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Assessing Flood Indirect Impacts on Road Transport Networks Applying Mesoscopic Traffic Modelling: The Case Study of Santarém, Portugal

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Abstract: The key aspect for the quantification of indirect impacts of flooding is the assessment of the disruption of the transportation service considering social and economic consequences. To investigate how flooding can affect road transportation, it is essential to analyze interaction during the flood event itself, as well as on the following days. In this work, two static and dynamic traffic models are applied to a study zone for quantification of the performance and functionality of the network during the flood and after the failure of infrastructure components. A mesoscopic simulation was applied to identify the traffic disruption in the face of flood events. This simulation is capable of considering the road network model, assigning trip paths with the impact of road closures and speed reductions, and evaluating travel time and vehicle volume redistribution in a given disruption scenario. By comparing the traffic analysis results (travel time, travelled distance and street speed changes) in normal and flooded situations, the impact of flooding on a transportation network could be examined. Moreover, modelling outputs from a case study in the Santarém region (Portugal) indicated that in analyzing the flood impacts on a traffic network, even non-flooded infrastructures must be taken into account because of their service disruption.

Keywords: road network disruption; flood indirect impacts; mesoscopic simulation; static and dynamic traffic modelling

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Citation: Shahdani, F.J.; Santamaria-Ariza, M.; Sousa, H.S.; Coelho, M.; Matos, J.C. Assessing Flood Indirect Impacts on Road Transport Networks Applying Mesoscopic Traffic Modelling: The Case Study of Santarém, Portugal. *Appl. Sci.* **2022**, *12*, 3076. https://doi.org/10.3390/app12063076

Academic Editors: Yosoon Choi and Salvador García-Ayllón Veintimilla

Received: 23 October 2021
Accepted: 8 March 2022
Published: 17 March 2022

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 relies on their proper performance [1]. For instance, in December 2019 two major storms struck the Iberian Peninsula in less than a week, causing severe winds and floods. In central Portugal, the heavy rain disrupted train services after flooding of the rail tracks, brought down power lines, cutting electricity to thousands of citizens, and caused disruption and damages to road infrastructures, namely embankments, slopes, and culverts. The impacts were estimated at EUR7.7 million by the Médio Tejo Intermunicipal Community, an organization that supports local municipalities in regional planning [2]. 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, and thus where the greater investments are needed to implement measures to reduce the impacts of these events [2]. In fact, within the plan of measures to elaborate for the period between 2016 and 2021, a total of 81 measures, estimated at EUR70 million, were needed [3]. The proposed measures, ordered from the highest to the lowest investments, varied among structural measures, green measures, exposure reduction, vulnerability reduction, and learning and recovery. Thus, a deeper understanding of compound interactions between the system's inherent vulnerabilities and the hazard features could lead to cope better with floods.

Risk reduction of a road transport network can be achieved either by decreasing direct impacts (i.e., caused directly by the flood event physical damage to the infrastructure) or indirect impacts (i.e., 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) [4]. In particular, the indirect impacts due to rerouting traffic, as a consequence of floods, have been found to be potentially larger than direct impacts [5]. Consequently, it is fundamental to carefully examine these impacts in order to define efficient management strategies to decrease road transport risk. The main aim of this paper is to analyze options for making the flood consequences estimation more valid.

Previous research mostly analyzed the indirect impacts of floods by considering a static integration of the flood and traffic models [6]. This integration cannot adequately explain the events that occur when a transport system is facing a progressive flood, ignoring the domino effects of the links with reduction speed on other sectors and the whole network [7]. The static integration of the flood and traffic models produced just a binary representation of flooding, which can be a reasonable solution for assessing the effects of the flood on the transport system in the following days of the flood. Progressive flood is indeed a dynamic natural hazard that makes a complex interaction between floodwater and the transport system [7]. Therefore, in flooding duration, dynamic integration of flood and traffic may deem to provide more appropriate conclusions regarding the flood effects on the road network. In order to apply the temporal and spatial variation of traffic during the flood, the mesoscopic simulation can be used to compute vehicle movements with queues that may run up to 100 times faster than a microscopic model [8].

The remainder of the present paper is developed as follows. Section 2 provides a brief review of the existing literature on the impacts of floods on a road network. Section 3 describes the framework for the integration model, followed by a discussion of the data source and sample used in the empirical analysis, in Section 4. In Section 5, the description of the results is presented. In the final section, conclusions and some directions for future research are put forward.

2. Literature Review

Several descriptive research works have been done to evaluate the impacts of floods on a road network. The Department for Transport UK [9] assessed one day of flooding. Their results showed that this flood event on the UK's road network caused about 2% of the annual delays all around the country. Affleck and Gibbon [10] reported how a 15-min ride turned into a two-hour journey after many bridges in Workington collapsed. As another example, the Desmond storm cost EUR3.8 million in traffic disruption in Ireland, according to McDermott et al. [11]. Based on these research examples, flooding impacts significantly affect transportation networks and their users.

The key aspect for the quantification of indirect impacts of flooding depends on reliably assessing 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 traffic flows through an impaired network with closed or reduced speed links while satisfying both demand and capacity [12]. For example, Martínez-Gomariz et al. [13,14] analyzed the effects of flood depths and flow speeds on vehicle stability. Other researchers have worked on the relationship between standing-water depths on road surfaces and vehicular speed [15,16]. They investigated the significance of the flooded roads within a network. Most approaches found in the literature have used macroscopic traffic models for this purpose [6]. For example, Suarez et al. [17] found that climate change might possibly double both travel distance and time, while Chang et al. [18] found that traffic delays were a greater concern than the increased distance. It is reasonable to assume that because the urban environment provides numerous rerouting alternatives, the travel distance may not increase as much as the travel time due to traffic congestion. The robustness and vulnerability of the traffic network in York, UK, were studied by Balijepalli and Oppong [19]. Nine streets were identified as being at risk of floods and were either closed to traffic or had their capacity decreased. The vulnerability and resilience indices were derived based on the assumption that each flooded street is independent. This may be considered unrealistic because flooding normally impacts a greater area than just one street. Despite this simplification of the problem, they could identify the most vulnerable streets.

All of this research used macroscopic traffic modelling, which is capable of representing congestion or diversion in 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 provide very precise results since individual vehicles are tracked on the network at small time steps [20]. Costa et al. [21] performed a micro-scale modelling of traffic for the Italian city of Messina considering network disruptions for thousands of possible earthquake scenarios in order to sample uncertainties within a probabilistic framework. However, microsimulation is rarely used to represent large geographical areas because of the higher computational cost and the level of detail needed regarding the input data. Thereby, a mesoscopic simulation, which falls between these two modelling approaches, can portray a feasible alternative for the assessment of flood impacts in transportation networks [22]. Mesoscopic modelling 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 microscopic simulation [23]. In a mesoscopic model, every individual vehicle is considered with a specific origin, destination, departure time, and routes, while their movements are defined following a set of macroscopic traffic flow relations [24]. However, mesoscopic models in the transportation field are still lagging in practical application and findings are still limited to the laboratory tests [25]. For more information regarding the basis of different modelling scales please see the reference [26].

In order to minimize fatalities and financial loss, it is vital to understand the flood conditions that cause vehicles to become uncontrollable. The traction of full-scale vehicles in varying static water was investigated by Smith et al. [27] using a small vehicle (Toyota Yaris) and a typical large 4-wheel drive (4WD, Nissan Patrol). The latter was considered because of the increased number of 4WD-related fatalities in Australia [28]. The experiments indicated that deeper standing-water depths result in less traction. The Toyota Yaris floated entirely at 0.6 m standing water depth, whereas the Nissan Patrol floated at 0.95 m, according to the tests. Most authors agree that the stability criteria for still-water depth should be 0.3 m for small passenger vehicles and 0.5 m for 4WD vehicles [27,29].

Previous studies have addressed the potential impacts for transportation networks during flood events, but the impacts of flood disruption may persist long after the flood has subsided, which also needs to be considered. This paper, as an extension of the published investigations of the authors regarding this case study [30], contributes to the existing literature by applying a deeper look and valid alternative modelling into the flooded road network. The mesoscopic simulation was used to build the road network model, assigning trip paths with the impact of road closures and speed reductions, and evaluating travel time and travel distance after the failure of infrastructure components such as roads and bridges because of a flood event in a specific case study. Moreover, a novel approach for accurate quantification of the flood disruption effects on the road network is developed considering both the dynamic situation of flooding on the day of the flood and one following day, when the flood has subsided but its disruption effect remains in the traffic network. For this purpose, by combining a flood model and a mesoscopic traffic model, phenomena of queueing during the flooding were simulated. This can provide insight into how the transportation system behaves under time-varying flood conditions and traffic supply reductions that facilitate the identification of vulnerable links.

3. Framework

To capture the relationship between road transport system and flood, integration of flood and traffic during the flood and after the failure of assets is carried out, flood maps were obtained using a time-series of water levels, and their outcomes were translated into time traffic model inputs. The rationale is that severity (depth and extent) and propagation of flood over time determine the condition on the road [6]. During a flood, a consistent and homogenous approach is developed to incorporate the temporal change of both flooding and network capacity to enable comprehensive and dynamic communication between the flood and the traffic models. Depending on the depth of flood, certain roads may be attributed to delayed traffic while others may already be considered closed to traffic. According to previous research on flooded vehicle stability thresholds, a criterion for distinguishing shallow from deep water flows was defined [6]. In order to guarantee consistency for all simulated vehicles in the road network, a value of 0.3 m water depth has been considered a criterion for street closures, whereas for values lower than 0.3 m a reduction of speed to 20 km/h was considered for that link [6]. When a street is blocked from traffic, vehicles that were previously going through it are rerouted just before the link closure by taking the shortest path from their current place to their destinations. In this rerouting process, it is assumed that drivers are not aware of the flooded part of their route until they approach the closed link and then they choose a new route to their destination considering the shortest path.

A framework that translates spatially fluctuating flood information into a traffic model output could ensure the interoperability of the previously stated activities. This framework may be applicable for both static and dynamic ways of modelling. Dynamic integration of flood and traffic models applies flood maps at different time steps of an event. To do so, in the traffic model, temporal flood propagation is directly translated into speed reductions or road closures. On the other hand, for all flooded roads, the static integration employs a single flood map within a whole day period. This method could be sufficient and practical to simulate the disruption effects because of flooding in the days following the event itself, but all the flooded links are closed to the traffic for activities such as dredging or repairing, while the transport network adapts to the new situation. This paper simulates both dynamic and static integrations of a flood event, respectively during the day of the flood and on one following day, when flood has subsided but its disruption effects on the transport network remain. Figure 1 presents the different steps of the integrated framework.

In this research, a mesoscopic simulation has been employed for the flood impacts assessment. With a mesoscopic modelling technique, the trips must be computed for each travel mode in the network. Mesoscopic simulation computes vehicle movements with queues and may run up to 100 times faster than a microscopic model [8]. Furthermore, by using a coarser model, it is more tolerant of network modelling errors than microscopic simulation. In this perspective, mesoscopic traffic models can provide a complete picture of congestion as well as an intermodal explanation of different types of vehicles.

After running the traffic model with the flood information, its impacts on the road network can be achieved by comparing the traffic model results under flood and normal conditions. The effects on the traffic system are expressed as additional travel time and additional travel distance. Using this method, the effects of flood risk management and traffic improvement systems can be evaluated.

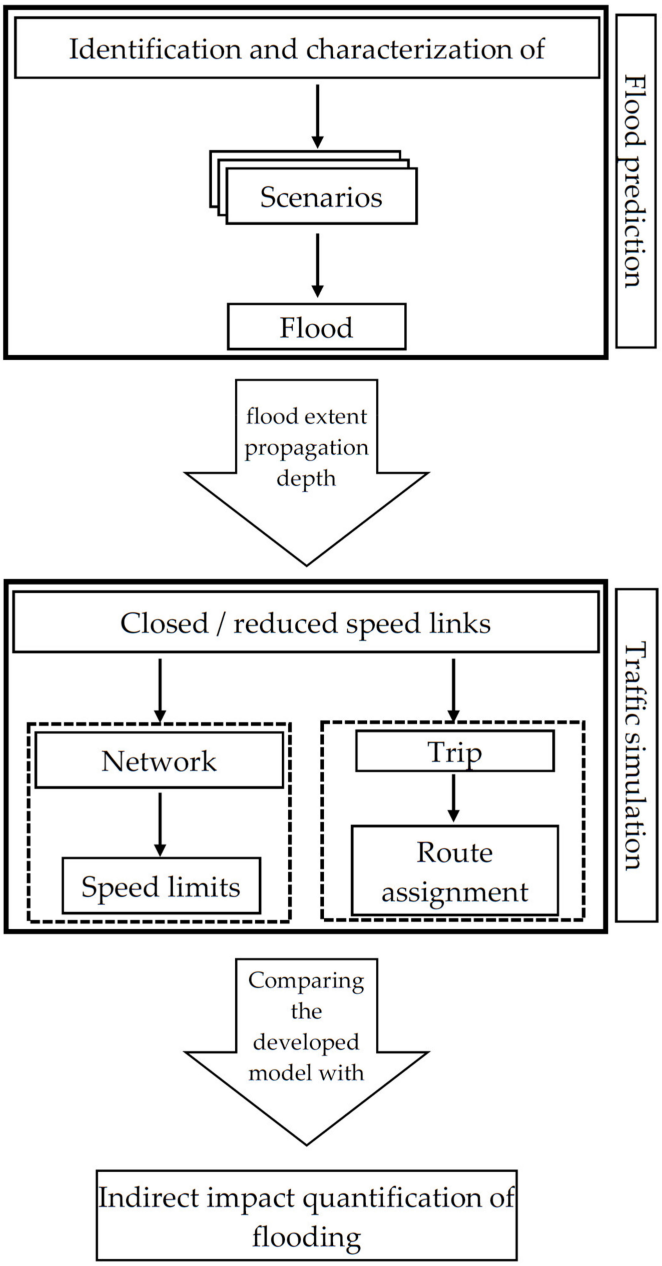


Figure 1. Framework for indirect impact quantification of flooding.

4. Materials and Method

The proposed framework was applied to the Santarém district in central Portugal (Figure 2), which lies along the Tagus River. The lower valley of the Tagus River is where the more extreme flood events in Portugal have occurred in recent decades, which have resulted in an extensive floodplain (over 800 km^2) being completely submerged [31]. Therefore, this case study is considered appropriate for the demonstration of the framework, since indirect impacts on the road network because of closed roads throughout one to several days frequently occur. Moreover, given the strategic importance of the Tagus valley to agriculture and groundwater resources within Portugal, flooding events have led to significant economic consequences, as well as harmful social and health conditions [32]. Thus, the application of the integrated framework will provide insights regarding the behavior of the road network under this type of disruptive event, which will endorse the definition of priority plans for enhancing the resilience of the transportation system in that area.

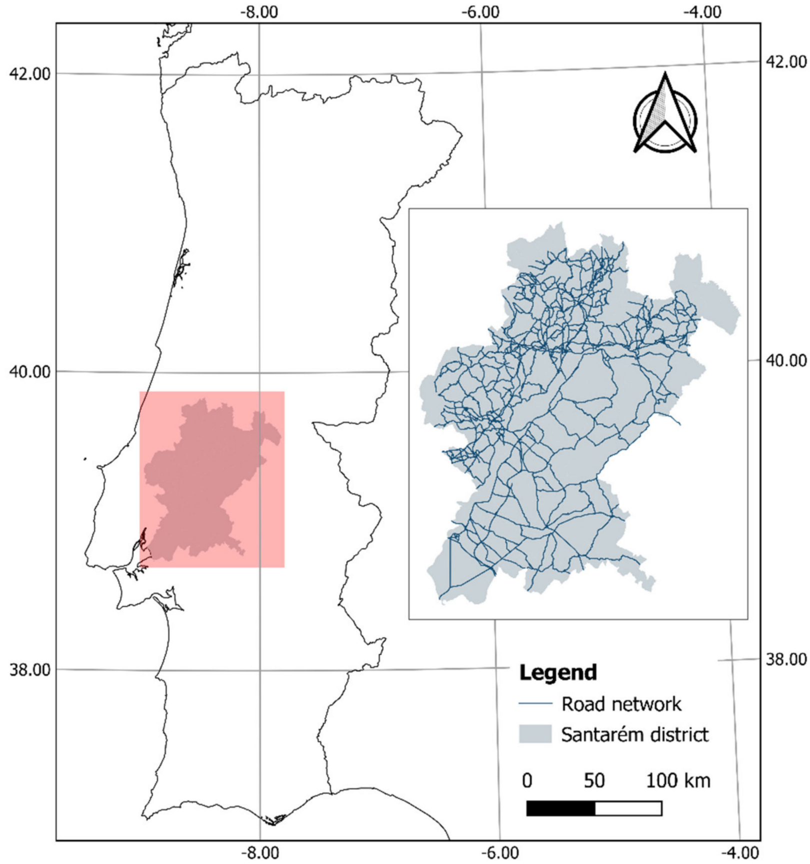


Figure 2. Location of the case study area in Portugal.

4.1. Flood Model

The case study area of Santarém is particularly prone to progressive floods, i.e., those caused by prolonged heavy rainfall in large basins such as that of the Tagus River [32]. Hazard maps for flood scenarios with return periods of 20, 100 and 1000 years, related to events with a high, medium, and low probability of occurrence, respectively, were elaborated for Portugal within the scope of the EU directive 2007/60/CE on the assessment and management of flood risks. The maps are accessible to the general public on a Web GIS portal and include the delineation of the flood extent, the water depth, and the flow velocity for each scenario. Historical time series of precipitation and annual maximum instantaneous stream flows were used to build hydrological and hydraulic models for flood calculation [3].

The methodology implemented for obtaining flood models for static and dynamic integration is shown in Figure 3. For the case of static integration between the flood and the traffic model, the water-depth hazard maps were used to identify the closed links through geographical coincidence with the road network, since the goal was to simulate the disruption effect in the days following the flood event and it is assumed that the flooded links remain closed to traffic because of cleaning up and/or repairing works.

Conversely, for the dynamic integration, flood maps at different time steps during the event are needed to analyze the spatial-temporal evolution of the flood. The latter is required to estimate the impacts on road traffic during the event. To this end, the proposed methodology builds on water-level measurements from past flood events to characterize the progression of the flood.

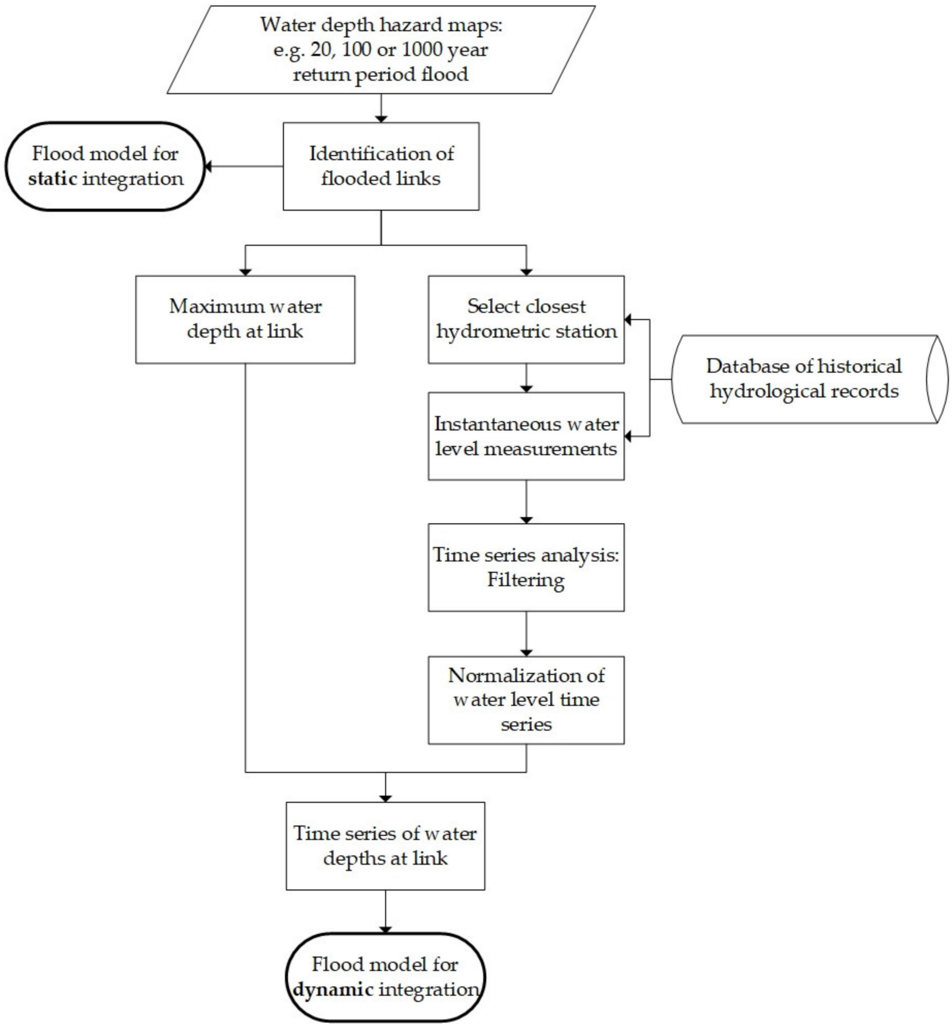


Figure 3. Methodology for producing flood models for static and dynamic integration.

After identifying the affected links using the water-depth hazard maps, the next step consisted of selecting a hydrometric station for each link following a geographical proximity criterion. The main assumption here was that the temporal evolution of the water depth in the link follows the same shape of the instantaneous water levels measured at the closest hydrometric station. Subsequently, the base water level was removed from the recorded measurements to determine the portion corresponding to the flood event itself and, afterwards, the obtained values were normalized by the peak water level at the hydrometric station. At the same time, the maximum water depth at each flooded link was extracted from the overlapping of the water-depth hazard map with the road network. Lastly, the normalized curve was multiplied by the maximum depth found for each link. In this manner, the temporal series of water depth were defined at each time step for every flooded link and were later interpreted as speed reductions or road closures in the traffic model.

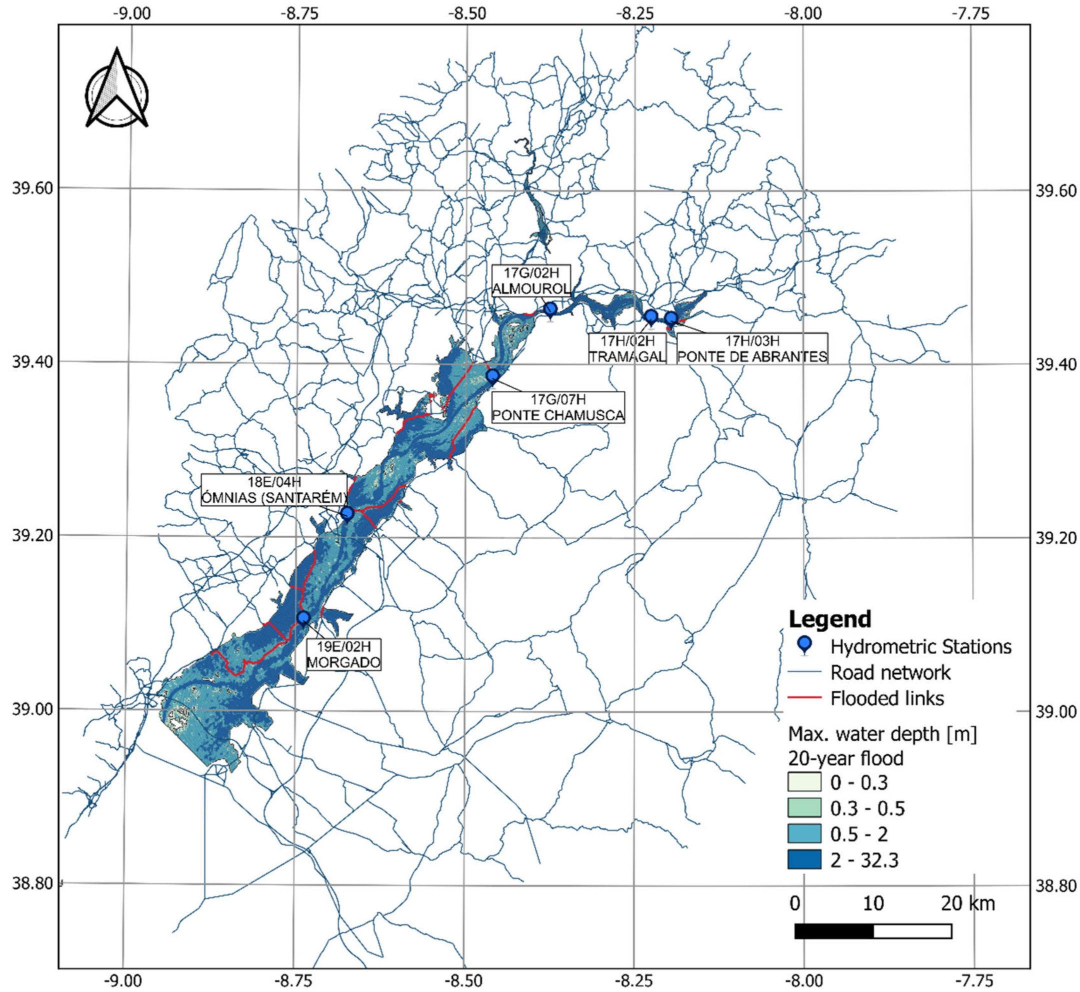
For the application of the methodology to the case study, instantaneous water levels and annual maximum stream flows measured at six hydrometric stations over the Tagus River (see Figure 4a), namely Ponte de Abrantes (17H/03H), Tramagal (17H/02H), Almourol (17G/02H), Ponte Chamusca (17G/07H), Ómnias (18E/04H) and Morgado (19E/02H), were retrieved from the National Water Resources Information System database (SNIRH, Lisbon, Portugal) [33]. The oldest available records at some of the stations (e.g., Tramagal and Almourol) date from 1990 while the oldest records available at others (e.g., Chamusca) date from 2002. However, there are large periods of unavailability of data in several stations, and some of them are allegedly out of service since the latest records date from 2010. Consequently, only records from the period between 2002 and 2010 were considered for further analysis. During this period, the highest instantaneous streamflow was recorded in Almourol hydrometric station, on 25 November 2006. Based on the streamflow measured, i.e., 5470 m^3/s, it can be stated that this event has a high probability of occurrence (the estimated 20-year return period peak flow at Almourol hydrometric station is around 10,000 m^3/s). Damage surveys provided by the Portuguese National Authority of Civil Protection recorded the submersion of several national and municipal roads in the Santarém region, beginning on the 24 and until 29 November 2006. Therefore, this flood event with an approximate duration of five days was selected for demonstrating the proposed framework. Since the flood event has a high occurrence probability, the water-depth hazard map corresponding to a 20-year return period was used for both the flood model for static and dynamic traffic integration (see Figure 4a). Moreover, the instantaneous water level measurements from the period of analysis at each station were retrieved from the SNIRH database (Figure 4b). Thereby, through the application of the methodology, both the static and the dynamic characterization of the flood event were achieved. It is worth noting that the impact of a flood depends on several factors, including water depth, flood duration, the spatial extent of inundation, and water velocity [34]. These factors were considered explicitly in the methodology except for water velocity. However, the flood event under analysis conducts to flow velocities lower than 1 m/s. Therefore, the flood intensity and its impacts are driven mainly by the water depth [8]. Thus, the assumption of using the water depth to perturbate the road network is reasonable.

More detailed and precise models can be employed to derive the flood propagation information, i.e., the spatial and temporal attributes of the flood event. However, because of the Tagus River basin extent (approximately 25,000 km^2 in Portuguese territory) and the demand for detailed data to develop precise hydrologic and hydraulic models for different time steps of the flood event such as digital elevation model (DEM), Manning roughness coefficients, among others, render the use of more sophisticated models a time-consuming task with elevated computational cost, which are beyond the objective of this research. Therefore, the methodology conducted based on data from past events is sufficient for illustrating the proposed dynamic integrated framework for indirect impact quantification of flooding. Nonetheless, the framework supports the updating of the employed models for more advanced and accurate ones, and thus the analysis can be easily updated in the future if such models are made available.

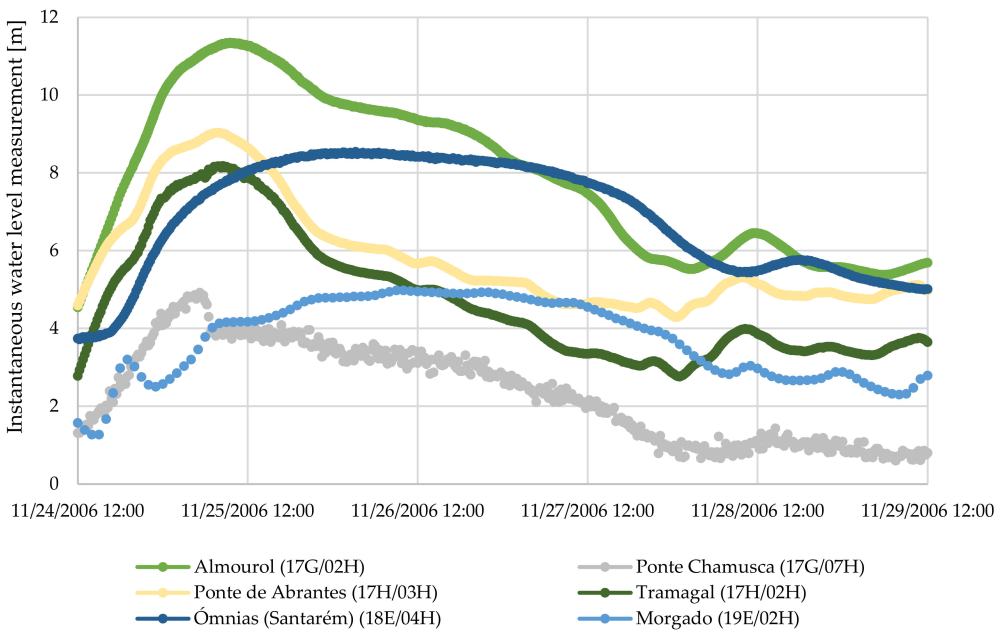
4.2. Traffic Model

All traffic models comprise two main parts, which are the traffic supply and the traffic demand. Traffic supply determines the capacity of the infrastructures, whereas traffic demand describes the behavior of travelers. Traffic modelling simulates how these two components interact with each other. In the current study, the Open Source "Simulation of Urban Mobility" (SUMO) [35] software is used for developing the traffic model.

The analyzed network consists of 7025 links and 879 nodes. Links have multiple attributes including, but not limited to, the free-flow speed, number of lanes, and capacity. The geometric configuration of the model includes 917 traffic assignment zones. The static origin/destination (OD) matrix included 462,720 vehicles in a day. Based on the initial static OD matrix and using the od2trips tool of SUMO, a time-dependent OD matrix was estimated. The od2trips is a program that generates trip tables from the OD matrix and assumes that the matrix is coded as the number of vehicles that travel from one district or traffic assignment zone (TAZ) to another in a certain time. In traffic demand modelling, a trip is defined with starting point (origin), end point (destination) and beginning time. The traffic demand data of the pilot zone was obtained from Infraestruturas de Portugal (IP), the Portuguese transportation infrastructures management. A constant demand was assumed, i.e., users do not change their travel mode because of the flooding.



(**a**)



(**b**)

Figure 4. (**a**) Overlapping of the roadway network with water-depth map for a 20-year return period flood; (**b**) Instantaneous water level measurements at each hydrometric station (in meters).

Od2trips allows splitting OD matrices, which define a long time period, into smaller parts that contain definite percentages of the whole. It is possible to split the matrix into 24 subparts—this means the number of fields is fixed to 24—allowing to spread an OD matrix over a day describing it by hours. In dependence to the week day and the type of traffic, one could set the appropriate time line. Some common daily time lines from Germany are retrieved and could be found in SUMO documentation [20]. In the current paper since there is no available information regarding daily time lines from Portugal, data from Germany were used to determine the vehicles distribution over time during the simulation to approximate rush-hour flows. Figure 5 depicts the number of vehicles introduced to the network over time during the simulation for a 462,720-vehicle scenario.

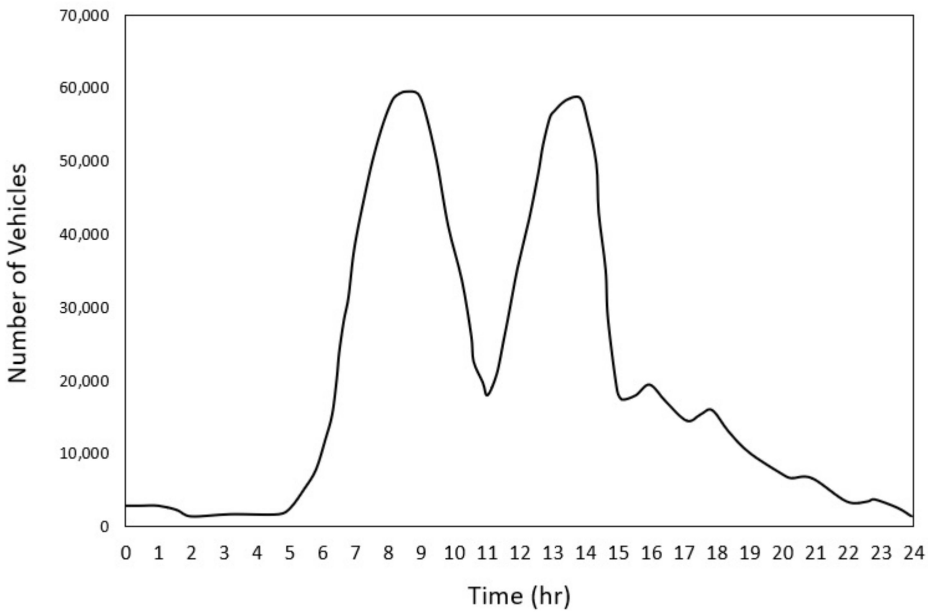


Figure 5. Number of vehicles in the network over time for the 462,720-vehicle scenario.

Because of the interactions of the individual drivers during their travel through the network, the route choice and travel times are strongly coupled. The route choice is based on travel times and the travel times result from the route choice. Therefore, it is necessary to apply a model for link flows that reproduce the dynamic findings of traffic flow. In this paper, a mesoscopic simulation-based dynamic traffic assignment (DTA) model on the road network of Santarém region was performed. Traffic assignment models, especially simulation-based dynamic traffic assignment models, are commonly used in a wide range of applications, including traffic management and transportation planning [36–38]. Route choice and network loading, as the main components of DTA models, aim to represent the dynamics of vehicle movements in a network. The Santarém road network was imported to SUMO using shapefiles of this network, which were received from IP. The evolution of the traffic flow over the links of the network once the route choice was determined are represented by network loading. Although the stability and the convergence of the simulation-based assignment algorithms usually cannot be proven, a realistic description of traffic dynamics which is essential with respect to the usability in real-world applications, could be gained.

Generally, Santarém has a robust road transportation system, but there is a factor that may affect mobility in this network. Since drivers may not be permitted to make a U-turn before passing through a flooded part of the roads, the 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 incremental assignment that is an alternative to the iterative user assignment. In this case, each vehicle computed a fastest-path computation at the time of departure that prevented all vehicles from driving blindly into the same traffic jam. As a result, rather than assuming that cars travel in an isolated manner, their travel times were calculated as interacting participants of the travel system. The basic assumption in this paper was that drivers have complete knowledge of the road network, which is reasonable to assume in commuter traffic.

4.3. Validation and Verification of Results

Because of the lack of traffic data during the flood situation, the model could be validated with the average travel time of the typical traffic for a day that was obtained from IP. The calibration of the traffic model was achieved by comparing the estimated average travel time matrices between TAZs for all of the departed vehicles from one TAZ to another. To this end, this matrix was compared to the IP results matrix. Then, one of the most common metrics to measure the forecasting accuracy of a model, which is mean absolute percentage error (*MAPE*), was calculated. The formula to calculate the *MAPE* is as Equation (1):

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{E_t - S_t}{E_t}\right| \times 100 \quad (1)$$

where n is the number of fitted data, E_t is the travel time reported by IP, S_t is the predicted travel time. This measure is estimated to be 12%. Overall, this measure indicates reasonable prediction fits. Therefore, it can be said that the potential uncertainties of the model and concerns about its accuracy in the next stages of the model integration with flood spots decreases.

Table 1 shows the estimated average travel times received from IP and predicted values in the current research for the first 10 TAZs in the network. The average travel times in Table 1 are rounded to the closest minute.

Table 1. Estimated average travel times for the first ten origin/destination (OD) pairs in the network. (Values in parentheses show the current research predictions).

O/D	1	2	3	4	5	6	7	8	9	10
1	0 (0)	0 (0)	0 (0)	0 (5)	49 (52)	60 (51)	0 (0)	24 (27)	0 (0)	0 (0)
2	0 (0)	0 (12)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
3	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
4	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
5	49 (67)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
6	60 (69)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
7	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
8	24 (20)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
9	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
10	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)

It is worth mentioning that the applied method in the current research for validation of results is similar to that published in Bhat [39]. In addition, the model results can be verified in case of disruption, but at the moment those are credible predictions but not validated. Although a higher uncertainty is found for the situation where the disruption took place, the framework presented in this paper demonstrates the potential of combining flood maps and traffic models to estimate the probable consequences of changes. It also indicates that impact of flooding includes the time it takes for the network to be recovered in addition to the time when there is standing water on the road surface.

5. Results and Discussion

In the previous works, floods and traffic models were mostly integrated statically on the day of flood occurrence. In this paper, both dynamic and static integration of flood and traffic models for assessing the indirect impacts of flood, respectively during the flood and after passing it, are investigated. In the next two subsections, the same data are used, taking into account that a higher uncertainty is found for the situation where the disruption took place. First, a dynamic approach in Section 5.1 is used for estimating the effects of the flood on the transport system during the flood day. This is the valid alternative modelling approach where dynamic integration is demonstrated. Then, a more standard static approach in Section 5.2 is applied for estimating the impacts of the flood on the transport system in the following days of the flood. However, this static integration presents weaknesses that are pointed out at the end. The selection of the spatial scale was taken based on the nature of each phase of the flooding event. The time resolution for the dynamic component was assumed as 24 h (1 day) since this is the time in which the water level is increasing. It is worth mentioning that only one day is considered for the static simulation as the equal duration of the dynamic simulation. Since this work is an exploratory analysis of different models in the context of flood consequences analysis, such assumptions are considered reasonable. In future advancements in this work, the correlation between the choice of these parameters and the underlying type of action will be considered.

5.1. Flooding Day

In order to determine which roads will be faced with speed reduction and which will be closed to traffic, a relationship between vehicle maximum permitted speeds and flood depths is necessary. Pyatkova et al. [6] previously discretized flood threats by relating maximum allowable speed limits along road sections to flood depths along those sections. Table 2 depicts the discrete limits along road sections in relation to flood depths.

Table 2. Flood depths' effect on traffic flows.

Flood Depth (m)	Maximum Vehicle Speed (km/h)
Depth < 0.1	Road Speed Limit
0.1 ≤ Depth < 0.3	20
0.3 ≤ Depth	0 (Road Closed)

The input parameters (speed limit) of links within the traffic model are modified using an intersect analysis, which analyzes the depths of water on road surfaces. The characteristics of the 44 national and municipal roads (0.7% of the total number of roads in the traffic network), that were found to be impassable or suffer slower traffic because of a 20-year flood, are listed in Table 3. It is worth noting that the capacities and the location of the flooded links in traffic is more crucial and effective than their proportions.

Table 3. Number and length of flooded or reduced speed streets. Deep flooding (over 0.3 m) will result in street closures, while shallow flooding (0.1–0.3 m) will cause traffic to proceed more slowly.

	Number of Streets	Proportion to the Whole Network	Length of Streets (m)	Proportion to the Overall Length of the Network
Closed streets	38	0.6%	231,798.4	2.8%
Reduced speed streets	6	0.1%	2330.7	0.02%

Previous research on integrating traffic models and flood events employed a static flood map [17,18]. This method is inadequate to represent how flood dynamics change the traffic flow because flood development affects the sequence of the street closures and it is crucial for traffic simulation. Flooding could not be characterized as a binary problem in a transport model, which may be addressed using a start and end of a single flood map. Therefore, one could argue that the given results with different closure periods may be equally correct or incorrect. However, the potential vulnerable locations of the transport network could be pointed out. This section describes the flooding impact on traffic considering a dynamic integration between the flood and traffic models.

For representing the flood influence in the traffic simulation during a flooding day, the dynamic integration of flood and traffic should be considered. To do so, the traffic model was updated every hour with flood propagation information to provide a spatial and temporal variation of both speed reductions and street closures. The whole period of the simulated flood was one day (24 h). The impact of flooding on the transport system is expressed by rerouters so that vehicles passing through the flood would need to change their routes. Therefore, the initial perturbation in the network can be defined as the number of rerouted cars. Figure 6 shows the change of rerouted vehicles during the day as a direct consequence of the traffic demand changing, the number of street closures, and the spatial dimension of street closures. For example, there was a considerable demand around 9:00 h, even though just in the upper catchment some streets were flooded and did not affect many trips, but as a result of the flooding on the main road, there was an increase in the number of vehicles that were rerouted. As it is shown in Figure 6, because of the non-constant demand during the day, the frequency of closed streets forced cars to be rerouted in a nonlinear manner. Given the fast changes in traffic demand around 13:00, the maximum street closure affected about 5000 vehicles. Hence, the number of closed streets did not directly translate into the number of rerouted vehicles.

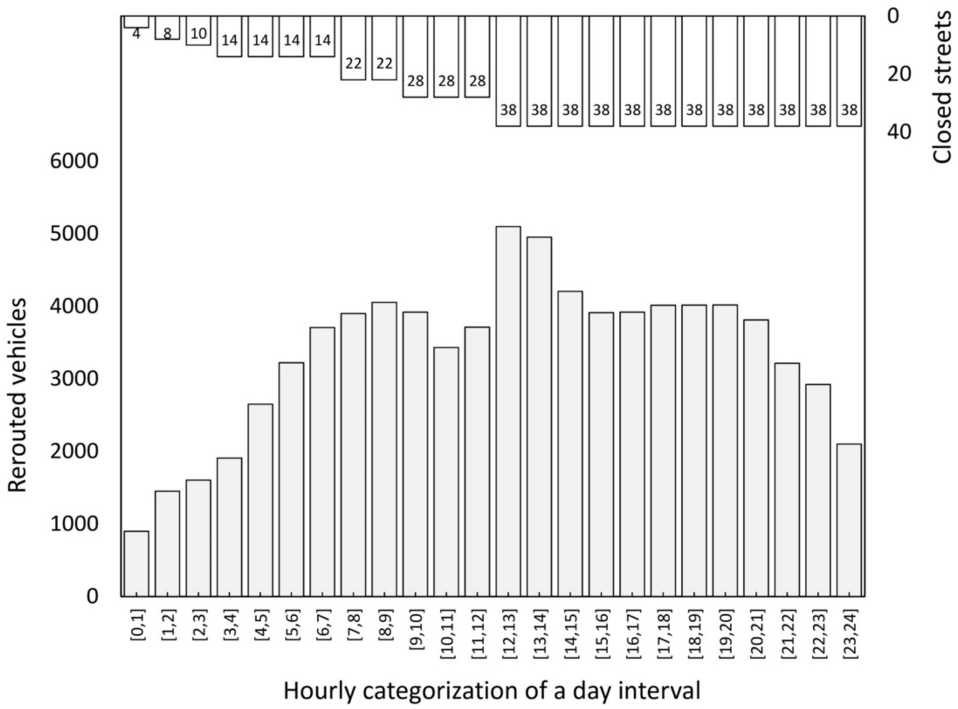


Figure 6. Rerouted vehicles and closed streets during the one-day flood.

Several parameters such as travel time and travelled distance were investigated to determine how flood propagation affects the transportation system. The real impacts are determined by the differences between normal and flooded conditions. To represent both the total consequences and their temporal fluctuation, average values for the whole simulation and hourly averages were calculated. Based on the starting time of vehicles' trips in the normal situations, the hourly traffic was analyzed because, due to departure delays, the same vehicles may start their trips at different hourly intervals. The hourly estimates of vehicle trips may not accurately reflect the real traffic conditions in that time period. In fact, this comparison was done to ensure that all vehicle trips were examined considering the temporal aspect.

5.1.1. Travel Time

To evaluate the differences between the flooded and normal simulations, several aspects of travel delays must be considered. A key consideration is the definition of a delay. The simplest explanation could be that a delay is registered for a vehicle if the simulation in a flooded situation takes longer than the normal situation. Nevertheless, it is sensible to establish a threshold that defines the circumstances under which a journey is delayed. The travel-delays threshold can be set as a constant value unit or as a proportionate value. Since Santarém is a small region with short durations and distances of most trips, the proportionate threshold was considered more adequate to be used. Therefore, delays of 10%, 20% and 50% of the original travel time under normal conditions were considered (see Table 4). The 50% increase in travel time was presented as a statistic that describes the system rather than a threshold of travel delays. The proportions of delayed vehicles depend on the selected threshold, but all have registered the highest proportion of delayed vehicles between 12:00 and 13:00—ranging from 20 to 40% (10% and 20% duration increase threshold). This threshold defines the average delay of the affected vehicles as a proportion of the normal situation travel time as well. Considering the delay threshold of 20% increase in travel time, 10% of the vehicles will experience a 50% increase in trip duration. Moreover, about 3% of the vehicles experience a delay of more than 50% of their original trip duration, seeing a 100% increase in travel time on average.

Table 4. Flood effects on travel time.

	Travel Time	8–9 h	12–13 h	Overall (0–24 h)
	Dry condition (h)	23,572.9	23,957.6	109,200.7
	Flooded condition (h)	26,431.7	31,539.3	130,854.4
	Difference (h)	2858.8	7581.7	21653.7
	variation (%)	12.1	32.1	20.0
With 10% delay	Vehicles percentage	23.8	37.6	28.1
	Average delay/journey time (%)	43.2	59.2	42.3
	No variation vehicles (%)	45.7	38.3	27.2
With 20% delay	Vehicles percentage	21.6	23.7	10.3
	Average delay/journey time (%)	43.6	47.9	56.8
	No variation vehicles (%)	43.2	37.8	33.4
With 50% delay	Vehicles percentage	11.8	12.6	2.7
	Average delay/Journey time (%)	61.5	67.9	127.9

The overall travel time difference between flooded and normal situations is 20%, calculated as the difference between the sums of all the trips in both conditions. It is worth noting that, while most vehicles face traffic delays, some travel faster than usual. Roads, immediately after a road closure point, have reduced traffic loads, and thus vehicles can move faster. Summation of all trips in a network would not be the optimal strategy because early journeys cannot compensate for individual trip delays. Indeed, some researchers argue that both traffic delays and time gains might be viewed as a loss of work time [40].

5.1.2. Travel Distance

The most commonly mentioned impact of a disrupted transportation network could be interpreted as the travelled distance because it does not necessitate the use of a traffic model and can be analyzed using road network assumptions. In a congested urban region, the additional travel distance may not be very important because there are many available alternatives. On the other hand, flooding may result in several closures in the same location, thereby fragmenting a network and making reroutes longer. The key statistics about the travelled distance in the two peak durations of demand are shown in Table 5. When the number of rerouted cars is compared to the number of cars taking longer routes, it is obvious that rerouting does not always imply higher distances traveled. More than half of the rerouted vehicles took longer routes between 12:00 and 13:00. Since in route choosing shorter travel time is preferred over shorter travel distance, perhaps some cars after a route change can reduce their travel distance. As another reason, in case of a car stuck in traffic, the flooded road segment may be reopened to traffic by the time that car reaches that segment. As it is shown in Table 5, the additional travelled distance (e.g., 24% for travel time between 8:00–9:00) and number of rerouted cars did not increase proportionately to each other (19.3%).

Table 5. Flood effects on travel distance.

Travel Distance	8–9 h	12–13 h	Overall (0–24 h)
Dry condition (km)	1,639,482	1,729,737	21,384,880
Flooded condition (km)	2,038,912	2,829,310	23,492,319
Difference (km)	399,430	1,099,573	2,107,439
Variation (%)	24	64	10
Vehicles with longer routes (%)	11.7	18.3	16.2
Rerouted vehicles (%)	19.3	25.8	26.9

5.2. Day after Flooding

The use of static integration requires the closure of all disrupted streets at the same time. In this step, in the traffic model, defining the closures duration is vital. In fact, assets closures for dredging may not co-occur during a day, making it difficult to determine a realistic period of the event. Furthermore, if the selected time interval is too long, the traffic delay will be exaggerated. Likewise, there is also a risk that the flood impacts are underestimated.

Effects of closed links on travel time and travel distance are represented in Table 6, respectively. The overall travel time rose to 137,883 h, and the additional travel distance increased to 23,514,722 km. The sharper increase in trip duration supports previous studies' findings that in an urban region, transportation disruptions are more likely to cause travel delays than greater trip distance. The various increases in travel time and distance are clear indicators of widespread gridlock throughout the transportation network. Although the traffic model has confidently simulated the flood consequences, the way that closed links were applied to the system was ambiguous. The main concern is determining the closed links and the duration of their closure. Applying maps of the maximum flood depth in order to assess the worst damage of flood impacts on the built environment has become common.

Table 6. Flood effects on travel time and travel distance.

Effect on Travel Time			Effect on Travel Distance		
Trip Duration	Dry Conditions	Flooded Conditions	Travelled Distance	Dry Conditions	Flooded Conditions
Sum (hours)	109,201	137,883	Sum (km)	21,383,980	23,514,722
Absolute difference (hours)	-	28,682	Absolute difference (km)	-	2,130,742
Relative increase (%)	-	26	Relative increase (%)	-	10

The given results were based on an arbitrary principle for determining the closure duration of links, by assuming a whole day for dredging.

5.3. Streets Speed Changes

For a better understanding and management of the transportation system, the impact of the spatial variation of flood is crucial. To this end, the traffic conditions on every street were aggregated for a day interval. In order to identify and quantify the differences between the normal and flooded situations, Figure 7 shows the speed differences between these two conditions for the whole road network during a day. The speed reduction indicates that traffic was slower on a particular road during flood than it was under normal condition.

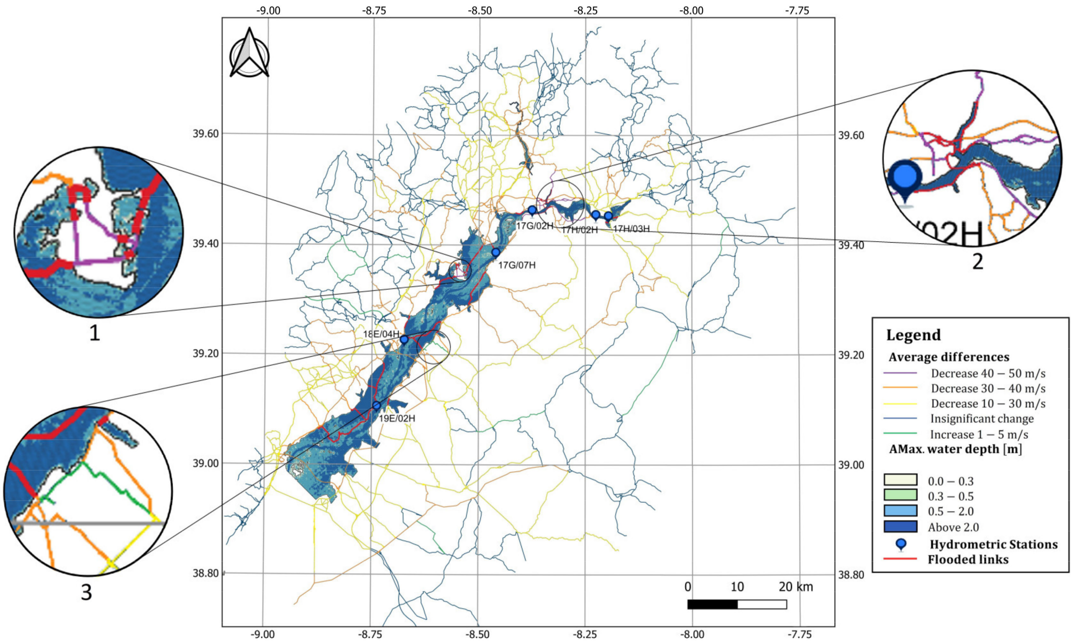


Figure 7. Speed differences between flooded and normal conditions during a day.

Generally, it is difficult to predict where the traffic congestion will build up, but certain spots consistently received slower traffic during the flood. These locations are zoomed and marked by numbers on the map. They could be argued as the most vulnerable sections of the transportation network. From Figure 7 it is clear that the progressive flood had a domino effect of the reduction speed on the whole network. The flooded roads and bridges are shown with the red color. By moving from the river toward the border of the region, the flood effects on the road sections have been decreased. Roads nearby the river, especially where the flooded roads were the only way to reach rest of the region from that isolated by flooded neighborhoods, experienced the most reduction speed because of the flood and they are shown by number 1. Vehicles in this location were locked about 4 h from 13:00–17:00 Location 2 in normal situation has registered slow traffic, but traffic problems during the flood worsen for an extended duration. The red road segments nearby the location 2 were flooded for 5 h between 11:40 and 16:40 , but the traffic disruption lasted 7 h with purple road segments being reduced with 40–50 m/s. It is worth noting that, while most vehicles faced traffic delays, some traveled faster than usual. Some roads, immediately after a road closure point, had reduced traffic loads, and thus vehicles could move faster. Location 3 is an example of these roads.

6. Conclusions

Flood impacts on a transport network may be intense and last for days. They also can lead to domino effects on other sectors and even human losses. Therefore, policymakers must integrate their decision-making process about the transport sector in a crisis management framework. This adjustment will help them make more effective and practical decisions before, during, and after a flood. This paper described an approach to analyze the impacts of a progressive flood on an urban transportation system on both the day of flooding and the day after the flood.

This work is an exploratory analysis of different models in the context of flood-consequences analysis. The main aim was to analyze options for making it as valid as possible. Looking into the traffic disruption evolution, two scenarios could be distinguished. There is a dynamic scenario of the flood on the day of flooding, in which parameters such as car speed are changing during the event. On the other hand, there is a static scenario on the day after the flood subsidence in which the roads are either closed or opened, depending on whether they need intervention or not. The adopted models aimed at clearly addressing these two different situations. Therefore, the selection of the mesoscopic spatial scale was taken based on the nature of each phase of the flooding event. The time resolution for the dynamic component was assumed as 24 h (1 day) since this is the time in which the water level is increasing. For this exploratory analysis, such assumptions were considered reasonable.

The static integration of the flood and traffic models produced just a binary representation of flooding, which can be a reasonable solution for assessing the effects of the flood on the transportation system in the following days of the flood. Therefore, in flooding duration, dynamic integration of flood and traffic was deemed to provide more appropriate conclusions regarding the flood effects on the road network. To this end, the mesoscopic simulation was used to evaluate travel time and travel distance after the failure of infrastructure components because of a flood event in the Santarém district in central Portugal.

According to the results, congestion does not evolve proportionally to a decrease in traffic supply, and the impact on the traffic system could be revealed with a delay. Some of the major findings of this research are:

- Because traffic jams sometimes accumulate far from flooded areas, the locations of closed streets cannot be easily equated with areas of traffic interruption.
- In a disruption situation, some roads receive more traffic and some others that are located right after closure will receive fewer traffic volumes. If there is one-way traffic on certain roads, the situation will become even worse.
- Although predicting the exact roads where the system will struggle the most is very difficult, the results make it possible to identify the vulnerable locations that have experienced more speed reduction during the flood situation.

Intangible and indirect impacts of traffic disruptions should be considered in the ex-ante or post-event analysis. Future research would be required on how relatively simple solutions might boost the resilience of the transportation network to improve traffic system management, as these affects may have important consequences yet are difficult to quantify.

Author Contributions: Conceptualization, F.J.S., H.S.S. and M.C.; methodology, F.J.S. and M.S.-A.; software, F.J.S. and M.S.-A.; validation, H.S.S. and M.C.; formal analysis, F.J.S. and M.S.-A.; investigation, H.S.S. and M.C.; resources, H.S.S.; data curation, H.S.S.; writing—original draft preparation, F.J.S. and M.S.-A.; writing—review and editing, H.S.S. and M.C.; visualization, H.S.S.; supervision, J.C.M.; project administration, J.C.M.; funding acquisition, J.C.M. All authors have read and agreed to the published version of the manuscript.

Funding: 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.

Data Availability Statement: For the flood model, publicly available datasets were analyzed in this study. These data can be found here: https://sniamb.apambiente.pt; https://snirh.apambiente.pt; (accessed on 5 August 2021). For the traffic model, restrictions apply to the availability of these data. Data were obtained from Infraestruturas de Portugal (IP), with whom the authors' institutional affiliations signed a collaboration and information exchange agreement.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, or in the decision to publish the results.

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