Analyzing the Impact of Floods on Urban Mobility Using Mobile Phone Data: A Case Study of the Vesdre Catchment Area

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***Abstract*—In Belgium, floods are acknowledged as one of the most frequent natural disasters, posing serious threats to people's lives and property. Growing evidence suggests flood risks will intensify in the coming decades, driven by climate change, population growth, and evolving land use patterns at the catchment scale. These compounding factors make improved flood risk understanding and management an urgent priority. The impact of floods on the transportation system primarily stems from road interruptions, which significantly affect travel demand. Exploiting mobile phone data collected by providers makes it possible to geolocate mobile phone users over time to derive time-dependent crowding maps. By intersecting these maps with flood inundation data, we can quantify human exposure to flood risks. This integrated approach enables a detailed analysis of both the spatial extent of floods and temporal changes in population movement patterns during flood events. In this context, we propose a sensitivity analysis based on mobile phone data collected from pre- and post-flood calendar periods in the Vesdre catchment area (Wallonia, Belgium). In light of the floods that occurred in July 2021, mobile phone data collected in 2018 and 2022 have been processed and compared. Meanwhile, we investigate the impact of the transportation infrastructure disruptions on mobility within the Vesdre catchment area and apply a Tobit regression model to analyze the significant parameters. As a result, we observe a decrease in interaction between the valley and the plateau, except between urban centers in the valley and neighboring residential communes in the heights, along with a general decline in mobility in the most affected communes. This suggests that the flooding has incited people to get further away from the river. Besides, we find that the parameter representing the number of out-of-service transportation infrastructures per kilometer is significant in the 2022 flow regression.**

***Index Terms*—floods, mobile phone data, transportation infrastructure, disruption, Tobit regression**

I. Introduction

The unprecedented impacts of the 2021 floods concentrated in the Vesdre River valley on the local population have prompted public authorities to take rapid measures to repair the affected critical infrastructures. Transportation infrastructures serve as crucial focal points for the movement of people traveling along or across the Vesdre River. Thus, the manner in which residents adapt their travel behaviors in response to the degradation of some infrastructure directly impacts the choices regarding the measures that need to be enacted. In addition, policymakers are pressured to implement adaptation strategies to strengthen disaster resilience in response to the increasing frequency and intensity of flood hazards in the future [1]. Implementation of Intelligent Transportation Systems (ITS) represents a transformative approach to building more efficient, sustainable, and resilient urban transportation systems [2]. Individuals unknowingly participate in the collection, transmission, and application of Big Data within ITS, thereby contributing to the ITS data gathered through passive collection methods [3]. The rapid evolution of mobile technologies has enabled the use of passive Big Data within ITS, including mobile phone-based origin-destination (OD) matrices constructed from cellular network signaling data [4]. These datasets have proven particularly valuable for studying human mobility patterns [5] and natural hazard management, supporting applications ranging from real-time evacuation modeling and population displacement tracking to post-disaster recovery assessment and infrastructure damage inference [6].

Understanding shifts in human mobility caused by external factors (for example, natural disasters) can help develop responsive transportation strategies. After disruptions caused by floods in July 2021 in Belgium, mobile phone data (MPD) can be applied to analyze traffic patterns and movement restrictions experienced during the incident to improve future responses. This can include identifying critical failure points in the transportation system that can be strengthened against similar events. Despite the consensus that failures in infrastructure systems may cause societal disruptions, empirical evidence on the impacts of floods on these systems is still limited [7]. Therefore, there is a growing demand to enhance studies examining the effects of floods on traffic systems [8]. The research presented in this paper aims to bridge the gap between empirical evidence on the damage to transportation infrastructure and the changes in mobility patterns that occur in the medium term following floods.

This study is structured around several axes: first, it aims to determine how movements within the watershed have evolved in the medium term following the floods. Next, it will involve a detailed assessment of the damage to the engineering structures of the Vesdre River valley. The final objective of this research is to establish whether changes in the mobility habits of populations living in the Vesdre watershed correlate with the damage and disruptions observed in the transportation network's structures. Beyond the case study of the Vesdre watershed, this work seeks to demonstrate whether the disruption of mobility infrastructure due to a major climatic event has a lasting impact on the mobility of a territory.

The remainder of the paper is organized as follows: Section II presents data related to the Vesdre watershed, to identify the unique characteristics of the research area. Section III analyzes whether there is a correlation between disrupted transportation infrastructures and changes in mobility. This analysis is performed using a Tobit regression model, which is based on the OD flows calculated from the MPD and the parameters established in the database that reflect the state of the transportation network. In Section IV, we present the main evolution of mobility within the Vesdre catchment area and identify the criteria that have significantly influenced mobility choices. Finally, we expand our discussion in Section V and conclude in Section VI.

II. Data

A. Context

The Vesdre is a river that originates in the heart of the Belgian Ardennes, at an altitude of over 600 meters, and flows into the Meuse River in the southeastern suburbs of Liège. Its length is 73 kilometers. The entire Vesdre watershed encompasses an area of 700 square kilometers [9]. The morphology of the territory has been shaped by the development of the railway during the 19th century, with industries established along two historic railway lines: one runs along 80% of the Vesdre, and the other follows two of its tributaries. This development led to urbanization around the valley floor communities, which later extended along the historic road during a second wave of urbanization after World War II [10]. Advancements in the automobile industry subsequently led to the development of the road network in the valley. In contrast to the historic roads that traverse the valley, three highways were added to this network after World War II, connecting the various surrounding plateaus: the Liège - Aix-La-Chapelle motorway north of the Vesdre, the Liège - Luxembourg to the west, as well as a motorway crossing the Vesdre at Verviers, in the heart of the basin (Fig. 1). Subsequently, urbanization expanded onto plateaus.

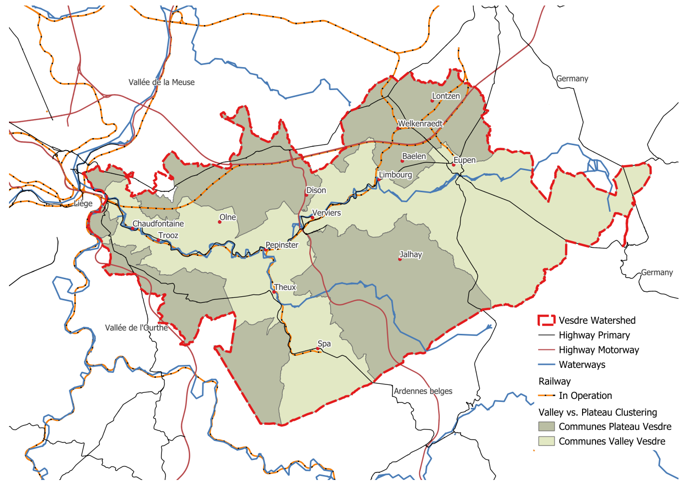

Fig. 1. Transport network within the Vesdre watershed.

From July 12 to 16, 2021, exceptionally heavy rains fell in eastern Belgium and Germany. The Vesdre River valley, which was the most severely affected by the inclement weather, experienced two peaks in precipitation on July 14 and 15, resulting in some of the highest rainfall amounts [10]. All municipalities in the valley suffered damage during the 2021 floods. Throughout the Vesdre watershed, a total of 142 crossing structures were damaged, including 27 that were destroyed and 83 that were affected in their functionality. The Walloon region reported 39 bridges that were either partially or completely out of operation during this disaster [10]. Moreover, 15 road connections facilitating inter-communal travel were interrupted [11]. This mainly concerns structures with lower heights and central piles, both of which retain the solid debris and obstruct the flow. Reference [12] reported that more than 4,400 cubic meters of visible debris had accumulated against the bridges of the Vesdre River.

Public surveys conducted by the Belgian mobility service in 2010 [13] and 2017 [14] provide insights into the mobility habits of the Belgian population. The car remains the most preferred mode of transportation. In 2017, 84% of Belgian households owned at least one car, which serves as the primary means of commuting to work [14]. In Wallonia, where the Vesdre River valley is located, 73% of residents preferred to use a car, while 10% preferred public transportation and 2% chose to cycle.

B. Mobile Phone Data

Two data sets are available: one collected between January 9 and March 19, 2018, and the other between March 7 and June 7, 2022. Public holidays and school vacations were excluded, while weekends were included in this study. In the remainder of this document, these datasets will be referred to as 2018 and 2022 for simplification, respectively. The methodology for data collection and rectification, along with its main advantages and disadvantages, will be described first, followed by a discussion of significant results, particularly in relation to the impact on mobility infrastructure disruptions.

The MPD originate from the network operator Proximus, which holds about 40% of the market share in 2022 mobile phone operations in Belgium. The data collection is based on signal transactions: each mobile phone emits signals when it is used by its owner, primarily for communication, but also when switched off to maintain regular contact with the global network. Thus, an individual with a phone using a Proximus package can be located geographically several times a day, depending on their phone usage. This method allows for the use of a wide range of data regarding individuals' locations. However, the location is approximate as only the position of the antenna receiving the signals is known. Therefore, the position of the mobile phone can be determined at the scale of the antennas, assuming the mobile phone transmits to the nearest one. Each transaction of an individual Proximus user is geolocated using the coordinates of the antenna segment where it occurs, creating a Voronoi diagram representing Proximus' cellular coverage in Belgium. As a result, the movements of mobile phone users can be analyzed. Proximus estimates that an inter-communal move occurs from zone A to zone B when a mobile phone does not transmit a signal in any area other than zone B for at least one hour. If the mobile device is connected to an antenna for less than an hour, then zone B is regarded as merely a transit point and does not appear in subsequent movement data.

Due to the Regulation General on Data Protection (GDPR), data were aggregated when it fell below a certain threshold. Aggregation of MPD was conducted in both space and time by Wallonia SPW Mobilité et Infrastructure, allowing data to be reported hourly, daily, or averaged over several days. The data received represent the average daily flows for each origin-destination pair, categorized by specific time slots. To accurately reflect the entire population, Proximus adjusted the flows of two sets of MPD using an undisclosed algorithm based on population statistics and the most probable place of residence. The research area in this study encompasses 17 municipalities and 52 sub-communes.

C. Post-flood Transportation Conditions

All potential infrastructures included in the inventory were assessed and surveyed, including bridges, footbridges, railways, retaining walls, dikes, and tunnels. The inventory also includes ford crossings. Information was collected concerning the name of the infrastructure, the municipality to which it belongs, and its nature. Moreover, if the infrastructure was cut off during the floods, the date of reopening was noted if it was not immediately restored. The status of whether the infrastructure was functional at the time of the 2022 Proximus data collection was also noted. Data were gathered through various interviews and discussions with work managers and asset managers, specifically the affected municipalities, the Public Service of Wallonia (which oversees national road works), and Infrabel (which manages the majority of rail infrastructure). A visual inspection was also conducted on-

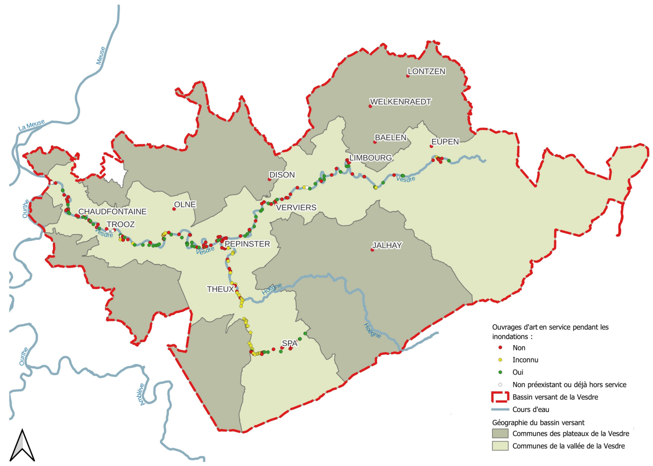

Fig. 2. Condition of infrastructures at the time of the floods of July 2021.

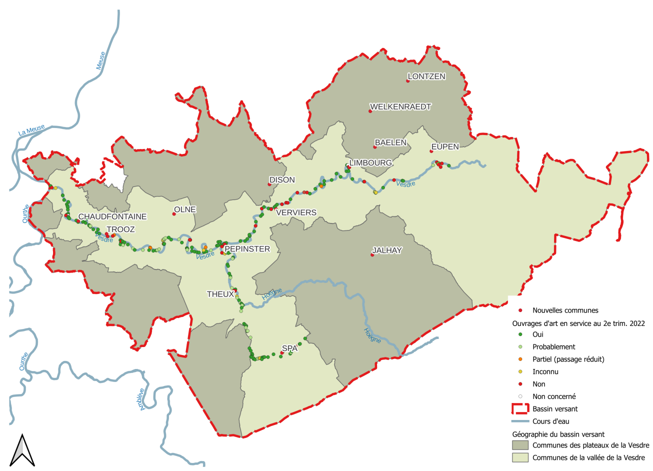

Fig. 3. Condition of infrastructures at the time of the Proximus data collection, during the second quarter of 2022.

site to assess the condition of structures three years after the events, in order to gain a better understanding of their overall state. Additionally, information was collected from municipal Facebook groups, as well as from national and local media outlets (Vedia, Sud Info, La Four, RTBF). Fig. 2 and Fig. 3 illustrate the status of transportation infrastructure during the floods and during the collection of MPD in 2022. Infrastructure status is color-coded as follows: red for out of service, green for in service, and yellow for unknown status. Overall, we found:

- 232 infrastructures in total, including 142 bridges, 52 footbridges, 12 tunnels, 5 viaducts, and 4 dikes, etc.
- 96 infrastructures interrupted during the floods, about 41% of the total existing in 2021, compared to 76 remaining in service, and 60 without information. The high number of infrastructures lacking information is primarily due to a low response rate.
- 186 infrastructures in certain or probable operation during the 2022 Proximus survey, approximately 80% of the total

existing at that time, compared to 27 out of service (undergoing work, interrupted pending work, or not rebuilt), 6 in partial service (with alternating or narrowed road circulation) and 13 without information.

Among these infrastructures, the reopening times of train lines in the affected railway network were influenced by the number of structures that each line needed to cross, as well as the extent of the damage sustained. For instance, one Belgium-Germany TGV line, which crossed only one structure on the Vesdre at Chênée, resumed service on July 19, 2021. In contrast, the downstream section of line 37 (Liège-Verviers) reopened on September 1, while the upstream section recovered on September 13, as it involved multiple structures that were affected. Additionally, one line (Liège-Eupen) was diverted over the plateau during the rehabilitation works due to the disruptions. In terms of the road network, which remained the most utilized, Vesdre cities such as Verviers had the highest number of out-of-service infrastructures in the second quarter of 2022, with a total of 7, followed by Eupen with 4 and Trooz with 3. Among all the infrastructures that were out of service or in partial service, the vast majority (77%) are managed at the municipal level. Only 4 infrastructures are located on the national roads that run alongside the Vesdre River over a length of approximately 10 kilometers.

III. Modeling Impact of Disruption on Mobility

This section aims to connect the observations made in MPD and the post-flood engineering conditions to determine whether a link exists between the failure of transportation infrastructure and the evolution of mobility in the Vesdre River valley, using a specific statistical method: Tobit regression. The first part will outline the principles of Tobit regression. The second part will detail the variables of the regression model. Finally, the method will be applied to various parameters from the database constructed in Section 3 to assess its influence or lack thereof on mobility changes.

A. Tobit Regression

In this study, the dependent variables are the flows between municipalities A and B in 2022, with A and B representing any of the 52 sub-communes in the Vesdre watershed. The independent (explanatory) variables include the flows between A and B in 2018, along with various parameters describing the state of the transportation network in 2022 as impacted by floods. First, linear regression is a theoretically valid method for estimating the evolution of mobility. However, we observed that the origin-destination matrices contain numerous zero values, particularly when the two municipalities are separated by several dozen kilometers. One possible method to address the prevalence of zero values is the use of Tobit regression, as Tobit models refer to regression models in which the arrangement of the dependent variable is constrained in some ways [15]. The use of the Tobit regression model to handle sparse OD matrices has precedents, such as in [16], where it was employed to relate Twitter-based OD flows to traditional travel demand models. The Tobit model is also known as a censored or truncated regression model, which estimates the dependent variable (y) according to the following equation:

$$y_i^* == \begin{cases} \beta_0 + \beta_k x_{ik} + \epsilon_i & \text{if } y^* > y_0 \\ 0 & \text{if } y^* \leq y_0 \end{cases} \tag{1}$$

where $\epsilon_i \sim N(0, \sigma^2)$, $y_0 = 0$, indicating that the number of flows during regression is constrained to be non-negative, which means that the observed flow $y_i = 0$ is left-truncated. The difference between truncation and censoring is that truncation is a model of selection bias (selecting only those data points whose values are non-negative), whereas censoring is a model of missing observations (there is an underlying true value that is hidden) [17]. The calculation is performed based on the maximization of the log-likelihood function (L) for the Tobit regression model:

$$\begin{aligned} L(\beta, \sigma) = & \sum_{i \in \text{untruncated}} \log\left(\frac{1}{\sigma}\phi\left(\frac{y_i - x_i\beta}{\sigma}\right)\right) \\ & + \sum_{i \in \text{left-truncated}} \log \Phi\left(\frac{y_i - X_i\beta}{\sigma}\right) \end{aligned} \tag{2}$$

with probability density function ϕ and cumulative distribution function Φ. It directly reflects how likely it is for observed values to fall at or below the censoring point (0) based on the fitted model.

B. Explanatory Variables

We sampled all OD pairs in the Vesdre River valley, totaling 2,704 items. The 2022 flows were used as the dependent variable to be explained. For the explanatory variables regarding 2018 flows, we included two for all tests: the 2018 flows and a binary variable that equals 1 if it is an intrazonal trip, and 0 otherwise. This allows us to account for the differing treatment of these flows during data processing. In addition, explanatory variables regarding the status of transportation infrastructure in relation to floods include:

1) The number of out-of-service infrastructures in the origin and destination during the 2022 survey;
2) The number of infrastructures that experienced flooding in 2021 in both the origin and destination;
3) The number of out-of-service infrastructures during the 2022 Proximus survey located on the shortest route between the urban centers of the origin and destination;
4) The number of infrastructures that experienced flooding in 2021 situated along the shortest route between the urban centers of the origin and destination.

The shortest paths were calculated using the shortest path algorithm in QGIS, based on the entire Belgian road network accessible by car, excluding local roads. These routes are not necessarily the fastest or most preferred in practice. The specific choice of route is less critical here, as we are primarily concerned with the bridges crossed. At this scale, the number of possible crossings is significantly reduced. During the data collection, we noticed that Vesdre cities Pepinster and Eupen have a municipal bridge located less than 150 meters from a national transit river bridge. In such cases, if the algorithm indicates a route through the municipal bridge, it is manually adjusted to use the national bridge instead. Additionally, urban centers were manually positioned in the most densely built-up areas along the highest-grade road crossing.

IV. Results

A. Evolution of Mobility

The Vesdre catchment area is centered around two main hubs: Verviers, which attracts flows from nearby municipalities, and Eupen, a secondary hub drawing from surrounding German-speaking areas. There is also a less-defined hub in the west, likely related to the city of Liège, located just outside the catchment. The three largest flow pairs are Verviers-Andrimont, Verviers-Heusy, and Eupen-Kettenis. Andrimont and Heusy are the main suburbs of Verviers, while Kettenis is the only municipality directly next to Eupen and mainly functions as a residential area with limited amenities. As a result, these municipalities depend more on nearby urban areas for daily activities. We analyzed specific municipalities in the valley by looking at the flow changes from the cities studied to others. For each destination B and potential origin A, we calculated the trip ratio from A to B among all flows to B for 2018 and 2022. Fig. 4 and Fig. 5 display the differences in these ratios (2022 minus 2018), allowing us to evaluate the attractivity of representative municipalities.

Starting with Verviers (Fig. 4), we see a significant decline in attractivity for nearly every other municipality. Apart from Andrimont and Heusy (blue line in Fig. 4), which show an increase, indicating that these residential areas rely heavily on Verviers for shopping and employment. Since Verviers is the main center of the catchment area, it was greatly impacted by flooding, particularly in its older central areas where shops and infrastructure are located. Many of these remained closed in 2022, allowing secondary centers in nearby municipalities, like Ensival and Dison, to grow. Additionally, studies aimed at reducing future flooding risks resulted in the demolition of many buildings near the river.

In contrast, Eupen did not experience significant effects from the 2021 floods, with noticeable declines only for the municipalities of Jalhay and Goé (red line in Fig. 5), which are located on the opposite side of the Vesdre. However, the infrastructures crossing the Vesdre were mostly preserved during the flooding. Eupen remains well-connected to northern municipalities, as most of the city is situated on the right side of the river, alongside the train station and highways leading to Liège and Germany. As a result, the floods did not disrupt the travel routines of Eupen's residents. Additionally, the connection with Kettenis has increased by 20.2%, as both municipalities are developing in proximity to each other, while Kettenis still lacks a secondary city center.

Finally, we conducted the same analysis by aggregating the municipalities based on their proximity to the Vesdre valley, specifically, those that are partially located in the valley (meaning that at least one district borders the Vesdre

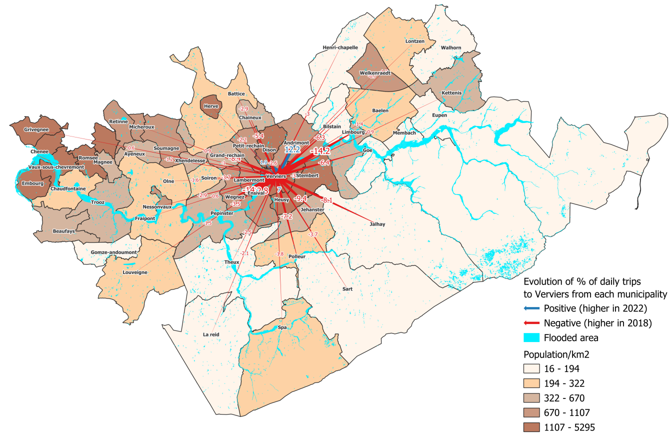

Fig. 4. Evolution of Verviers attractivity inside the catchment area between 2018 and 2022

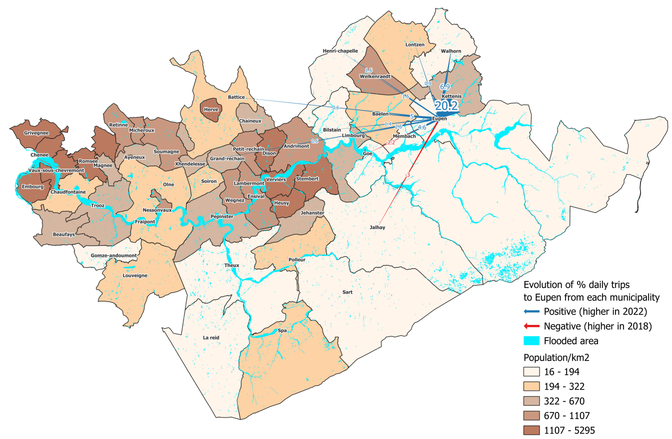

Fig. 5. Evolution of Eupen attractivity inside the catchment area between 2018 and 2022.

or one of its tributaries) versus those that are not, which are classified as being at higher elevations. We observed an increase in trips within municipalities located in the heights, at the expense of flows connecting these municipalities to those in the valley. Flows between the two municipalities in the valley remain relatively stable. This indicates a gain in attractiveness for the municipalities in the heights, as they have more space for growth and new construction projects, while valley municipalities are largely constrained by existing developments and geographical features (such as slopes and rivers). This trend also suggests that these developing municipalities are becoming more independent, further supporting the observations made regarding Verviers.

B. Impact of Distruption

The Tobit regression analysis initially tests the significance of a binary parameter indicating inter-communal travel, finding it significant with a coefficient ($\beta = 18440$), suggesting that the evolution of mobility has an effect on intra-communal

TABLE I
PARAMETERS FOR TOBIT REGRESSIONS

Parameter	DF	Estimate	SD	t Value	P Value
Intercept	1	-1.49	0.12	-12.96	<0.0001
β_1	1	1.39	0.14	98.66	<0.0001
β_2	1	18.90	0.84	22.49	<0.0001
β_3	1	-4.26	0.38	-11.10	<0.0001
Sigma	1	5.40	0.08	68.00	<0.0001

flows. However, due to methodological uncertainties, extrapolating this result to real conditions is not feasible.

Subsequently, the explanatory variables related to the disruption were tested one by one. We found that the gross number of out-of-service infrastructures is not significant in explaining the variations in flows between 2018 and 2022. However, when these data are weighted by distance, significance was observed in the impact on travel demand between the departure and arrival sub-communes. This indicates that the number of impassable roads does not affect mobility habits, but internal accessibility by car does.

Table I presents the final results of parameter estimation. The coefficients are as follows: β_1 is the parameter for flows 2018, β_2 corresponds to intra-communal, and β_3 is the parameter for the number of out-of-service transportation infrastructures per kilometer. The coefficient β_1 reveals that the 2022 flows are, on average, 1.39 times higher than those in 2018. The estimation is based on the assumption that the trip rate remained consistent between 2018 and 2022. Therefore, we rescaled the 2018 data to meet this condition. Apart from β_1, the other estimated parameters in Table I were scaled by a factor of 1000. Therefore, β_2 demonstrates that the intra-communal trips in 2022 are 18.9 times higher than those in 2018; β_3 indicates a loss of 4,260 trips for each out-of-service infrastructure per kilometer between sub-communes. This highlights the significant impact of transportation infrastructure disruptions on the mobility of residents. Furthermore, the Pearson coefficient, which incorporates out-of-service infrastructures in relation to distance, is 88.33%.

V. DISCUSSION

The cross-analysis of MPD and the state of the transportation infrastructure network conducted in this project results in an analytical study that outlines current mobility habits without recommending any specific course of action. However, the findings have the potential to influence the design of transportation networks, urban areas, and engineering structures more broadly. Given the anticipated increase in flood risk over the coming decades due to climate change, this project can serve as a valuable guide for navigating one aspect of the environmental transition concerning flood risk management. It also addresses social transition, as populations affected by floods - or those whose mobility depends on vulnerable infrastructure - are among the first to feel the impacts of necessary changes. Moreover, this paper enables a detailed understanding of how specific events, such as floods, affect mobility patterns in particular locations and provides valuable insights into developing adaptive strategies. The insights gained can guide the incorporation of resilient features into new designs or modifications to existing infrastructures. The research can foster collaboration among various stakeholders, including local municipalities, transportation agencies, and emergency services, to create integrated transportation systems that are responsive to flood risks. By utilizing ITS analytics, these groups can collaborate to develop a cohesive strategy that enhances overall infrastructure resilience.

While this study offers valuable insights, certain considerations should be noted to inform future research. For instance, the MPD used may reflect varying market shares between 2018 and 2022, which could introduce some variability in the results. Additionally, seasonal trends were not explicitly analyzed, presenting an opportunity for further exploration. The granularity of the data, while sufficient for identifying broad mobility patterns, limits more detailed behavioral interpretations. Finally, although validation of the observed mobility evolution was beyond the scope of this project, future studies could build on this foundation to conduct more comprehensive validations. Addressing these areas can enhance the robustness and applicability of future mobility and infrastructure resilience analyses.

VI. CONCLUSION

We examined specific changes in people's mobility related to the flood of 2021 using MPD collected in 2018 and 2022. Comparison of OD matrices enables us to assess medium-term developments between municipalities within the territory. In addition, we developed a comprehensive database detailing the condition of all transportation infrastructures vulnerable to flooding in the Vesdre River valley. This allowed us to assess the overall state of the transportation service during the floods and in the second quarter of 2022, enabling us to examine the impact of disruptions on mobility patterns.

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