The indirect impact of flooding on the road transport network: A case study of Santarém region in Portugal

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The indirect impacts of flooding on transportation networks include, among others, consequences of the service disruption for the users. Indirect impacts are of a wider scale and with a longer incidence in time than direct impacts. The key aspect for the quantification of indirect impacts of flooding is the assessment of the disruption of the transportation service, with social and economic consequences. In this work, a traffic model for a pilot zone is constructed for accurate quantification of the functionality of the network after the failure of infrastructure components such as road segments and bridges. A mesoscopic simulation, which is capable of building a road network model, assigning trip paths with the impact of road closures, and evaluating travel time and vehicle volume redistribution in a given disruption scenario, was used to identify the traffic disruption in the face of flood events. Modelling outputs from a case study in the Santarém region of Portugal indicate which roads are more congested in a day. A comparison between the baseline and a flood scenario yields the impacts of that flood on traffic, estimated in terms of additional travel times and travel distances. Therefore, simulating and mapping the congestion can largely facilitate the identification of vulnerable links.

Keywords: Road networks, Traffic disruption, Indirect flood impacts, mesoscopic simulation.

1. Introduction

The occurrence of natural hazard events, such as floods, has led in the past to severe impacts to transportation networks and consequently to its users and the society that rely on their proper performance. For instance, in December 2019 two powerful storms struck the Iberian Peninsula in less than a week, causing severe floods and winds. In central Portugal, the heavy rain disrupted train services after flooding on the rail tracks, brought down power lines so thousands of people were without electricity, and caused disruption and damages to road infrastructures, namely embankments, slopes, and culverts. The impacts were estimated in €7.7 million by the Médio Tejo Intermunicipal Community (CIMT) (Agencia Lusa 2020). This region has been identified by the Portuguese Environment Agency (APA) as the river basin district with the largest proportion of affected population due to floods, where the greatest investments are needed to implement several measures for reducing the catastrophic impacts. In fact, within the plan of measures to elaborate for the period between 2016 and 2021, a total of 81 measures, estimated in €70 million, were needed (APA and MODULERS 2014). The proposed measures, ordered from the highest to the lowest investments, varied among structural measures, green measures, reduction of exposure,

Proceedings of the 30th European Safety and Reliability Conference and
the 15th Probabilistic Safety Assessment and Management Conference.
Edited by Piero Baraldi, Francesco Di Maio and Enrico Zio
Published by Research Publishing, Singapore
ISBN: 981-973-0000-00-0 :: doi: 10.3850/981-973-0000-00-0 esrel2020psam15-paper

reduction of vulnerability, and learning and recovery.

Vulnerability reduction of a road transport network can be achieved either by increasing the capacity of road infrastructure components through structural measures, or by decreasing the impacts of flooding. These impacts may be classified as direct, i.e. caused directly by the flood event including casualties, injuries, and physical damage to the infrastructure; and indirect, resulting from the unavailability of the damaged transport infrastructure, e.g. additional travel time and travel distance, and the loss of access to certain areas (Erath and Alexander Lucas 2011). Indirect impacts due to rerouting traffic as a consequence of floods have been found to be potentially larger than direct impacts (Pregnolato et al. 2020). Consequently, it is fundamental to carefully examine these impacts in order to define efficient management strategies for decreasing the road transport vulnerability.

The key aspect for the quantification of indirect impacts of flooding consists of reliably assess the magnitude of the disruption of the transportation service. To this end, traffic models have been used to understand the behavior of road networks under disruption scenarios, i.e. to simulate how the traffic flows through an impaired network with closed links, while satisfying both demand and capacity (e.g. (Liu et al. 2018)). Most approaches found in literature have used macroscopic traffic models for this purpose. This modelling approach is capable of representing a large region but cannot represent individual vehicles or people on the network. Thus, the dynamics of the transportation system during a flooding event cannot be properly addressed. Conversely, other modelling approaches such as microscopic simulation provides very precise results since individual vehicles are tracked on the network at small time steps. However, microsimulation is rarely used to represent large geographical areas since the computational cost and the level of detail needed regarding the input data makes this modelling approach prohibitive. Thereby, mesoscopic simulation which falls between these two modeling approaches can portray a feasible alternative for the assessment of flood impacts in transportation networks. Mesoscopic modeling can represent large geographic areas with more precise results than macroscopic simulation since vehicles in the transport system are represented, while the computational cost is reasonably lower in comparison to micro-simulation. In fact, this modelling approach has been recommended at regional scale for evacuation planning purposes after natural hazard events (Hardy and Wunderlich 2007).

In this work, a traffic model for a pilot zone is constructed for accurate quantification of the functionality loss of the road network after the failure of infrastructure components such as roads and bridges. For this purpose, a mesoscopic simulation was used to build the road network model, assigning trip paths with the impact of road closures, and evaluating travel time and vehicle volume redistribution for a given disruption scenario. The impact of the road closures was thus measured by means of additional travel time at each link. Therefore, this allowed to identify the most vulnerable links causing a severe loss of functionality on the road transport network in the face of flood events.

2. Methodology

The static framework for the incorporation of flood condition into a mesoscopic traffic model is illustrated in Figure 1.

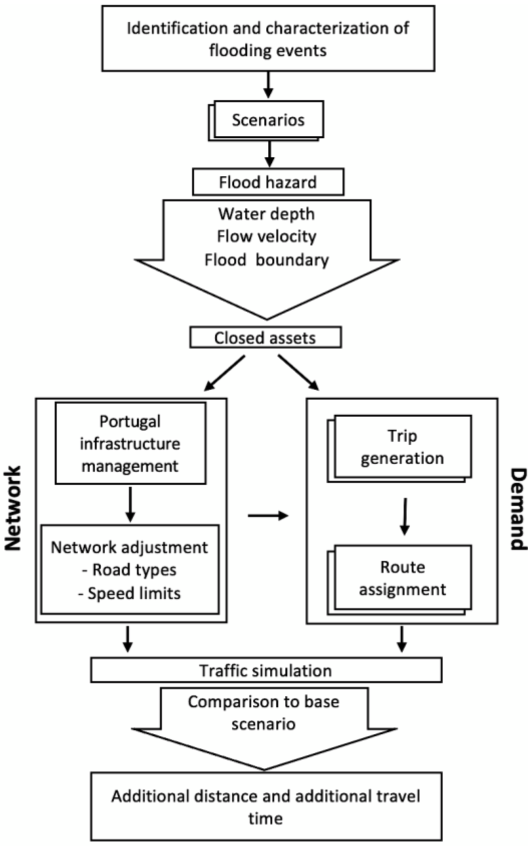

Fig. 1. Flowchart of the methodology.

The following flood intensity in terms of depth, speed and propagation determines if a link in the road network will be closed to the traffic. This closure would affect the trips in the road network and leads to route assignment changes. Routes passing through a flooded area will be rerouted to initially undesired routes, and trips with an origin or destination in the flooded links will be cancelled.

It is assumed that drivers have information about the flooded and closed parts of the network, and the rerouting process in their mind is done before starting their trips. This rerouting process and new route assignments happens based on the fastest-path computation at the time of departure which prevents all vehicles from driving blindly into the same jam.

In this research a mesoscopic simulation has been employed for the assessment of flood impacts. With a mesoscopic modeling technique, the trips must be computed for each travel mode in the network. Mesoscopic simulation computes vehicle movements with queues and runs up to 100 times faster than the microscopic modelling. Additionally, due to using a coarser model, it is more tolerant of network modelling errors than micro-simulation. Generally, there are several reasons to adopt a meso-simulation technique for the assessment of flood impacts. First, a meso-simulation technique facilitates a more detailed representation of the traffic processes than the macroscopic simulation. Second, mesoscopic transport modeling simulates every single vehicle in the transport system. Third, it is capable of modeling different transport modes and driving behaviors. Finally, a comprehensive representation of congestions and the intermodal description of different vehicle types could be achieved by mesoscopic traffic models.

For situations with and without flooding, the outcomes of the traffic simulations will be compared. The results will be presented in terms of additional travel times. Using this method, the effects of flood risk management and traffic improvement systems can be evaluated.

The traffic model used in this paper is SUMO (Simulation of Urban Mobility) (Krajzewicz et al. 2012). It is an open-source model with free scripts and different schemes.

3. Santarém case study

Santarém district is located in central Portugal and lies along the Tagus River. The lower valley of the Tagus River is where the more extreme flood events in Portugal have occurred, resulting in an extensive flood plain (over 800 km^2) which ends completely submerged during the largest floods (Ramos and Reis 2002). An example of indirect impacts that often occur in the Tagus basin consists of closed roads, i.e. cut-off over a period of one or more weeks by flooding. Given the strategic importance of the Tagus valley to agriculture and groundwater resources within Portugal, such events have led to significant economic consequences, as well as harmful social and health conditions (Santos et al. 2020a).

In order to quantify the functionality loss of the road network under flooding events, the first task consists of identifying the exposure of the infrastructure assets. This can be achieved through geographical coincidence of flood hazard maps with the road network. The EU directive 2007/60/CE on the assessment and management of flood risks, established the need for elaborating hazard and risk maps for several return periods. Consequently, flood hazard (water depth, flow velocity, inundation boundary), consequence and risk maps were elaborated for Portugal for several return periods (20, 100, 1000 years), and are accessible to the general public on a Web GIS portal[1] (APA and MODULERS 2014) . Figure 2 depicts the inundation boundary corresponding to a 100-year flood in the Santarém region. The spatial extent of the inundation covers a significant area of both agricultural lands and critical infrastructures such as sensitive buildings (hospitals, schools, fire stations, cultural heritage etc.), and road and rail transportation networks.

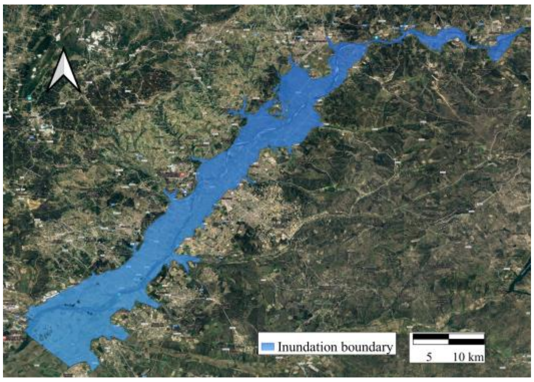

Fig. 2. 100-year flood inundation boundary

The following task consists of determining the fragility of the infrastructure components given their exposure, i.e., the probability of exceeding an undesirable limit state for a given magnitude of the hazard. In this study, the service disruption is assumed to be associated to floodwater on a road. Essentially, the road is assumed to be impassable when the limit of 30 cm is reached as suggested by (Pregnolato et al. 2020). It should be noted that

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[1] https://sniamb.apambiente.pt/

the service disruption can also occur due to physical damage to different assets, e.g., collapse of a bridge. Either way, the disruption scenario can be simulated through the closure of the corresponding link in the traffic model.

4. Traffic model

The road network details were obtained from Infraestruturas de Portugal (IP), a public organization managing the largest stock of assets in Portugal, ensuring all street types and their corresponding speed limits are correct. The closed streets and their closure duration could be understandable from the flood maps. The water depth map corresponding to a 100-year flood was selected for this study, as this return period is often the key design criterion in flood risk management. In other words, the flood was described in the model by a single flood map with a fixed duration specified for the whole network. Figure 3 illustrates the location of the flooded area in the transportation network by overlaying the road network with the maximum flood depth in a GIS environment.

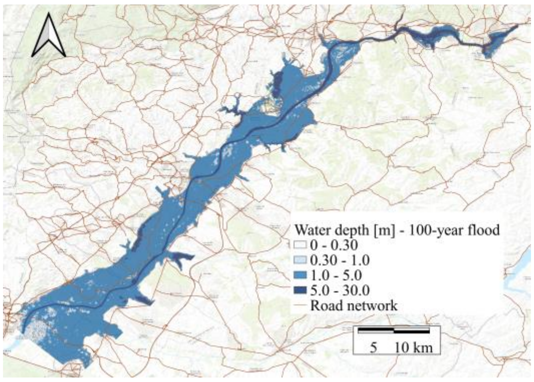

Fig. 3. Overlapping of the roadway network with water depth map for a 100-year flood

From this overlapping procedure, 23 national and municipal roads were found to be impassable due to a 100-year flood as it is shown in Figure 4. Thus, the functionality loss of the road network on the face of this failure scenario was investigated. It is worth mentioning that the definition of this scenario was corroborated with information available regarding damage surveys from past flood events occurring on the Santarém region, which were provided by the National Authority of Civil Protection[2] from Portugal. Moreover, the duration of this scenario may be reasonably assumed as 1 day, since the occurrences recorded by the Civil Protection during past flooding events lasted between 15 to 27 hours.

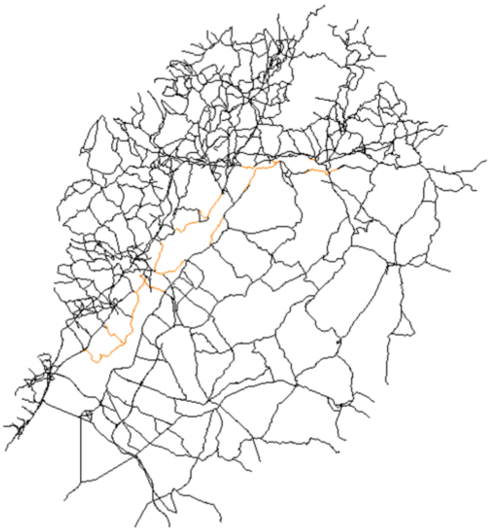

Fig. 4. Closed assets (in orange) by flood disruption.

All traffic models are comprised of two main parts: traffic supply and traffic demand. Traffic supply determines the capacity of the infrastructures and traffic demand describes the behavior of travelers. Traffic modelling simulates how these two components interact with each other, different elements of this model and their integration were shown in Figure 1. In traffic demand modelling a trip is defined with starting point (origin), end point (destination) and beginning time. Using a mesoscopic modelling technique, the trips could be computed for every vehicle in the network. The traffic demand data of the pilot zone was obtained from IP. A constant demand was assumed, i.e. users do not change their travel mode because of the flooding.

Generally, Santarém has a strong road transportation system but there is a factor that may affect mobility in this network. Since drivers may not be allowed to make a U-turn before the flooded section of a road, existence of a large number of one-directional roads could limit rerouting options. Following the definition of trips, a route assignment model should be used to compute the most likely routes to connect origins and destinations. This model was represented by an alternative to the iterative user assignment which name is incremental assignment. In this case each vehicle computed a fastest-path computation at the time of departure which prevented all vehicles from driving blindly into

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[2] http://www.prociv.pt/

the same jam. As a result, rather than assuming that cars travel in isolation, their travel times were calculated as interacting participants of the travel system. The primary assumption in this approach was that drivers have perfect knowledge of the traffic system, which is reasonable in commuter traffic.

5. Results and discussion

The static approach has been the most standard approach for integration of floods and traffic models (Chang et al. 2010; Suarez et al. 2005). Thus, to address the effects of flooding on road transportation network, the simulation was run with static flood condition as described in the previous chapter. The characteristics of the 23 national and municipal roads (0.004% of the total number of roads in the traffic network), that were found to be impassable due to a 100-year flood, are listed in Table 1. In traffic modelling, the proportions of flooded streets are less important than the locations and the capacities of these roads. Thus, the functionality loss of the road network on the face of this failure scenario was investigated.

Table 1. Number and length of flooded streets. The deep flooding (above 0.3 m) will lead to street closure.

Number of closed streets	Proportion to the whole network	Length of streets (m)	Proportion to the overall length of the network
23	0.004	123857.448	0.015

Static integration necessitates the closing of all flooded streets at the same time. On this stage, determining the duration of the flood-induced closures in the traffic model is necessary. In this study the traffic conditions were simulated with flood duration of a full day. Tables 2 and 3 present changes in travel distance and time delays for the flood event, respectively. The overall travel time rose to 211479 hours, and the additional travel distance increased by 2406.622 km.

Table 2. Flood induced changes in travel distance.

Travelled distance	Regular conditions	Flooded conditions
Sum (km)	14898961.606	15139623.812
Absolute difference (km)	–	2406.622
Relative increase (%)	–	1.02

Table 3. Flood induced changes in travel time.

Trip duration	Regular conditions	Flooded conditions
Sum (hours)	208511	211479
Absolute difference (hours)	–	296
Relative increase (%)	–	1.02

Although a transportation model simulates the flood conditions in a confident manner, the way flood was depicted in the system was ambiguous. The main concern was determining the duration of flood event when using a single flood depth map. For assessing the flood impacts on assets, the use of maximum flood depth maps has become a norm to determine the worst damage on a property level. When analyzing the effect of flooding on transportation that both of them have highly dynamic systems, flood’s development information should be acquired. Such information could be displayed in one map only if that flood develops slowly and has a prolonged duration like the flood condition considered in this research.

6. Conclusions

This research assessed the indirect impacts of service disruption due to the flooding in Santarém region of Portugal. The results captured characteristics of a flooded transport system that were not described previously, and showed that congestion does not evolve proportionately with the reduction of traffic supply. The static integration of flood and traffic model could be a workable solution only if the flood develops slowly and lasts at least one day. The methodology of this paper is same as many previous research papers in this area with the aim of exploring the flood on road transport network with a 100-year return period event, yet making use of a mesoscopic modelling technique which allows for a more detailed and precise representation of the dynamic traffic processes occurring during a flood disruption scenario at an efficient computational cost.

The flooded conditions caused disruptions to the transport system. Here are some of the findings of this research:

- In a disruption situation, some roads will inevitably become faster in terms of the average travel time. On the other hand, some roads receive more traffic, and some others that are located immediately after closure would receive fewer traffic volumes. If these roads have one-way traffic, the situation will become even worse.
- Although predicting the exact roads where the system will struggle mostly is so difficult, the results make it possible to identify the vulnerable locations that have experienced more travel time during the flood situation.

Although the monetization of the potential intangible impacts of flooding on transport system are ignored in this research, other aspects of transport system such as frustration of the thousand drivers that experienced delay in their trips, must be focused on. Therefore, intangible and indirect impacts of traffic disruptions should be considered in ex-ante or post-event analysis. Since these impacts may have essential consequences but are difficult to quantify, future research on how relatively inexpensive measures can increase the resilience of the transportation system would be required to improve the traffic systems management.

Acknowledgement

This work was partly financed by FCT / MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB / 04029/2020.

The first author would like to thank FCT – Portuguese Scientific Foundation for the research grant 2020.06035.BD.

The second author would like to thank FCT – Portuguese Scientific Foundation for the research grant SFRH/BD/144749/2019.

This project has received funding from the European Union’s Horizon 2020 research and innovation program under grant agreement No 769255. This document reflects only the views of the author(s). Neither the Innovation and Networks Executive Agency (INEA) nor the European Commission is in any way responsible for any use that may be made of the information it contains.

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