also raised questions about the capability of the resilience assessment methodology. Judging from the number of vehicles in the network during peak hour, IM3 managed to improve the system performance significantly. However, the resilience indicators did not capture this gain because it happened within the reliability bounds of the system. The case with IM1 was the exact opposite – it had more vehicles during the peak hour, but they were not included as a negative influence on the system performance. Such discrepancy was not unexpected when developing the methodology. After all, the rationale of the resilience methodology was to filter out the performance associated with normal conditions and describe the system's behaviour under exceptional conditions. Another critical point for the representation of the resilience in the transport system is related to the data selection. The reference demand Scenario 5 in its dry version has less than average vehicles during its peak hours. That means that the reliability bounds are further from it than from other demand scenarios. Consequently, exceeding the reliability bounds requires a significant accumulation of vehicles in the simulation of the flooded conditions.

The framework successfully assessed the system performance under different intervention measures during flooding. The resilience assessment focused on both maximums (time and magnitude), but also the variation of the system performance over time (severity). These indicators are perceived as independent values, but they must be prioritised to select the best possible outcome. Such prioritisation is best assigned to the purposes of individual studies. For such dynamic systems as transport, maximum values may not be fully representative of the system performance. A performance with a double peak can be misinterpreted if the severity is not examined.

To sum up, transport resilience is a very delicate matter because of its quickly changing conditions. Improving the resilience of a system includes the implementation of various interventions and their ex-ante assessment. Moreover, contingency plans are essential to aid the system to better absorb negative consequences. Expert knowledge of the system might not always be enough to improve systems' performance. For example, in the case of IM1, balancing traffic on both directions of the busiest road was a sensible idea, but it did not produce the expected results. The reduced traffic volumes in one of the directions which were experiencing very heavy traffic at that time of the day consequently lead to a large accumulation of vehicles in the network. All things considered, achieving higher resilience of the transport network can be accomplished by preparation in several steps: expert planning -> modelling -> assessment -> contingency plans -> required infrastructure installation.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Thesis Summary

Flood impacts on road transportation is a topic which has not been studied in detail in the past despite the extensive individual development of flood impact studies and road transport systems vulnerabilities. The thesis ventured into this multidisciplinary area to examine in detail the interactions of flood and transport models. These interactions are complex and result in a significant knock-on effect on the flooded transportation system.

The main aim of this thesis was to study these interactions by applying a novel methodology of integrating flood and transport models. The framework was translated into a user-friendly ArcGIS and Python tool, which automates the integration of the two models and allowed establishing different types of integration – static, semi-dynamic and dynamic. The former two kinds of integration have not been previously applied, and it was essential to draw the theoretical frames so that the different interpretations of flood propagation description are incorporated in the traffic model. Another objective of the software tool was to 'bridge the gap' between the flood and the traffic models and to encourage its application beyond this PhD thesis.

To achieve the previously mentioned aims, a microscopic traffic model was set up in two very different locations – Marbella, Spain and island Saint Martin in the Caribbean. As the PhD was funded by the FP7 European Commission project PEARL, it had a limited selection of case studies, and none of them provided any traffic data. Saint Martin had no traffic data, whereas the traffic data for Marbella could not be accessed. There was evidence of an alarming lack of collaboration between different city services, where the transport authorities refused to provide traffic measurements to a water company in Spain. And perhaps this lack of cohesion, which was the case in the other PEARL case studies, is the reason for the underdevelopment of the research in this field. Due to the lack of traffic information, the traffic model in Saint Martin was based on randomised data and the traffic model in Marbella employed a sophisticated activity-based traffic model that was consequently validated with Google Traffic information.

Once the different type of flood-traffic integration was applied successfully to the case studies, the flood consequences on the traffic system were assessed. The impact assessment was not a trivial task because microscopic traffic model results are sophisticated. Each vehicle in the system is modelled individually, and when the system is flooded, some vehicles might have travelled in a different hour than their planned journeys, which makes the translation of overall system results into an hourly output very challenging. The question of upscaling detailed data is not new, but it still posed a challenge to representing information in the most objective manner. The impacts were presented as statistics of changes in traffic delays, travelled distance, fuel consumption and CO_2 emissions. On a system level, the changes in average speeds per time were illustrated as maps.

Once the impacts were appraised, the vast potential and opportunity to assess system performance was recognised. Transport system resilience concepts were studied and a novel methodology to determine the resilience of the transport system was developed. This methodology was constructed based on an amalgam of ideas from both water science and transport systems. The novelty in the resilience assessment rationale was in defining variability of the system performance as reliability and using it as the definition of standard conditions. If performance ventured outside the reliability bounds, the system was operating under exceptional conditions, and its resilience was recorded. Three independent indicators determined the performance under resilience – duration, magnitude and severity. The objective function of any resilient system is to minimise these indicators.

Lastly, in Chapter 6 the resilience assessment methodology was applied to assess the reference resilience of the original flooded transport system and consequently was implemented to compare how three different intervention measures influenced the overall resilience of the system. The intervention measures focused on improving system performance at particularly vulnerable locations in the city and explored improvements of various properties of the system: its design, its operation and contingency planning.

7.2 Originality and contribution to science

It is suggested that this PhD study has made the following novel contributions:

- Developed a methodology allowing a straightforward translation of spatially varying flood intensity into transport model capacity restrictions (speed closures for the deep flooding or speed reductions for the shallow flooding).
- Developed an innovative tool that automates the integration of flood and road transport models.
- Demonstrated a semi-dynamic and dynamic integration of flood and traffic models.
- Employed for the first time a microscopic traffic model to assess the impacts of inundation on traffic conditions.
- For the first time in flood impact assessment, the traffic model employs temporary fluctuating traffic demand, which was found to be one of the crucial factors affecting the system's ability to absorb shocks.
- There is no indication reliability has been previously separated from resilience in a performance-based resilience assessment of combined water science and transportation systems.
- Assessed the changes in resilience if intervention strategies are implemented to the initial system.

7.3 Conclusions

The conclusions are categorised according to the initial objectives of the thesis as outlined in Chapter 1.

1. Examine the existing methods and consider the best available options for the proposed research, while available software is discussed.

The literature review revealed a considerable gap in the previous means of evaluating flood impacts on road transportation. The previous literature regarding flood impacts on road transportation used crude methods but indicated that flooding would affect traffic negatively, potentially exacerbated in the future by climate change and population increase. What previous research could not grasp was the assessment of the knock-on effect of floods on traffic and how these impacts propagate in both time and space after floods apply capacity constraints on the transport network. These limitations were mainly technology driven because traffic models used for the assessment of flood impacts didn't have a representation of congestions. Without a description of congestions, travel delays in the time of disasters can be misrepresented and misunderstood. Therefore, the key to decipher interruptions' knock-on impacts on traffic was being able to model congestions. Using microscopic traffic model could unlock the possibility to investigate in detail both direct and indirect flood impacts on road transportation. Another deficiency in the previously discussed research was the static representation of both flood dynamics and traffic demand. Both flood and traffic systems exhibit highly dynamic features, which mustn't be overlooked. On top of this, flood and traffic models have not been integrated in a dynamic manner where the changes in flood propagations over time would be translated into time-varying traffic supply reduction. In fact, the thesis applied static and dynamic integration to the same case study and examined significant differences in the results.

Previous research underlined that the most considerable flood impact on transportation would be the time lost in traffic and therefore a section of the literature review was devoted to monetizing travel delays. As monetizing time is a multifaced issue and is a complex amalgam between wage data, stated and revealed preferences, perhaps the final values may not reflect reality, but the thesis employed the study with most convincing methodology.

Last but not least, the literature review focused on the description of resilience both in the water and traffic systems. The concept of resilience has potential in describing system dynamics, but it has been rarely applied in practice. It was imperative to adopt a framework that can evaluate systems resilience form a performance viewpoint. Being a term that has no universal definition yet, it was not surprising that resilience is perceived slightly differently in water and traffic systems. While reading and writing the literature review about resilience, the main aim was to incorporate ideas that can be applied in practice with the wealth of data that a microscopic model can provide. The notion of reliability was considered central for defining the difference between normal and exceptional conditions and the methodology proposes a novel approach to assess resilience in a traffic context.

2. Introduce a novel methodology for the one-way dynamic integration of flood and traffic models.

The methodology had to main aims. Firstly, it had to achieve the translation of spatial and temporal variations of flood propagation into a traffic model input. More specifically, flood intensities dictate road network capacity constraints, whereby deep flooding would close a street for traffic and a shallow flood depth would require speed reductions. Secondly, this framework to be versatile enough, so that it would allow different interpretations of the interaction between flood and traffic systems. And indeed, the methodology facilitates the implementation of three different types of flood-traffic integration – static, semi-dynamic and dynamic. The static integration works as the flood depths of one map (i.e, maximum flood depth) determines the street closures and speed limits reductions for a period of time. The semi-dynamic integration also employs one map, but this is the map of flood duration at each location. Thus, we can set up different closure durations depending on the flood propagation at specific locations. The dynamic integration employs a series of flood maps (e.g. for Marbella the timestep is 10 min) and runs them iteratively so that the flood propagation will be translated into temporary varying transport supply constraints. The semi-dynamic and dynamic integrations have not been previously implemented to represent the flood impacts on traffic and are necessary because flood duration differs in different locations. An example can illustrate that such integrations are not only details to the integration of the system but can be crucial to its understanding. It turned out the duration of a statically integrated flood is nearly impossible to determine for the fear that it can either be under or over representing the disaster. In Marbella two durations were considered acceptable – 50 and 90 min and they were applied globally for all street closures in the case study. After the dynamic integration was run, it turned out that the busiest street closes for 10 and 20 min in the different directions and the two previously defined durations cannot portray that variability. Finally, it is essential to highlight that this interdisciplinary approach relates to an off-line analysis of combined flood and traffic modelling. The methodology lends itself nicely for real-time modelling and decision making for coupled flood and traffic management systems.

3. Based on the methodology, build a robust software tool to convert data from the temporary varying flood model output to temporary varying traffic model input.

The developed framework for integration of flood and traffic models was successfully translated into a user-friendly tool with the main purpose automating the tedious translation of flood-induced capacity restrictions in the dynamic simulation (for example a dynamic simulation required writing around 600 XML files). The temporal variations in flooding are achieved by running the tool iteratively with maps of the flood propagation and ensuring the temporal changes reflect the timing in the traffic model. This tool makes it possible to analyse multiple flooding and traffic scenarios and could be a central device in the development of contingency plans for the operation of road-transport systems under strains starting from flooding and far-reaching to terrorist attacks.

4. Development of a software tool, which can facilitate its application outside this research.

The developed software tool can be executed either from Python console or ArcGIS. The ArcGIS version of the tool has a user-friendly interface and it requires very little knowledge of the underlying processes. The tool is open source and hopefully, its easy access would encourage development in the field of flood impacts on road transport.

5. Demonstrate the application of the tool in a static, semi-dynamic and dynamic flood-traffic model integration

Demonstrating the feasibility of both the methodology and the tool was a fundamental element of the thesis which aimed at developing novel interpretations of the way flood impact traffic. The tool assisted in accomplishing the different types of integrating flood and traffic modes, as well as dealing with different types of flood model result data. For example in Saint Martin the available .DFS2 result files allowed creating a single map of spatially distributed the flood durations, which consequently was the foundation of the semi-static integration. As previously discussed, the durations of street closures had an essential role in the way traffic is impacted by the flood. Therefore, it was meaningful to compare different types of flood-traffic integration and discuss their benefits and drawbacks.

The semi-dynamic integration considerably improves the accuracy of the representation of the spatially distributed flood durations (ranging between 10 and 350 min). However, this method fails at providing information about the beginning of the flood at each location. This necessitates assuming that flooded areas with similar durations would appear simultaneously. As the semi-dynamic integration requires only one flood map, the integration is very quick and does not involve iterating and the specifics of data formatting for dynamic simulations. Considering, this method has significant theoretical advantages over static integration, it is surprising that the semi-dynamic integration of flood and traffic has not been applied before.

Comparing the static and the dynamic integration results was one of the cornerstones of the thesis which aimed at proving that existing methods are not good enough to describe the dynamic processes enfolding when a road transport system is flooded. static and dynamic model integration was applied in Marbella with significant differences in the way the flood propagation is interpreted. Due to the characteristics of the quickly developing flood in Marbella, the temporal dynamics of the flood propagation were essential for the description of the inundation in the traffic model. After comparing the results of the two integrations was concluded that static integration may be feasible only for very slowly developing and long-lasting floods. Otherwise, it can jeopardise the flood description by either over- or underrepresent it. The results from the static integration suggested a 250-400 % increase in travel time, whereas the dynamic integration yielded only about a 30 % increase. These discrepancies are explained with the short duration of the flooding on some of the major roads which were misinterpreted by the static model. There are large discrepancies between the results of the dynamic and the static integration of the flood and traffic models. Therefore, we argue that static integration is not sufficient to represent the complexities of the processes involved and to set the foundation for the assessment of the flood impacts on transportation

6. Assess flood impacts on traffic

The results clearly agreed with expectations that the description of the knock-on effects is central for the representation of flood impacts on road transportation. The most significant flood-induced traffic impact is the increase in travel time. Depending on the assumed threshold for a trip delay 25 to 65 % of all trips might be affected. The delays are exacerbated in the busiest time segment between 9 and 10 AM. Moreover, 10 % of all trips were delayed with more than 50 % of their initial travel time with an average travel time grew four-fold. The directly affected vehicles were only 14% of all vehicles, and their trips were longer by 5% on average. That meant that despite the large flooded area, vehicles were not obstructed too much in finding alternative routes. Regardless of the incremental increase of travelled distance, the GHG emissions in some segments registered a spike of 40 % in one of the time segments. And the only explanation of the previously summarized results is congestion. The accumulated congestion is an example of indirect impact – its spatial extent is much larger than the flood and even after the flood has receded, the transport system is still struggling to recover.

With a focus on critical infrastructure, the research investigated how trips to and from the hospital would be affected by the flood. Although the hospital is located a kilometre away from the flooded zone, the trips to the hospital sustained considerable delays. More than 50 % of the trips of the hospital were rerouted, and nearly 60% of the vehicles spend twice longer in traffic that they would normally do. The trips to the hospital registered substantially longer travel delays that the average vehicles in the simulation. Analysing the effect on hospital trips raised fundamental questions about the necessity to evaluate different types of trips within the city. For example, the value of delayed doctor to the hospital cannot be expressed only with the monetised lost time but crucial lost opportunities.

Monetising the time loss in traffic and the additional fuel consumption gave € 15,000, which is marginal compared to the direct tangible damage. For the record, the static simulation results predicted time losses costing from € 66,000 to 130,000. Even if we accept that the static integration results are close to reality, the monetary impact of floods cannot be considered substantial. However, the low monetary value of lost time in traffic is not justification for ignoring impacts that are difficult to quantify. These impacts are distributed among many drivers, with some experiencing substantial delays. The low monetary value of the impacts can encourage the implementation of operational decisions which can be effective without necessarily requiring massive capital investments.

The spatial distribution of the flood impacts on traffic has a central part in this thesis. Speed maps were produced for the hourly segments of aggregated traffic and were analysed to identify the most affected areas in the transportation system. For example, the main road was flooded for only 10-20 min (different flood duration for the different directions), but it was consistently congested for 4 hours with speed reductions from 50-70 km/h. The maps enabled the identification of six vulnerable locations that can have a crucial role in the attempts to alleviate the negative consequences of flooding. Almost all of the identified vulnerable roads were flooded for different durations, but some remained dry (slip-roads did not flood but suffered queues). Even though most roads were significantly slowed down, others had faster traffic than the reference scenario. Such roads were generally located just downstream of a flooded area and had reduced traffic volumes until the road was open for traffic.

One of the neighbourhoods in Marbella becomes fragmented to its topology, and the flooding and residents are not able to access the rest of the city for 40 minutes. This is a perilous situation, where a whole neighbourhood is cut off from the rest of Marbella. Interestingly, a similar observation was observed in Saint Martin (most likely just a coincidence that both have a neighbourhood with just one outlet because they are surrounded by hills). It is crucial such considerations to be communicated with transport authorities to identify whether these roads have to be protected, or their redundancy increased.

It is noteworthy that even though the transport model results are not prescriptive the managed to capture characteristic features of the road transportation system. The results clearly demonstrated that the knock-on impact of disruptions to traffic systems are a fundamental element for identification of most vulnerable locations. By describing knock-on effects, we can also analyse how the traffic system would recover both spatially and temporally. Another aspect is related to the cancelability of critical infrastructure: the results showed that the vast majority of vehicles travelling to and from the hospital suffered unacceptable travel delays. Road network fragmenting due to the flood-induced closures must be avoided and it is essentially to water and transport authorities to exchange information about potential impacts of flooding in order to alleviate negative consequences.

7. Establish a framework for resilience assessment of a transport system

The thesis developed a novel approach to assess transport system resilience as performance-based criteria. Its biggest contribution is that it draws a fuzzy line between normal and exceptional conditions to discern reliability from resilience. Theoretically, the difference between reliability and resilience has been discussed for a long time, but its actual application has not been studied well. To overcome that mismatch between theory and practice, the introduced framework proposes a solution to an original solution that is applicable both in water and transport systems. The methodology is based on an amalgam of water science, transportation systems and general engineering concepts. The concept of failures is often used in water engineering to define resilience, but in transportation, this notion cannot be applied because the system is better connected and the actors are capable of self-organising. By introducing the reliability bounds, the methodology overcomes the lack of definition of failure in traffic systems. The resilience assessment is based on traditional parameters – duration and magnitude and severity. The proposed approach is not limited to floods but can be applied to assess system resilience to other threats to road transportation.

8. Assess the effectiveness of intervention strategies for the improvement of system resilience

The lasts chapter concentrated on applying intervention measures in the traffic system that would boost its original resilience not only to flooding but other disasters and incidents. Moreover, these measures are considerably inexpensive, compared to the cost of flood protection schemes. The thesis argues that involving such measures in contingency planning can significantly enhance the performance of any transport system that is exposed to capacity restrictions.

There is no evidence of other studies investigating changes in flood/traffic systems' resilience by applying intervention measures.

Three intervention measures we applied in the most vulnerable locations in Marbella and consequently the resilience of the new systems due to flooding were assessed

1) The best scoring intervention measure aimed at reducing the traffic demand at the most severely affected areas. This measure also requires the most operational effort in identifying the most vulnerable locations, informing citizens and businesses such scheme exists and finally providing information about approaching dangerous events.
2) The system design intervention measure that involved the installation of a smart traffic light to a particularly vulnerable location led to intriguing results. The expectations were that this intervention measure would be very successful and such a device can potentially be used for other purposes by the traffic managers. However, the final results were not assuring that the system can benefit significantly from that measure. The leading reasons were the short duration of the measure (only 10 min) and the particularities of the traffic demand when the intervention measure was applied in the flooded network. A central conclusion from that investigation was that even expert knowledge of the network might not be enough to predict the response of highly non-linear systems. Future management strategies must be modelled in advance with different sets of traffic demand to assess how they can contribute to better system performance.
3) The planning intervention measure aimed at enhancing the redundancy of the system in the time of emergencies. The intervention allowed vehicles to travel on a pedestrian-only street for the duration of the flood. The measure made slight improvements in duration and severity but scored 10 % better in magnitude. Although that increase might not seem significant, it is worth noting that this intervention measure costs very little (the value of several flexible traffic posts and their installation).

Another interesting observation was that because transport networks are generally well connected, it was not complicated to establish potential strategies for alleviating the traffic in the areas that were deemed most vulnerable

To summarise, inexpensive strategies for better management have a considerable potential to improve the performance of road transport systems. These strategies are case and site-specific and must be developed with the expert knowledge of the systems' specifications. However, the proposed intervention measures also have to be tested in a modelling environment to assess their effectiveness. Contingency plans produced in advance are necessary to shorten the distance between scientific analyses and timely application of emergency planning.

7.4 Top five uncertainties

Uncertainties are inevitable in a modelling-oriented study, especially when it has gone through a lot of assumptions (Sections 3.6 and 5.6). Acknowledging the key uncertainties is crucial when dealing with risk management and decision making. Modelling interdisciplinary phenomena complicates the uncertainty assessment as a result of combining inherent uncertainties of each of the involved systems. Here is a list of the top five uncertainties in the thesis:

1. The *traffic demand model*. In St Marten, the traffic demand was based on random trips and in Marbella, the demand model was an activity-based model which produced synthetic travel demand.
2. The *traffic model* in Marbella had very limited validation and no calibration due to the lack of transport data. In St. Martin there was no validation or calibration due to the lack of data. It is possible that the traffic network has been also altered alter hurricane Irma brought destruction to the island.
3. The *flood model* in Marbella is designed for the purpose of capturing flood extends and depths but its flood propagation did not seem resealable and had to be readjusted with a reduction constant that aided its presumed issue with insufficient drainage connections. In St Martin, the drainage capacities were not included in the 1D-2D models applied in several locations of the island. However, flood propagation was developing and receding considerably well. The issue of flood models being trained for

one particular purpose worryingly common. It is clear that one model can never answer all possible questions about a particular event. However, overtraining of models to represent one particular characteristic of the event should be avoided.

4. The *rerouting design* requires either road police to close roads or the unrealistic expectation that drivers will be able to judge whether the flood depth is above or under 0.3 m. The current research studying the reasons drivers decide to drive into flood waters identified many factors in the decision-making process and by applying a global flood depth threshold all that diversity in the human behaviour responses are disregarded.
5. T*he time of the occurrence of the flood event* is morning peak hour in the simulated scenarios. As the traffic demand varies considerably during the day, the time of the interruption is crucial for the final impact assessment. The preliminary simulations showed that interruptions to the morning and the evening peak hour could result in different impacts. However, with time the idea to compare interruptions to different traffic demand situations dropped out in order to invest time in the resilience framework.

After describing the key uncertainties of the research, it is crucial to accentuate that the aim of the thesis was never to be a prescriptive study, but rather to demonstrate how original ideas can be applied in practice and give an example how these ideas can be developed further for the benefits of a more resilient road transport system.

7.5 Recommendations for Further Research

This PhD thesis discussed only the beginning of the application of microscopic traffic models in disaster risk and resilience assessment. This section presents various proposals that can be further developed to enhance either the representation of the flood in the traffic model or the evaluation of the effectiveness of strategies to boost the system resilience. Many of the recommendations were not feasible at this stage, because they might have required major update in the SUMO source code or gaps in other areas of research. Others were deemed too time-consuming for the added value to the research in this thesis. An intriguing characteristic of all the recommendations is that none of them has been applied in previous studies.

7.5.1 Description of the flood in the transport model

The methodology of the flood description in the traffic model can potentially be improved in various ways to address different process in the transportation system. These are the following:

The threshold for a street closure plays a central part on both the framework of research and the PEARL tool. Ideally, this threshold would be the product of flood depth and velocity. Changing the threshold is straightforward to model, but the limit value itself is problematic. The current experimental research in the area of stability of vehicles in flooded waters has substantial disagreement what the critical combinations between depth and velocity are. All of these papers used model vehicles in various scales to investigate under what conditions vehicles become uncontrollable. Only one paper used real vehicles in experiments but focused only on flood depth thresholds. With more research in that scientific area, it will be possible to apply a stability curve that would identify flooded roads on more sophisticated merit. For case studies with flash floods a threshold that includes velocity can be critical in determining safety on the road. Traffic management services can also benefit from such information, because in some locations even a 10 cm supercritical flow may be enough to make vehicles behaviour unpredictable. Identifying locations with such conditions is pivotal for the installation of traffic signs that would inform drivers about the dangers of flooded waters in such areas.

Different thresholds for different vehicle types. In this research, emergency vehicles were not included in the model because the rerouters did not the capacity to apply different conditions for different vehicles. Ambulances and especially fire engines have different stability thresholds, and their intervention during disasters is crucial. Another obstacle is modelling the behaviour of emergency vehicles in a traffic system, because of their exclusive rights on the road. At this moment modelling their unique behaviour in SUMO is partially possible by driving in a virtual middle lane and disregarding some rules.

Some drivers might choose to disrespect the street closure. It is currently technologically available to set up a certain proportion of drivers avoiding the street closures in SUMO. The development of the research on the behaviour of individuals towards flood-risk (Aerts et al., 2018) and the choice whether to drive through flooded streets (Haynes et al., 2017) can contribute to significant improvement in the processes described in that thesis.

Implementing speed reductions due to adverse weather before the flood has developed. The speed reductions prior to the flood were not included only because the flood in Marbella developed very quickly (only 10 min before the flooded conditions) and in Saint Martin, the flood dynamics were described synthetically, so implementing such measure required more assumptions. This feature is crucial for prolonged rainfall events, where the flood would start developing in a system which is already struggling capacity restraints.

Implementing the flood conditions in different hours of the day. Flood conditions in different hours of the day were discussed in (PEARL, 2017) but were not further developed in the PhD thesis. The afternoon peak traffic showed different behaviour while flooded – there were more rerouted vehicles, but the overall loss of time was slightly less than the morning peak while inundated, but it took the system longer to go back to normal conditions. When people leave work, the origins of their trips are less diversified, and some are close to the flooded area, so the system reacted in a different way to the flooding. Although these differences were not deemed of crucial importance to the PhD thesis and its primary goals, they can potentially reveal valuable insight from the viewpoint of performance of the mitigation measures.

7.5.2 Traffic model reliability

Data availability. As previously explained the traffic models in both Marbella and Saint Martin did not take advantage of traffic measurements. The models were sufficiently good to be a proof of concept, but unfortunately cannot be prescriptive or predictive. However, microscopic models are intensively data-demanding and often set up by a team of people, so it was possible that access to required data would not have been enough to build a predictive model.

Rerouters modelling established diversions. As it stands, the SUMO model is not capable of modelling diversions after a street closure. The idea is that such diversions routes can be established prior to the flood and can ensure drivers are safely rerouted to a location free of flooding. As each driver has their destination, this strategy may not be optimal for all, but only this strategy can assure drivers may not get stuck between two flooded roads.

Reliability bounds should be based on measurements. Portraying normality in the current research is based on 10 different simulations of the trip generation model. The variation between the results of these simulations may not reflect the fluctuations of everyday traffic. Using measurements two models can be calibrated with what is observed as heavy and light traffic. The model results of these simulations can be more representative of the reliability bands of normal conditions.

Implementing combinations of interventions. The PhD thesis analysed how single intervention measures would interact with the traffic dynamics and improve system's resilience. It is interesting to examine how combinations of these strategies would influence the resilience of the described system. Would it contribute to extensive or intensive improvements?

Employ various variables. The framework does not explicitly describe what variables must be used for the resilience assessment. Currently, the number of vehicles in the network is considered the most representative variable to describe system performance, but perhaps other variables can be analysed in future studies as well. The number of waiting vehicles has been discussed as a credible source of information about the system performance but should not be considered in isolation. Aggregating results on travel delays can also be a useful variable to investigate.

Weight indicators to produce and a single description of resilience. The proposed assessment of resilience assessment is based on three individual parameters. If this framework is employed for comparison of intervention scenarios, it might be dubious to select which scenario is best based on independent variables. It might be sensible to express the changes in each as percentiles and then weight them according to the aim of the research. It is not clear whether such logic has been applied for resilience assessment before, but the field of multicriteria evaluation has a wealth of examples for achieving this task.

7.5.3 The wider context of future development

The research identified that the duration and the type of flood event were among the most significant factors for the severity of the consequences. Therefore, a comparison between different flood events in the same location could reveal valuable insight into the way impacts propagate. As far as long-lasting events, it would be useful to prove whether static integration would be enough to describe the involved processes.

Another interesting observation was that in the beginning of the flooding the traffic system was capable of absorbing the capacity restrictions until it reached a tipping point, after which it started deuterating rapidly. Identifying and understanding this tipping point might be crucial for transport managers. Such a tipping point can also facilitate a new definition of reliability and normal conditions in the future.

An assessment of the resilience of interventions parallelly with the assessment of impacts on the emergency services operation can show whether the city/system-level performance indicators would enhance the effectiveness of these services. This matter is potentially a compelling theoretical question about how resilience in a global scale can be downscaled into particular features of a resilient system.

The developed interdisciplinary approach, the PEARL tool and the framework for road-transport resilience assessment relate to the off-line analysis of combined flood and traffic modelling. The methodology lends itself nicely for real-time modelling and decision making for coupled flood and traffic management systems. However, there are several steps that must be addressed. It seems individual city services do act as if urban areas are divided into bureaucratic entities (be it water, electricity, oil and gas, transportation, communications). Assuming different urban infrastructures exist individually may be convenient for administrative purposes, but it does not reflect the interconnectivity and co-dependencies of urban processes. Urban environments have become living organisms where nothing happens in isolation. Hopefully by popularizing the topic of road transport disruptions due to flooding transport and water services will see the mutual benefit of working together and will even push for further development of that field. Perhaps this is not far in the future but until then popularizing the topic would be a way forward. By developing a highly transferable approach and its own software tool the thesis pursued the goal of popularizing this area of research and hopefully soon it will receive its rightful place in the decision-making process.

APPENDICES

Appendix A: Using the PEARL tool

1. Description of the code

To run the flood-traffic integration tool ArcGIS 10.1 or higher is required. Python 2.7, which is typically installed together with ArcGIS, is also necessary. As mentioned previously, the tool can run both from Python and from ArcGIS. Once the scripts are set up with the correct input data and the desired output, they run with a double click of the mouse in Windows Explorer. If the First component is to be run in ArcMap, a toolbox has to be added to the ArcMap Toolbox menu. This operation is described in Section 4.4. The tool itself is free software and can be redistributed and modified under the terms of GNU General Public License, provided by the Free Software Foundation.

2. Description of the interface steps and menus
    a. How to run the first component of the tool?

From ArcGIS.

The tool is saved as a PEARL Toolbox that can be opened in ArcMap by opening the Arc Toolbox (click on the  icon) and add a toolbox (Figure A-0-1). After the location of the toolbox is selected, it shows six models. The PEARLfinal model is a sum of all the other models. The other five models are different sub-models of the PEARLfinal model that can be run in a sequence. The reason to include the submodels into the Toolbox was to make it less computationally expensive and to make the model flexible.

The interface of the models is the standard ArcGIS toolbox interface whereby input and output are required (Figure A-0-2). The right-hand sidebar shows tool help when different lines are selected. The model runs with only three inputs: Workspace folder, flood map in vector format and road network file. The other inputs are either a choice – to change the definitions for shallow and deep flood depths, or specifying names of the output files. The outputs of the model are ready to use for the next component of the tool – the Python code that translated the shapefile output to a SUMO XML input.

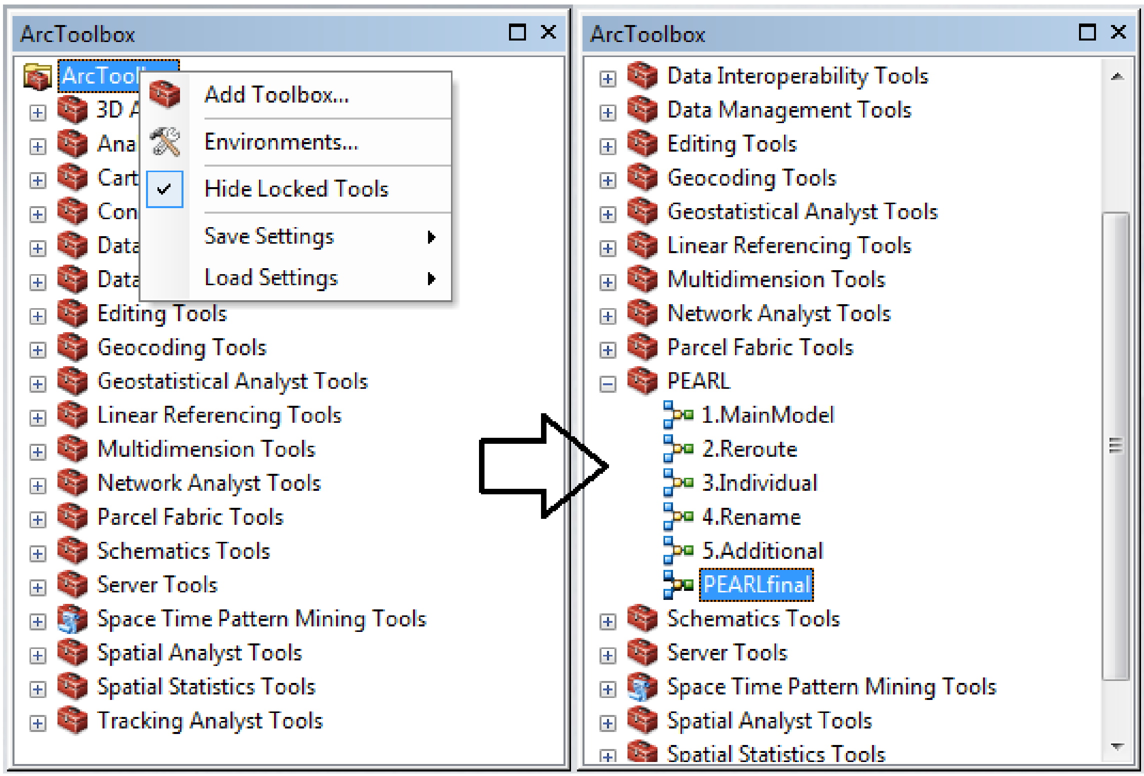


Figure A-0-1: How to add the PEARL toolbox

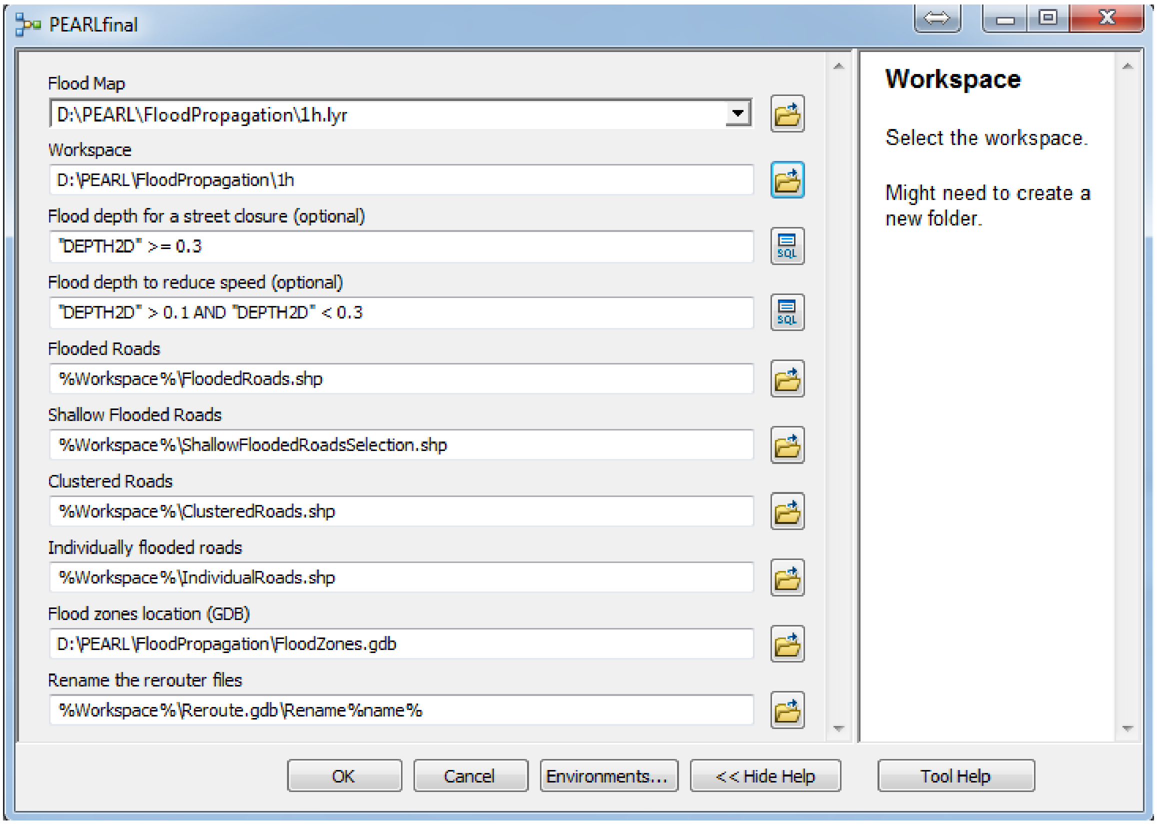


Figure A-0-2: Interface of the tool

1) From Python

The model PEARLfinal is adapted in Python and is recommended for multiple simulations. The Python model is also faster – a sample simulation in ArcMap took 6 min and 22 seconds to complete, and the Python script took 4 min and 12 seconds (Python is 34 % faster) on the same machine to run. The Python script includes comments that explain the individual steps and offer a reminder when user input is required. The Python model is set up in a way that the user input is limited to a minimum in the case of flood propagation multiple simulations. For example, if it is run with input for simulation time 1h, the only thing that has to be changed in order to run it for another simulation time is to find and replace all entries of '1h' with '1h10min' (provided that the simulation time is contained in the name of the flood map). The python script is supplied in Appendix B (p. 183).

b. How to run the second component of the tool

The second component of the tool is a Python script that translates the ArcGIS shapefile output into a SUMO XML input. This script also has added comments to describe different sections of the model and to remind when user input is required. The script is set up in a way that would reduce user input (Appendix C, p. 207). Once the main input folders are set up, the tool can run multiple simulations with a change of the folder name – for example, if all instances of '1h' are replaced by '1h10min'. The adequate naming of files is vital for the correct and execution of the dynamic integration of the flood and traffic models.

Input data set

The tool requires only a few files to run. Table A-0-1 presents all the possible input types for both components of the tool. The grey coloured rows are the first component's input files which are simulated in the tool in the ArcGIS environment. The actions in the yellow rows are necessary only in case of the dynamic integration of the flood propagation. The files remaining is included in the first component, and its purpose is to establish different file names for different time segments (e.g. all file names starting with "1h"). The green rows are the first component's the result files, which are employed by the second component of the tool.

File	First component		Second component	
	Required	Input type	Required	Input type
Road Network	✓	Layer File	✓	SUMO XML
Flood maps	✓	Polygon Shapefile	✗	
Flood Zones	✓	Feature Class in GDB	✗	
Workspace	✓	Folder Location	✓	Folder Location
Rename Files	✓	Manual Input	✗	
Update Simulation Time for SUMO	✗		✓	Manual Input
Reroute Files	✗		✓	Polyline shapefile
Additional Files	✗		✓	Polyline Shapefile
Shallow Flooded Roads	✗		✓	Polyline Shapefile

Table A-0-1: Table of the input files for the two components of the model.

Outputs

The output files of the model are multiple XML files which feed into SUMO's rerouting mechanism. These files are the following:

- Numerous rerouter files that supply SUMO with closure periods of roads during the traffic simulation
- Additional file providing all of the adjacent roads to the closed ones
- The second additional file that contains the roads with speed reductions, the new maximum speed limits and the interval of time that will occur

It is important to note that all additional files must be merged into one before the beginning of the SUMO simulation. In the case of dynamic integration based on flood propagation, hundreds of output files are created, and the specific naming of rerouters is crucial for correct traffic simulation. It is recommended that the names of the rerouter files consist of the time step of the flood map and their original name (example T1hFloodZone1).

Supporting material

The tool is stored in a folder named PEARL. If this folder is directly saved into D disc, the models can be run with the existing scripts. This folder consists of the following folders:

1) 'Tool' folder

  a) Toolbox named 'PEARL' runs from ArcGIS and is the first component of the model contains six models. ‘PEARLfinal’ runs the whole code at ones, and the others are sub-models of ‘PEARLfinal’. They must be run in a sequence shown by the number in their names.

  b) 'Component1' is a Python code that replicates the Toolbox

  c) 'Component2' is a Python code which translates the shapefile input for a) or b) into a SUMO XML file input

2) 'Flood propagation' folder

  a) '1h' folder - the result files from the first component

  b) 'FloodZones' folder - required input for the simulation

  c) 'AllStreets' shapefile - a polyline shapefile of the road network in Marbella.Required input for the simulation.

  d) '1h' polygon shapefile - the flood propagation at 1h of simulation time. Required input for the simulation.

3) 'SUMOtranslation' folder consists of all the outputs of the second component of the model

Appendix B: PEARL Tool Component 1

```
"""

@file    component1.py

@author  Katya Pyatkova

@date    2017-11-30


This script is the first component of a tool that integrates flood model output and traffic

model input. The flood map output must be a shapefile with a vector format. The script requires ArcGIS 10.1 or newer to run.


This tool is developed as a part of the PEARL project (http://www.pearl-fp7.eu/) in the University of Exeter Centre for Water Systems (http://emps.exeter.ac.uk/engineering/research/cws/).


Special thanks to Dr Albert Chen and Prof Slobodan Djordjevic.

"""

# Import arcpy module

import arcpy, os, fnmatch

from arcpy import env


def MainModel():

#Update flood map

    FloodMap = arcpy.GetParameterAsText(0)

    if FloodMap == '#' or not FloodMap:

        FloodMap = r"D:\Marbella\GIS\T100New.lyr"

#Update workspace

    Workspace = arcpy.GetParameterAsText(1)

    if Workspace == '#' or not Workspace:
```

```
        Workspace = r"D:\PEARL\FloodPropagation\1h" # provide a default value if unspecified

    Flood_depth_for_a_street_closure = arcpy.GetParameterAsText(2)
    if Flood_depth_for_a_street_closure == '#' or not Flood_depth_for_a_street_closure:
        Flood_depth_for_a_street_closure = "\"DEPTH2D\" >= 0.3" # provide a default value if unspecified

    Flood_depth_to_reduce_speed = arcpy.GetParameterAsText(3)
    if Flood_depth_to_reduce_speed == '#' or not Flood_depth_to_reduce_speed:
        Flood_depth_to_reduce_speed = "\"DEPTH2D\" > 0.1 AND \"DEPTH2D\" < 0.3" # provide a default value if unspecified

    FloodExtend_shp = arcpy.GetParameterAsText(4)
    if FloodExtend_shp == '#' or not FloodExtend_shp:
        FloodExtend_shp = "%Workspace%\\FloodExtend.shp" # provide a default value if unspecified

    ShalowFloodExtent_shp = arcpy.GetParameterAsText(5)
    if ShalowFloodExtent_shp == '#' or not ShalowFloodExtent_shp:
        ShalowFloodExtent_shp = "%Workspace%\\ShalowFloodExtent.shp" # provide a default value if unspecified

    FloodedRoads_shp = arcpy.GetParameterAsText(6)
    if FloodedRoads_shp == '#' or not FloodedRoads_shp:
        FloodedRoads_shp = "%Workspace%\\FloodedRoads.shp" # provide a default value if unspecified

    ShallowFloodedRoads_shp = arcpy.GetParameterAsText(7)
    if ShallowFloodedRoads_shp == '#' or not ShallowFloodedRoads_shp:
```

```
        ShallowFloodedRoads_shp = "%Workspace%\\ShallowFloodedRoads.shp" # provide a default value if unspecified

    ClusteredRoads_shp = arcpy.GetParameterAsText(8)

    if ClusteredRoads_shp == '#' or not ClusteredRoads_shp:

        ClusteredRoads_shp = "%Workspace%\\ClusteredRoads.shp" # provide a default value if unspecified

    Output__Individually_flooded_roads = arcpy.GetParameterAsText(9)

    if Output__Individually_flooded_roads == '#' or not Output__Individually_flooded_roads:

        Output__Individually_flooded_roads = "%Workspace%\\IndividualRoads.shp" # provide a default value if unspecified

    # Local variables:

    RoadNet = "D:\PEARL\FloodPropagation\AllStreets.shp"

    AllStreets_Layer1 = "AllStreets_Layer"

    AllStreets_Layer1__4_ = AllStreets_Layer1

    AllStreets_Layer1__2_ = AllStreets_Layer1

    ShallowFlood = "%Workspace%\\ShallowFlood"

    ShalowFloodExtent_shp__2_ = ShalowFloodExtent_shp

    ShalowFloodExtent_lyr = "ShalowFloodExtent.lyr"

    ShallowFloodedRoads1_shp = "%Workspace%\\ShallowFloodedRoads1.shp"

    Shallow_flooded_roads1 = "%Workspace%\\ShallowFloodedRoads1.lyr"

    ShallowFloodedRoads1_lyr = Shallow_flooded_roads1

    Flood = "%Workspace%\\Flood"

    FloodExtend_shp__2_ = FloodExtend_shp

    Intesect_shp = "%WorkSpace%\\Intesect.shp"

    ShallowClip_shp = "%Workspace%\\ShallowClip.shp"
```

```
    ShallowClip_Layer = "%Workspace%\\ShallowClip_Layer"

    ShallowClip_Layer__2_ = ShallowClip_Layer

    ShallowClip_Layer__3_ = ShallowClip_Layer__2_

    ShallowTr = "%Workspace%\\ShallowTr"

    ShallowTreshold__2_ = "%Workspace%\\ShallowTreshold"

    FloodedClip_shp = "%Workspace%\\FloodedClip.shp"

    Flooded_Layer = "%Workspace%\\Flooded_Layer"

    Flooded_Layer__2_ = Flooded_Layer

    Output_Feature_Class = Flooded_Layer__2_

    FloodedTr = "%Workspace%\\FloodedTr"

    FloodedTreshold_shp = "%Workspace%\\FloodedTreshold.shp"

    FloodedTreshold_Layer = "FloodedTreshold_Layer"

    FloodedTreshold_Layer__3_ = FloodedTreshold_Layer

    FloodedTreshold_Layer__4_ = FloodedTreshold_Layer

    Flooded_roads_Layer = "%Workspace%\\FloodedRoads"

    FloodedRoads = Flooded_roads_Layer

    FloodedRoads__2_ = Flooded_roads_Layer

    IntersectPoints_shp = "%Workspace%\\IntersectPoints.shp"

    ClusteredRoads_Layer1 = "ClusteredRoads_Layer"

    ClusteredTreshold = "%Workspace%/ClusteredTreshold"

    IndividualThreshold = "%Workspace%/IndividualThreshold"


#Update Geoprocessing environments

    arcpy.env.scratchWorkspace = r"D:\PEARL\FloodPropagation\1h"

    arcpy.env.workspace = r"D:\PEARL\FloodPropagation\1h"


    # Process: Make Feature Layer (5)
```

arcpy.MakeFeatureLayer_management(RoadNet, AllStreets_Layer1, "", "", "FID FID VISIBLE NONE;Shape Shape VISIBLE NONE;OBJECTID OBJECTID VISIBLE NONE;highway highway VISIBLE NONE;building building VISIBLE NONE;natural natural VISIBLE NONE;waterway waterway VISIBLE NONE;amenity amenity VISIBLE NONE;landuse landuse VISIBLE NONE;place place VISIBLE NONE;railway railway VISIBLE NONE;boundary boundary VISIBLE NONE;power power VISIBLE NONE;leisure leisure VISIBLE NONE;man_made man_made VISIBLE NONE;shop shop VISIBLE NONE;tourism tourism VISIBLE NONE;route route VISIBLE NONE;historic historic VISIBLE NONE;aeroway aeroway VISIBLE NONE;aerialway aerialway VISIBLE NONE;barrier barrier VISIBLE NONE;military military VISIBLE NONE;geological geological VISIBLE NONE;OSMID OSMID VISIBLE NONE;osmuser osmuser VISIBLE NONE;osmuid osmuid VISIBLE NONE;osmvisible osmvisible VISIBLE NONE;osmversion osmversion VISIBLE NONE;osmchanges osmchanges VISIBLE NONE;osmtimesta osmtimesta VISIBLE NONE;osmSupport osmSupport VISIBLE NONE;SHAPE_Leng SHAPE_Leng VISIBLE NONE")

Process: Make Feature Layer (9)

arcpy.MakeFeatureLayer_management(FloodMap, ShallowFlood, Flood_depth_to_reduce_speed, "", "FID FID VISIBLE NONE;Shape Shape HIDDEN NONE;zone_id zone_id HIDDEN NONE;element_no element_no VISIBLE NONE;sim_id sim_id HIDDEN NONE;event event HIDDEN NONE;prof_type prof_type HIDDEN NONE;retperiod retperiod HIDDEN NONE;duration duration HIDDEN NONE;ANGLE2D ANGLE2D HIDDEN NONE;CUMINF2D CUMINF2D HIDDEN NONE;DEPTH2D DEPTH2D VISIBLE NONE;EFFINF2D EFFINF2D VISIBLE NONE;elevation2 elevation2 HIDDEN NONE;froude2d froude2d HIDDEN NONE;POTINF2D POTINF2D HIDDEN NONE;SPEED2D SPEED2D HIDDEN NONE;SWCP2D SWCP2D HIDDEN NONE;unitflow2d unitflow2d HIDDEN NONE")

Process: Copy Features (5)

arcpy.CopyFeatures_management(ShallowFlood, ShalowFloodExtent_shp, "", "0", "0", "0")

Process: Repair Geometry (3)

arcpy.RepairGeometry_management(ShalowFloodExtent_shp, "DELETE_NULL")

Process: Make Feature Layer (4)

arcpy.MakeFeatureLayer_management(ShalowFloodExtent_shp__2_, ShalowFloodExtent_lyr, "", "", "FID FID VISIBLE NONE;element_no element_no VISIBLE NONE;DEPTH2D DEPTH2D VISIBLE NONE;EFFINF2D EFFINF2D VISIBLE NONE")

Process: Select Layer By Location (4)

```
arcpy.SelectLayerByLocation_management(AllStreets_Layer1, "INTERSECT", ShalowFloodExtent_lyr, "", "NEW_SELECTION", "NOT_INVERT")

# Process: Copy Features (6)

arcpy.CopyFeatures_management(AllStreets_Layer1__2_, ShallowFloodedRoads1_shp, "", "0", "0", "0")

# Process: Make Feature Layer (3)

arcpy.MakeFeatureLayer_management(ShallowFloodedRoads1_shp, Shallow_flooded_roads1, "", "", "FID FID VISIBLE NONE;Shape Shape VISIBLE NONE;OBJECTID OBJECTID VISIBLE NONE;highway highway VISIBLE NONE;building building VISIBLE NONE;natural natural VISIBLE NONE;waterway waterway VISIBLE NONE;amenity amenity VISIBLE NONE;landuse landuse VISIBLE NONE;place place VISIBLE NONE;railway railway VISIBLE NONE;boundary boundary VISIBLE NONE;power power VISIBLE NONE;leisure leisure VISIBLE NONE;man_made man_made VISIBLE NONE;shop shop VISIBLE NONE;tourism tourism VISIBLE NONE;route route VISIBLE NONE;historic historic VISIBLE NONE;aeroway aeroway VISIBLE NONE;aerialway aerialway VISIBLE NONE;barrier barrier VISIBLE NONE;military military VISIBLE NONE;geological geological VISIBLE NONE;OSMID OSMID VISIBLE NONE;osmuser osmuser VISIBLE NONE;osmuid osmuid VISIBLE NONE;osmvisible osmvisible VISIBLE NONE;osmversion osmversion VISIBLE NONE;osmchanges osmchanges VISIBLE NONE;osmtimesta osmtimesta VISIBLE NONE;osmSupport osmSupport VISIBLE NONE;SHAPE_Leng SHAPE_Leng VISIBLE NONE")

# Process: Make Feature Layer (10)

arcpy.MakeFeatureLayer_management(FloodMap, Flood, Flood_depth_for_a_street_closure, "", "FID FID VISIBLE NONE;Shape Shape HIDDEN NONE;zone_id zone_id HIDDEN NONE;element_no element_no VISIBLE NONE;sim_id sim_id HIDDEN NONE;event event HIDDEN NONE;prof_type prof_type HIDDEN NONE;retperiod retperiod HIDDEN NONE;duration duration HIDDEN NONE;ANGLE2D ANGLE2D HIDDEN NONE;CUMINF2D CUMINF2D HIDDEN NONE;DEPTH2D DEPTH2D VISIBLE NONE;EFFINF2D EFFINF2D HIDDEN NONE;elevation2 elevation2 HIDDEN NONE;froude2d froude2d HIDDEN NONE;POTINF2D POTINF2D HIDDEN NONE;SPEED2D SPEED2D HIDDEN NONE;SWCP2D SWCP2D HIDDEN NONE;unitflow2d unitflow2d HIDDEN NONE")

# Process: Copy Features

arcpy.CopyFeatures_management(Flood, FloodExtend_shp, "", "0", "0", "0")

# Process: Repair Geometry
```

```
arcpy.RepairGeometry_management(FloodExtend_shp, "DELETE_NULL")


# Process: Select Layer By Location

arcpy.SelectLayerByLocation_management(AllStreets_Layer1, "INTERSECT", FloodExtend_shp__2_, "", "NEW_SELECTION", "NOT_INVERT")


# Process: Copy Features (2)

arcpy.CopyFeatures_management(AllStreets_Layer1__4_, FloodedRoads_shp, "", "0", "0", "0")


# Process: Intersect (2)

arcpy.Intersect_analysis("%Workspace%\\FloodedRoads.shp #;%Workspace%\\ShallowFloodedRoads1.lyr #", Intesect_shp, "ALL", "", "LINE")


# Process: Select Layer By Location (5)

arcpy.SelectLayerByLocation_management(Shallow_flooded_roads1, "INTERSECT", Intesect_shp, "", "NEW_SELECTION", "INVERT")


# Process: Copy Features (9)

arcpy.CopyFeatures_management(ShallowFloodedRoads1_lyr, ShallowFloodedRoads_shp, "", "0", "0", "0")


# Process: Clip

arcpy.Clip_analysis(ShallowFloodedRoads_shp, ShalowFloodExtent_shp__2_, ShallowClip_shp, "")


# Process: Make Feature Layer (2)

arcpy.MakeFeatureLayer_management(ShallowClip_shp, ShallowClip_Layer, "", "", "FID FID VISIBLE NONE;Shape Shape VISIBLE NONE;OBJECTID OBJECTID VISIBLE NONE;highway highway VISIBLE NONE;building building VISIBLE NONE;natural natural VISIBLE NONE;waterway waterway VISIBLE NONE;amenity amenity VISIBLE NONE;landuse landuse VISIBLE NONE;place place VISIBLE NONE;railway railway VISIBLE NONE;boundary boundary
```

VISIBLE NONE;power power VISIBLE NONE;leisure leisure VISIBLE NONE;man_made man_made VISIBLE NONE;shop shop VISIBLE NONE;tourism tourism VISIBLE NONE;route route VISIBLE NONE;historic historic VISIBLE NONE;aeroway aeroway VISIBLE NONE;aerialway aerialway VISIBLE NONE;barrier barrier VISIBLE NONE;military military VISIBLE NONE;geological geological VISIBLE NONE;OSMID OSMID VISIBLE NONE;osmuser osmuser VISIBLE NONE;osmuid osmuid VISIBLE NONE;osmvisible osmvisible VISIBLE NONE;osmversion osmversion VISIBLE NONE;osmchanges osmchanges VISIBLE NONE;osmtimesta osmtimesta VISIBLE NONE;osmSupport osmSupport VISIBLE NONE;SHAPE_Leng SHAPE_Leng VISIBLE NONE")

```
    # Process: Add Field

    arcpy.AddField_management(ShallowClip_Layer, "Lenght", "DOUBLE", "", "3", "", "", "NULLABLE", "NON_REQUIRED", "")

    # Process: Calculate Field

    arcpy.CalculateField_management(ShallowClip_Layer__2_, "Lenght", "!shape.length@meters!", "PYTHON", "")

    # Process: Make Feature Layer

    arcpy.MakeFeatureLayer_management(ShallowClip_Layer__3_, ShallowTr, "\"Lenght\" >= 3", "", "FID FID HIDDEN NONE;Shape Shape HIDDEN NONE;OBJECTID OBJECTID HIDDEN NONE;highway highway HIDDEN NONE;building building HIDDEN NONE;natural natural HIDDEN NONE;waterway waterway HIDDEN NONE;amenity amenity HIDDEN NONE;landuse landuse HIDDEN NONE;place place HIDDEN NONE;railway railway HIDDEN NONE;boundary boundary HIDDEN NONE;power power HIDDEN NONE;leisure leisure HIDDEN NONE;man_made man_made HIDDEN NONE;shop shop HIDDEN NONE;tourism tourism HIDDEN NONE;route route HIDDEN NONE;historic historic HIDDEN NONE;aeroway aeroway HIDDEN NONE;aerialway aerialway HIDDEN NONE;barrier barrier HIDDEN NONE;military military HIDDEN NONE;geological geological HIDDEN NONE;OSMID OSMID VISIBLE NONE;osmuser osmuser HIDDEN NONE;osmuid osmuid HIDDEN NONE;osmvisible osmvisible HIDDEN NONE;osmversion osmversion HIDDEN NONE;osmchanges osmchanges HIDDEN NONE;osmtimesta osmtimesta HIDDEN NONE;osmSupport osmSupport HIDDEN NONE;SHAPE_Leng SHAPE_Leng HIDDEN NONE;Lenght Lenght VISIBLE NONE")

    # Process: Copy Features (8)

    arcpy.CopyFeatures_management(ShallowTr, ShallowTreshold__2_, "", "0", "0", "0")

    # Process: Clip (4)
```

```
arcpy.Clip_analysis(FloodedRoads_shp, FloodExtend_shp__2_, FloodedClip_shp, "")

# Process: Make Feature Layer (11)
arcpy.MakeFeatureLayer_management(FloodedClip_shp, Flooded_Layer, "", "", "FID FID HIDDEN NONE;Shape Shape HIDDEN NONE;OBJECTID OBJECTID HIDDEN NONE;highway highway HIDDEN NONE;building building HIDDEN NONE;natural natural HIDDEN NONE;waterway waterway HIDDEN NONE;amenity amenity HIDDEN NONE;landuse landuse HIDDEN NONE;place place HIDDEN NONE;railway railway HIDDEN NONE;boundary boundary HIDDEN NONE;power power HIDDEN NONE;leisure leisure HIDDEN NONE;man_made man_made HIDDEN NONE;shop shop HIDDEN NONE;tourism tourism HIDDEN NONE;route route HIDDEN NONE;historic historic HIDDEN NONE;aeroway aeroway HIDDEN NONE;aerialway aerialway HIDDEN NONE;barrier barrier HIDDEN NONE;military military HIDDEN NONE;geological geological HIDDEN NONE;OSMID OSMID VISIBLE NONE;osmuser osmuser HIDDEN NONE;osmuid osmuid HIDDEN NONE;osmvisible osmvisible HIDDEN NONE;osmversion osmversion HIDDEN NONE;osmchanges osmchanges HIDDEN NONE;osmtimesta osmtimesta HIDDEN NONE;osmSupport osmSupport HIDDEN NONE;SHAPE_Leng SHAPE_Leng HIDDEN NONE")

# Process: Add Field (4)
arcpy.AddField_management(Flooded_Layer, "Lenght", "DOUBLE", "", "3", "", "", "NULLABLE", "NON_REQUIRED", "")

# Process: Calculate Field (4)
arcpy.CalculateField_management(Flooded_Layer__2_, "Lenght", "!shape.length@meters!", "PYTHON", "")

# Process: Make Feature Layer (12)
arcpy.MakeFeatureLayer_management(Output_Feature_Class, FloodedTr, "\"Lenght\" >= 3", "", "OSMID OSMID VISIBLE NONE;Lenght Lenght VISIBLE NONE")

# Process: Copy Features (11)
arcpy.CopyFeatures_management(FloodedTr, FloodedTreshold_shp, "", "0", "0", "0")

# Process: Make Feature Layer (8)
```

arcpy.MakeFeatureLayer_management(FloodedTreshold_shp, FloodedTreshold_Layer, "", "", "OSMID OSMID VISIBLE NONE;Lenght Lenght VISIBLE NONE")

Process: Make Feature Layer (6)

arcpy.MakeFeatureLayer_management(FloodedRoads_shp, Flooded_roads_Layer, "", "", "FID FID VISIBLE NONE;Shape Shape VISIBLE NONE;OBJECTID OBJECTID VISIBLE NONE;highway highway VISIBLE NONE;building building VISIBLE NONE;natural natural VISIBLE NONE;waterway waterway VISIBLE NONE;amenity amenity VISIBLE NONE;landuse landuse VISIBLE NONE;place place VISIBLE NONE;railway railway VISIBLE NONE;boundary boundary VISIBLE NONE;power power VISIBLE NONE;leisure leisure VISIBLE NONE;man_made man_made VISIBLE NONE;shop shop VISIBLE NONE;tourism tourism VISIBLE NONE;route route VISIBLE NONE;historic historic VISIBLE NONE;aeroway aeroway VISIBLE NONE;aerialway aerialway VISIBLE NONE;barrier barrier VISIBLE NONE;military military VISIBLE NONE;geological geological VISIBLE NONE;OSMID OSMID VISIBLE NONE;osmuser osmuser VISIBLE NONE;osmuid osmuid VISIBLE NONE;osmvisible osmvisible VISIBLE NONE;osmversion osmversion VISIBLE NONE;osmchanges osmchanges VISIBLE NONE;osmtimesta osmtimesta VISIBLE NONE;osmSupport osmSupport VISIBLE NONE;SHAPE_Leng SHAPE_Leng VISIBLE NONE")

Process: Intersect

arcpy.Intersect_analysis("AllStreets_Layer #", IntersectPoints_shp, "ALL", "", "POINT")

Process: Select Layer By Location (3)

arcpy.SelectLayerByLocation_management(Flooded_roads_Layer, "WITHIN_A_DISTANCE", IntersectPoints_shp, "2 Meters", "NEW_SELECTION", "NOT_INVERT")

Process: Copy Features (4)

arcpy.CopyFeatures_management(FloodedRoads, ClusteredRoads_shp, "", "0", "0", "0")

Process: Make Feature Layer (7)

arcpy.MakeFeatureLayer_management(ClusteredRoads_shp, ClusteredRoads_Layer1, "", "", "FID FID VISIBLE NONE;Shape Shape VISIBLE NONE;OBJECTID OBJECTID VISIBLE NONE;highway highway VISIBLE NONE;building building VISIBLE NONE;natural natural VISIBLE NONE;waterway waterway VISIBLE NONE;amenity amenity VISIBLE NONE;landuse landuse VISIBLE NONE;place place VISIBLE NONE;railway railway VISIBLE NONE;boundary boundary VISIBLE NONE;power power VISIBLE NONE;leisure leisure VISIBLE NONE;man_made man_made VISIBLE NONE;shop shop VISIBLE NONE;tourism tourism VISIBLE NONE;route route VISIBLE NONE;historic historic VISIBLE NONE;aeroway aeroway

```
VISIBLE NONE;aerialway aerialway VISIBLE NONE;barrier barrier VISIBLE NONE;military military VISIBLE NONE;geological geological VISIBLE NONE;OSMID OSMID VISIBLE NONE;osmuser osmuser VISIBLE NONE;osmuid osmuid VISIBLE NONE;osmvisible osmvisible VISIBLE NONE;osmversion osmversion VISIBLE NONE;osmchanges osmchanges VISIBLE NONE;osmtimesta osmtimesta VISIBLE NONE;osmSupport osmSupport VISIBLE NONE;SHAPE_Leng SHAPE_Leng VISIBLE NONE")


    # Process: Select Layer By Location (2)

    arcpy.SelectLayerByLocation_management(FloodedTreshold_Layer, "INTERSECT", ClusteredRoads_Layer1, "", "NEW_SELECTION", "NOT_INVERT")


    # Process: Copy Features (3)

    arcpy.CopyFeatures_management(FloodedTreshold_Layer__3_, ClusteredTreshold, "", "0", "0", "0")


    # Process: Select Layer By Location (6)

    arcpy.SelectLayerByLocation_management(Flooded_roads_Layer, "ARE_IDENTICAL_TO", ClusteredRoads_shp, "", "NEW_SELECTION", "INVERT")


    # Process: Copy Features (7)

    arcpy.CopyFeatures_management(FloodedRoads__2_, Output__Individually_flooded_roads, "", "0", "0", "0")


    # Process: Select Layer By Location (7)

    arcpy.SelectLayerByLocation_management(FloodedTreshold_Layer, "INTERSECT", Output__Individually_flooded_roads, "", "NEW_SELECTION", "NOT_INVERT")


    # Process: Copy Features (10)

    arcpy.CopyFeatures_management(FloodedTreshold_Layer__4_, IndividualThreshold, "", "0", "0", "0")


    #Create a  File Geodatabase for the Rerouter files
```

```
    arcpy.CreateFileGDB_management ("%Workspace%", "Reroute", "CURRENT")

    #Create a  File Geodatabase for the Additional files

    arcpy.CreateFileGDB_management ("%Workspace%", "Additional", "CURRENT")
def reroute():
    arcpy.env.workspace = r"D:\PEARL\FloodPropagation\FloodZones.gdb"
#Update file location
    ClusteredRoads_shp = r"D:\PEARL\FloodPropagation\1h\ClusteredRoads.shp"

    outputFC = arcpy.GetParameterAsText(2)

    fcs = arcpy.ListFeatureClasses()

    for fc in fcs:
        print str("processing " + fc)
        field = "FILENAME"
        expression = str(fc) #populates field
#Update path
        output_path="D://PEARL//FloodPropagation//1h//Reroute.gdb//"

        arcpy.Clip_analysis(ClusteredRoads_shp, fc, output_path+str(fc), "")

def individual():
    IndividualRoads_shp = "%Workspace%\\IndividualRoads.shp"
    Individual = "%Workspace%\\Reroute.gdb\\Individual"
```

```
    Reroute_gdb = "%Workspace%\\Reroute.gdb"

    Reroute_gdb__3_ = Reroute_gdb


#Update workspace

    Workspace = "D://PEARL//FloodPropagation//1h//"


#Update Geoprocessing environments

    arcpy.env.scratchWorkspace = r"D:\PEARL\FloodPropagation\1h"

    arcpy.env.workspace = r"D:\PEARL\FloodPropagation\1h"


    # Process: Feature Class to Feature Class

    arcpy.FeatureClassToFeatureClass_conversion(IndividualRoads_shp, Reroute_gdb, "Individual", "", "OBJECTID \"OBJECTID\" true true false 10 Long 0 10 ,First,#,%Workspace%\\IndividualRoads.shp,OBJECTID,-1,-1;OSMID \"OSMID\" true true false 20 Text 0 0 ,First,#,%Workspace%\\IndividualRoads.shp,OSMID,-1,-1;SHAPE_Leng \"SHAPE_Leng\" true true false 19 Double 0 0 ,First,#,%Workspace%\\IndividualRoads.shp,SHAPE_Leng,-1,-1", "")


    # Process: Split By Attributes

    arcpy.SplitByAttributes_analysis(Individual, Reroute_gdb, "OBJECTID")


#Update path to delete the indivual file that was used for Split by attributes

    arcpy.Delete_management("D:\\PEARL\\FloodPropagation\\1h\\Reroute.gdb\\Individual")


def delete():


#Update path

    arcpy.env.workspace =r"D:\PEARL\FloodPropagation\1h\Reroute.gdb"
```

```
    fcs = arcpy.ListFeatureClasses()

    for fc in fcs:

        if int(arcpy.GetCount_management(fc).getOutput(0)) == 0:
          print str("Delete "+ fc)
          arcpy.Delete_management(fc)


def rename():

#Update path
    arcpy.env.workspace = r"D:\PEARL\FloodPropagation\1h\Reroute.gdb"

#Update path
    newpath = r"D:\PEARL\FloodPropagation\1h\Reroute"
    if not os.path.exists(newpath):
        os.makedirs(newpath)

    fcs = arcpy.ListFeatureClasses()

    for fc in fcs:
        print str("renaming " + fc)

# Update name to rename
        arcpy.Rename_management(fc, "T1h"+str(fc), "")
```

```
        print str("moving to Reroute")


# Update name to move the folder

        arcpy.FeatureClassToShapefile_conversion("T2h"+str(fc), newpath)


def additional():


#Workspace

    arcpy.env.workspace =r"D:\PEARL\FloodPropagation\1h\Reroute.gdb"


#Update output path for the feature classes

    output_path="D:\\PEARL\\FloodPropagation\\1h\\Additional.gdb\\"


#Update new path

    newpath = "D:\\PEARL\\FloodPropagation\\1h\\Additional"

    if not os.path.exists(newpath):

        os.makedirs(newpath)


    #Overwriting output is important for processing the iteration because it needs to everwrite file
Selection.shp each time

    arcpy.env.overwriteOutput = True


    #Road network file

    AllStre

ets = r"D:\PEARL\FloodPropagation\AllStreets.shp"

    #Make a feature layer for the road network (1)
```

```
arcpy.MakeFeatureLayer_management("D:\PEARL\FloodPropagation\AllStreets.shp","AllStreets_lyr")

    fcs = arcpy.ListFeatureClasses()

    for fc in fcs:
        print str("processing " + fc)

        #Make a feature layer for the flooded roads (2)
        arcpy.MakeFeatureLayer_management(fc,"layer_lyr")

        # Process: Select Layer By Location (1)
        arcpy.SelectLayerByLocation_management("AllStreets_lyr", "WITHIN_A_DISTANCE", "layer_lyr", "2 Meters", "NEW_SELECTION", "NOT_INVERT")

        # Process: Copy Features
        arcpy.CopyFeatures_management("AllStreets_lyr", r"D:\PEARL\FloodPropagation\Selection_shp", "", "0", "0", "0")

        #Make a feature layer for the selection (3)
        arcpy.MakeFeatureLayer_management("AllStreets_lyr","Selection_lyr")

        # Process: Select Layer By Location - select only the adjacent to the flooded roads(2)
        arcpy.SelectLayerByLocation_management("Selection_lyr", "ARE_IDENTICAL_TO", "layer_lyr", "", "NEW_SELECTION", "INVERT")

        # Process: Copy Features (3)
        arcpy.CopyFeatures_management("Selection_lyr", output_path+str(fc), "", "0", "0", "0")
```

```
        # Process: Feature Class To Shapefile (multiple) - converts the feature clases into shape files

        arcpy.FeatureClassToShapefile_conversion(output_path+str(fc), newpath)

        print str("Moving to "+str(newpath))


MainModel()

reroute()

individual()

delete()

rename()

additional()
```

Appendix C: PEARL Tool Component 2

```
"""

@file    component2.py

@author  Katya Pyatkova

@date    2017-11-30
```

This script is the second component of a tool that integrates flood model output and traffic model input. It translates shapefiles, produced by the first component, into a readable SUMO input of additional.add.xml and reouter.def.xml files.

This tool is developed as a part of PEARL (http://www.pearl-fp7.eu/) in the University of Exeter Centre for Water Systems (http://emps.exeter.ac.uk/engineering/research/cws/).

Special thanks to Dr Albert Chen, Prof Slobodan Djordjevic and Alexander Pyatkov.

```
"""


#This model processes data from ArcGIS into readable input for SUMO

import arcpy

import csv

import glob

import xml.etree.ElementTree as ET



def reroute():

    # This script creates rerouter files from the shapefiles created in ArcMap

    # It saves the values of column OSMID



#Update

    arcpy.env.workspace = r"D:\Marbella\GIS\FloodPropagation3\1h\Reroute"



    shapefileList = arcpy.ListFeatureClasses("*.shp")

    for table in shapefileList:

        fieldList = arcpy.ListFields(table)

        field_names = [field.name for field in fieldList]
```

```
    f = open("R_"+ str(table)+".def.xml", 'w')

    w = csv.writer(f, lineterminator='\n')

    f.write('<rerouter id = "'+ str(table)+'">\n\n')


#Update values for the interval for the street closures in SUMO simulation

    f.write('   <interval begin = "114001" end ="114600">\n\n') #from 7:40 AM to 7:50 AM


    for row in arcpy.SearchCursor(table):

        field_vals = []

        for field in fieldList:

            if field.name == "OSMID":

                val = row.getValue(field.name)

                # See if it's a geometry field; if so, use WKT

                try:

                    val = val.WKT

                except AttributeError:

                    # It's not a geometry, and that's okay

                    pass

                field_vals.append(val)

                streets = field_vals[0].encode("latin-1") # That way displays the string without the
UNICODE inherent from ARCGIS

                f.write('       <closingReroute id = "' + streets + '" />\n')

                f.write('       <closingReroute id = "-' + streets + '" />\n')


    f.write('\n    </interval>\n\n</rerouter>\n\n')


def edges():
```

```
#Road network map from SUMO is required
    tree = ET.parse('map.net.xml')
    root = tree.getroot()
    file = open('edges.txt','w')

    edges = []
    for edge in root.findall('edge'):
        identify = edge.get('id')
        # print identify

        file.write("%s\n" % identify)
    file.close()
    print ('edges file created')


def check():
#This scripts checks whether the streets selected for closure exist in the road
#network. The previous scripts assume that all roads have 2 directions, which is
#not always the case in Marbella. The script deletes the entries that are not in the
#road network file and removes non-existing road directions.



    with open('edges.txt') as f:
     content = f.read().splitlines()


#Update the path
```

```
    path = 'C:/Marbella/OSM/116/Flood/Dynamic/Morning/1h/*.shp.def.xml'
    files=glob.glob(path)
    for file in files:


        tree = ET.parse(file)
        root = tree.getroot()
        print (file)


        for parent in root.findall('interval'):
            for line in parent.findall('closingReroute'):
                identify=line.get('id')
                print (identify)


                if identify not in content:
                    print 'no'
                    parent.remove(line)




                tree = ET.ElementTree(root)
        tree.write(file)


    f.close()


def neededlanes():
#This script saves all of the lanes from the road network file and
#prepares all of the lanes with shallow flood depth in another file
```

```
    tree = ET.parse('map.net.xml') #road network file
    root = tree.getroot()
    file = open('lanes.txt','w')

    lanes = []
    for lane in root.iter('lane'):
        identify = lane.get('id')
        # print lane.attrib

        file.write("%s\n" % identify)
    file.close()

#Update workspace
    arcpy.env.workspace = r"D:\Marbella\GIS\FloodPropagation3\1h"
    f = open("RoadsShallowDepth.txt", 'w')
    w = csv.writer(f, lineterminator='\n')

    shapefileList = arcpy.ListFeatureClasses("ShallowFloodedRoads.shp")
    for table in shapefileList:
        fieldList = arcpy.ListFields(table)
        field_names = [field.name for field in fieldList]

        for row in arcpy.SearchCursor(table):

            field_vals = []
            for field in fieldList:
                if field.name == "OSMID":
```

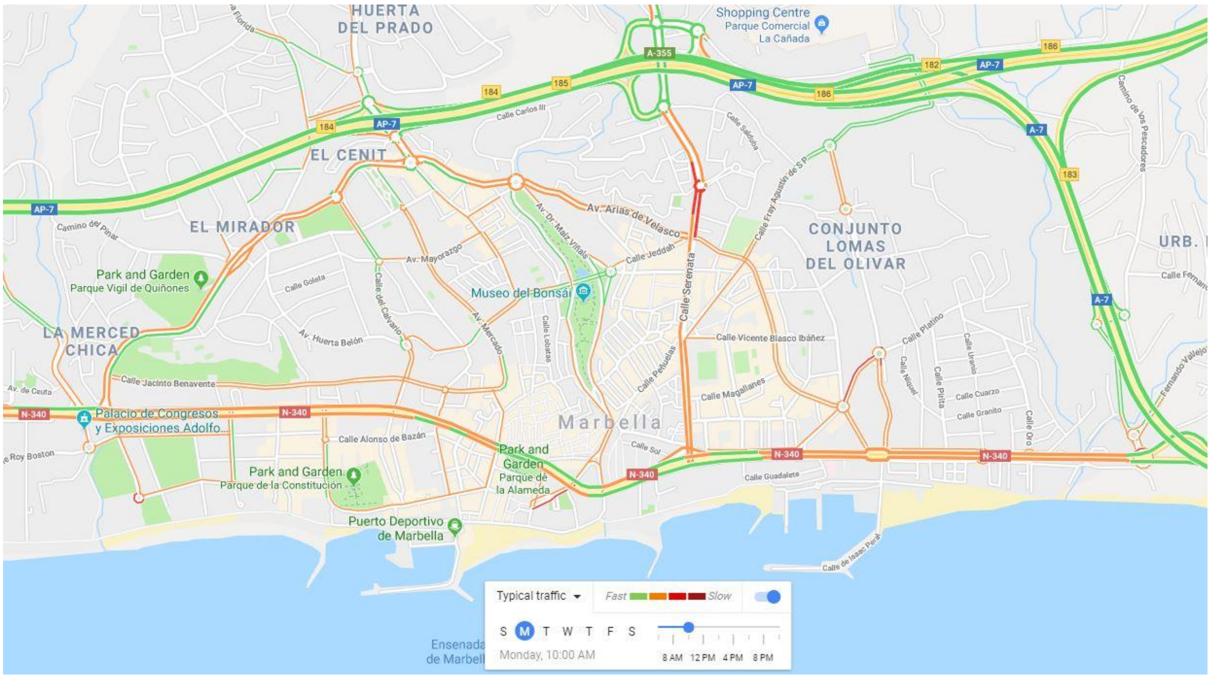
```
            val = row.getValue(field.name)

            # See if it's a geometry field; if so, use WKT

            try:

                val = val.WKT

            except AttributeError:

                # It's not a geometry, and that's okay

                pass

            field_vals.append(val)

            streets = field_vals[0].encode("latin-1") # That way displays the string without the UNICODE inherent from ARCGIS

            # writes streets with 2 lanes per direction

            f.write(''+streets+'_0\n-'+streets+'_0\n' +streets+'_1\n-'+streets+'_1\n')


    f.close


def VSS():

#This script compares the existing lanes with the written in file RoadsShallowDepth.txt.

#It saves the matching ones into a new additional file

    f = open('lanes.txt', 'r')

    f_match = open('RoadsShallowDepth.txt', 'r')

    f_output = open("VSSlanesMore.add.xml", 'w')




    f_output.write('<additional xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNamespaceSchemaLocation="http://sumo-sim.org/xsd/additional_file.xsd">\n\n')

    dictionary = []

    for line in f:

        a = line.split()
```

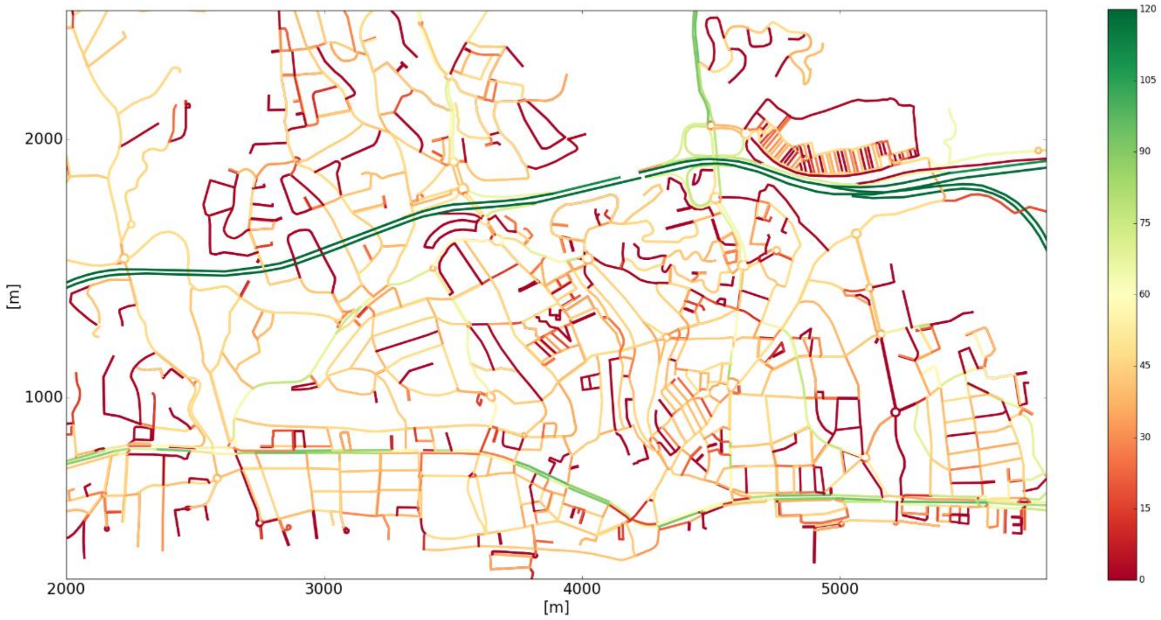
```
        dictionary.append(a)

    i=0

    for line in f_match:

        if line.split() in dictionary:

            i=i+1

            matchingLanes=line.split()

            print str(matchingLanes)


#Update the id of the VSS

            f_output.write('   <variableSpeedSign id="1h'+str(i)+'" lanes="')

            f_output.write(" \n ".join(str(line) for line in matchingLanes))




            f_output.write('" >\n\n')

#Update time steps

            f_output.write('        <step speed="5.56" time="114001" />\n\n') # 20 km/h starting from
7AM

            f_output.write('      <step speed="13.89" time="114600" />\n\n') #50 km/h starting from 11
AM

            f_output.write('  </variableSpeedSign> \n\n')


    f_output.write('</additional>')

    f_output.close


reroute()

edges()

check()

neededlanes()
```

VSS()

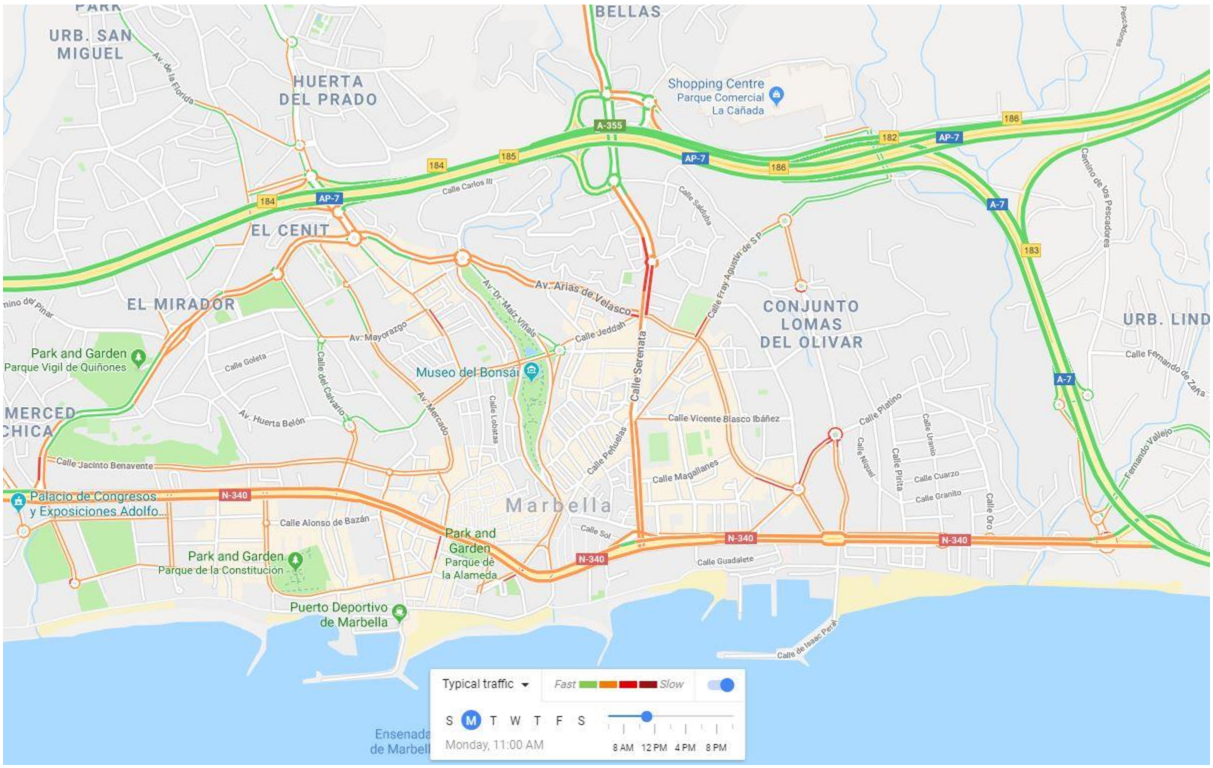
Appendix D: Traffic model validation

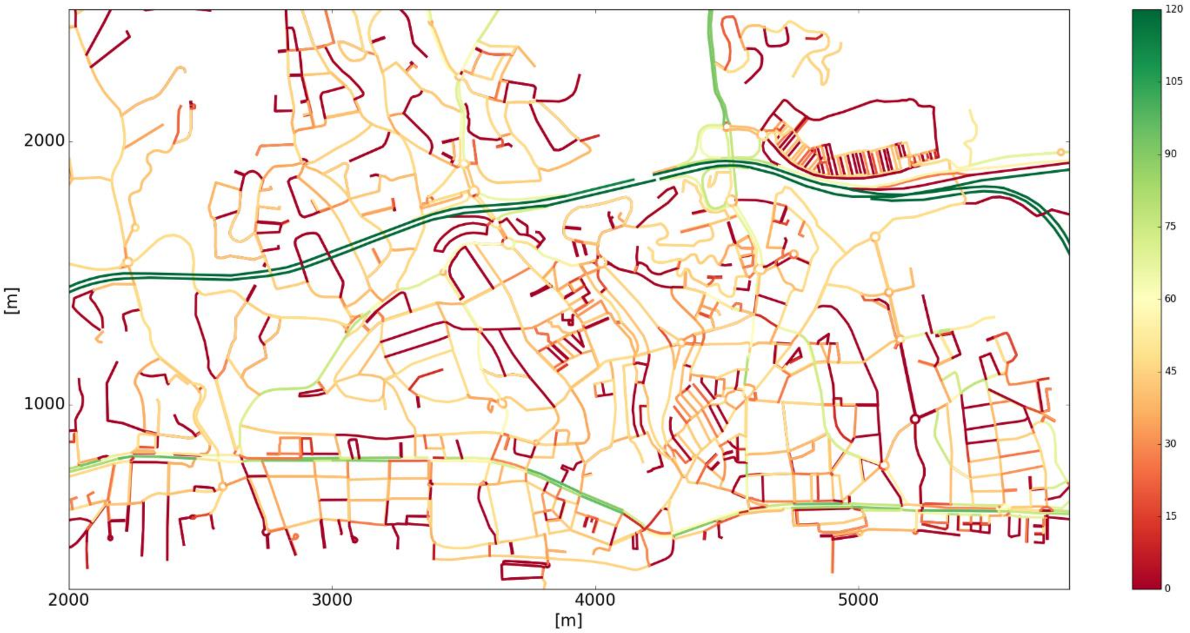
Validation of traffic results using Google traffic at 10 AM



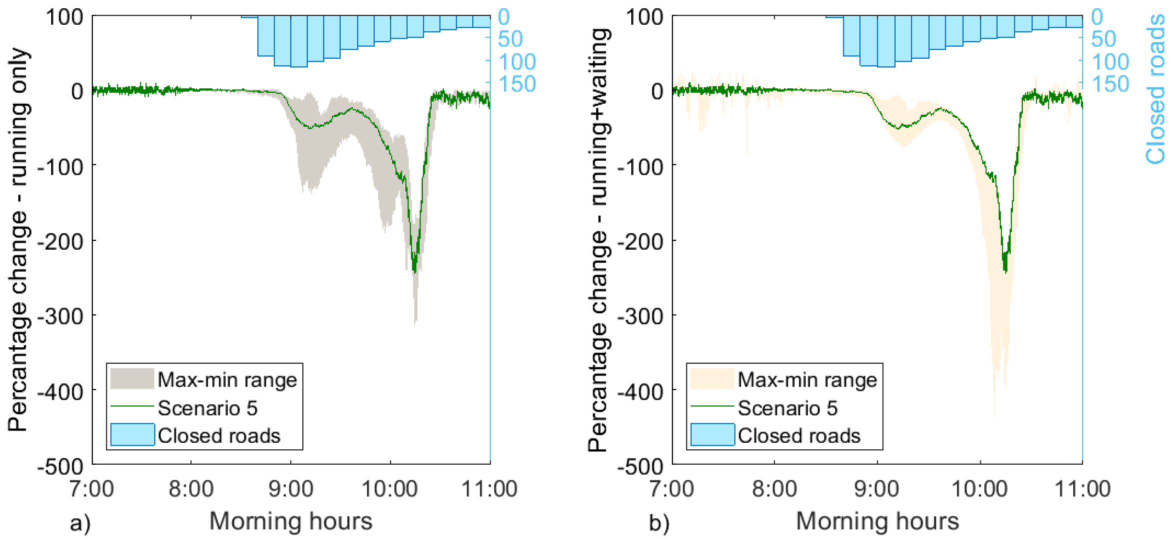


Validation of traffic results using Google traffic at 11 AM





Appendix E: Selecting a representative scenario



Percentage change in number vehicles between normal and flooded conditions when: a) only the running vehicles are considered; b) both the running and the waiting vehicles are considered

Appendix F: Publications

Pyatkova K, Chen AS, Djordjević S, Butler D, Vojinović Z, Abebe YA, Hammond M. (2015) Flood Impacts on Road Transportation Using Microscopic Traffic Modelling Techniques, 3rd Simulation of Urban Mobility Conference (SUMO), Berlin, Germany, 7th - 8th May 2015

Pyatkova, K., Chen, A.S., Djordjević, S., Butler, D., Vojinović, Z., Abebe, Y.A., Hammond, M., 2019. Flood Impacts on Road Transportation Using Microscopic Traffic Modelling Techniques, in Simulating Urban Traffic Scenarios, Lecture Notes in Mobility. Springer, Cham, pp. 115–126. https://doi.org/10.1007/978-3-319-33616-9_8

Pyatkova, K., Chen, A.S., Butler, D., Djordjević, S., 2019. Modelling Road Transport Congestion Due to Flooding, in Mannina, G. (Ed.), New Trends in Urban Drainage Modelling, Green Energy and Technology. Springer International Publishing, pp. 517–521.

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