Methodology for the damage assessment of vehicles exposed to flooding in urban areas

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Abstract: Within urban areas humans carry out a great diversity of activities, and some of them require the use of vehicles. Floods, especially in urban areas, can generate significant tangible direct damages to vehicles themselves and to the urban elements in case of loss of stability and collision, which cannot be dismissed. In this paper, after a state-of-the-art review on damage curves for vehicles, a methodology to assess the direct economic impact for vehicles exposed to flooding has been described, and applied within a study carried out in the framework of the BINGO H2020 EU Project. Only three different studies focused on damages to vehicles in contact with floodwater have been found. Contrasting damage curves for vehicles are found when comparing the three approaches, however the ones proposed by the USACE offer a high level of completeness and accuracy. Moreover, USACE's development is the most current research and all the steps for the development of the damage curves are comprehensively described. Finally, after the description of a detailed methodology for flood damage mapping for vehicles, a procedure to evaluate the Expected Annual Damage for vehicles is offered.

Keywords: Urban flood risk; vehicles; damage curves; Expected Annual Damage.

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1. Introduction

During an extreme flood event, mainly in urban areas, vehicles can suffer hydroplaning or instability due to three types of phenomena: floating, sliding or toppling (Shand et al. 2011). However, the most frequent are the first two and for most cases the instability occurs as a combination of both, floating and sliding. The instability of vehicles has been studied by different authors and a comprehensive analysis of the state of the art on this issue can found in Martínez-Gomariz et al. (2018). Moreover, after losing stability the vehicle becomes buoyant and may be washed away colliding with other urban elements, with potential injuries or fatalities (intangible damage). In this context, vehicles might be considered as massive debris washed away by the flood that could generate significant economic damage and even compromise pedestrian safety.

Floods can cause different damages: economic damage (national, community or individual) causing a certain number of properties affected, damage to individuals (deaths, injuries, affections) and/or ecologic and environmental damage (occasionally expressed in monetary terms). Flood damages can be tangible or intangible, defining tangible as those impacts measurable in monetary terms and intangible as those impacts, like people injuries or deaths, that generally are assessed in different terms (Landefeld and Seskin 1982). Within urban areas it can be said that, generally speaking, properties (tangible damages) and pedestrians (intangible damages) are the most affected when an extreme flood occurs. Urban elements like services or infrastructures are affected in a tangible manner by flooding, and particularly vehicles. In turn, flood damages can be classified also as either direct or indirect, whether, respectively, it is due to the physical contact with the water or not (Grigg and Helweg 1975; Hammond et al. 2015).

Therefore, floods, especially in urban areas, can generate tangible direct damages to vehicles themselves and to urban elements in case of loss of stability and collision. A clear illustration of these damages is the massive flash flood that occurred in Boscastle (UK) on 16 August 2004 caused by an extreme rainfall event up to 200 mm in 5 h, causing millions of pounds of damages and more than 100 vehicles washed away. Furthermore, the washed out vehicles caused the blockage of a bridge, which collapsed, aggravating greatly the damages.

Nonetheless, also indirect tangible damages (like loss of production) due to traffic disruption can be produced. Costs associated with traffic disruption are an often overlooked indirect impact of flooding

(Hammond et al. 2015). Furthermore, vehicles do not need to become unstable to suffer economic damages, because even if they do not reach the instability threshold, will be partially flooded, resulting in economic costs that cannot be neglected. Some US entities such as the National Auto Auction Association (NAAA, n.d.) conduct studies to detect when a vehicle being offered for sale was actually damaged by a flood.

In this paper, a methodology to assess the direct economic impact for vehicles exposed to flooding is described. Firstly, an overall description of traditional flood damage assessment in urban areas is presented, together with a review of the existing flood damage curves developed for vehicles. Subsequently, a description of the case study where the assessment has been conducted is presented, as well as the reasoning for the adequateness of the selected damage curves for vehicles. After the description of a detailed methodology to assess the economic damage of vehicles exposed to flooding, a procedure to evaluate the Expected Annual Damage for vehicles is offered. Finally, some conclusions are presented together with a proposal for future developments regarding the undertaken technique.

2. Criteria for direct flood damage assessment in urban areas

Flood damage assessment is one of the major concerns after a flood occurs, especially when it comes to flash floods striking urban areas. Usually, most studies undertaking this assessment focus on damages to properties, and the basic tool to carry out this task is the so-called flood damage curves or functions.

The pioneer in considering damage to properties was Gilbert F. White (1945) in his doctoral thesis entitled "Human Adjustment to Floods: A Geographical Approach to the Flood Problems in the Unites States". Among other issues White (1945) defined in greater detail the types of losses when a flood occurred, describing, among others, losses to properties and shops in urban areas. Losses in residential areas could be foundations and structure of dwellings, garages and other buildings, such as cars or other vehicles, damages to the terrain and others like loss of the property rental income. However White (1945) did not define direct or indirect damages per se. There was stated also that water depth and velocity were the variables which established the degree of severity for damages to foundation and structures of dwellings. According to White (1945), water depth was the most limiting condition for such losses.

In flood risks studies, particularly in urban areas, usually direct and tangible damage assessments (i.e. in monetary terms) based on hydrodynamic models are carried out by employing as input design storms related to different return periods. Direct and tangible damages to properties vary depending on the type of property, its value, and the restitution costs to initial state (Grigg and Helweg 1975).

Apart from either building types or land use, depending on the scale level of the analysis approach (Messner and Meyer 2006), the potential damage degree to a structure or a land use can be measured through damage curves, which are functions of water depth. These curves can measure damage percentages, according to the water depth around, for different flood event intensities, or may be represented based on monetary units over surface unit, format more useful for mapping purposes.

Several proposals of flood damage curves can be found worldwide, such as in Australia with the Queensland Government guidelines (EMA, 2002), in USA with the guidelines proposed by the Federal Emergency Management Agency (FEMA, 2015), in Spain (Valencia) with the criterion proposed within the EU Project CRUE (Francés et al., 2008), in Italy with a particular development proposed by the Research Institute for Geo-hydrological Protection of Turin (Italy) for river Boesio flooding (Luino et al. 2009), in the UK with the criterion proposed in the Multi-Coloured Manual (Penning-Rowsell et al. 2005) More recently new damage curves, focused on urban pluvial flooding, were performed for the district of El Raval (Barcelona) in the framework of the EU Project CORFU (Russo et al. 2013; Velasco et al. 2013).

Therefore, in case of a flood damage assessment for an urban area and if available the geo-referenced type buildings and the related damage curves, by employing GIS tools, the direct damage assessment for buildings can be conducted. On the other hand, a great diversity of vehicles can be found in urban areas, being cars the most predominant. Accordingly, the economic impact to vehicles when an urban flood occurs cannot be neglected.

3. State-of-the-art review: flood damage curves for vehicles

Damage curves associated with vehicles can be presented too, following the same criteria as for buildings, in order to find the damages to the vehicle as a function of the water depth. This approach is found in the literature although it is a less mature research than damage curves for buildings and has been carried out by a small number of authors. Only three developments have been found within the bibliography. The approaches, that are summarized in Table 1, are those proposed in the HAZUS-MH model developed by the US Federal Emergency Management Agency (2015), the criteria proposed in the CRUE project (Francés et al., 2008) and, finally, the one proposed by the U.S. Army Corps of Engineers

(USACE, 2009).

3.1. Federal Emergency Management Agency Criterion

The U.S. Federal Emergency Management Agency (FEMA) developed in 2003 the project HAZUS-MH (FEMA, 2015), which name comes from “Hazard United States-Multiple Hazards”. Through HAZUS-MH, science, engineering and mathematics are combined with GIS technology to estimate loss of lives and properties through mapping representation. HAZUS-MH estimates the physical, social and economic impact that a community might suffer because of an earthquake, flood or hurricane. This tool development aims to help, prepare, mitigate, response and recovery from a hazardous event such as earthquakes, floods or hurricanes. Specifically, the HAZUS-MH module aimed at floods is able to assess damages due to impacts of coastal or riverine flooding. It estimates potential damages caused to buildings, essential facilities, routes and agriculture areas, shelters and fatalities. Direct losses are estimated based on physical damage to the structure, contents and inside buildings. Flood damage to vehicles can also be estimated through HAZUS-MH (Scawthorn et al. 2006; FEMA 2015). The procedure to carry out this assessment is divided in four parts:

1. Calculation of vehicles inventory within the study area
2. Vehicles localisation according to any time of the day in different positions
3. Estimation of vehicles monetary value
4. Application of a damage curve according to the type of vehicle

The proposed method for the vehicles localisation aims to obtain the number of vehicles according to the car park type, vehicle age and type, and time of the day.

Moreover, the program associates a parked vehicles ratio per square meter of building structure which are categorized into 33 occupancy groups (11 are residential, 10 are commercial, and 6 are industrial). Several illustrative examples of the vehicles assignment procedure to any building category can be found in the HAZUS-MH manual. In this manner, the number of potentially vehicles at risk are determined, being this figure distributed among the different types of available car parks within the study area. On the other hand, vehicles were classified within three typologies: cars, light truck and heavy truck. Vehicles age distribution and trucks ratio versus cars was carried out by the National Automobile Dealers Association (NADA).

A price for each type of vehicle is proposed: 22618.47$ (cars), 20969.21$ (light trucks) and 76087.67$ (heavy trucks), as a result of averaging different values obtained by consulting car dealerships and websites. A used vehicle is allowed to be valued as 50% of the original price. In order to compute the total value of all vehicles located within the study area, the number of total vehicles will be multiplied by the percentage of cars/light trucks/heavy trucks, percentage of new/used vehicles and the average value of vehicles that match both categories.

The implemented flood damage curves for vehicles were developed by considering a gradual damage due to the water level. That is to say, whereas for 30 to 60 cm (1 or 2 feet) of water depth damages to the vehicle are unlikely, a total damage will be caused when the engine compartment will become totally submerged. Moreover, an early warning system is considered to avoid the damage completely because the vehicles' owners have time enough to move them to safety areas. The development of the flood damage curves was conducted with the support of an expert in this field. Their development was based on the delimitation of three levels of water depths: under the vehicle's carpeting, between the carpeting and dashboard, and beyond the dashboard. These flood damage curves are shown in Figure 1a.

3.2. CRUE EU Project Criterion

ERA-Net CRUE is a network of European government departments who directly fund flood risk management programmes and related research actions. The creation and implementation of a European research area in flood risk management – as intended by the CRUE ERA-Net - is an important contribution to an improved trans-national perspective for flood-related research in Europe.

Each of the seven successful joint projects within CRUE's 1st funding initiative for flood risk management research was designed to understand different national approaches to the use and appraisal of non-structural measures, explore what is successful, and what can be improved in terms of efficiency and effectiveness of such measures themselves.

One of the sections of this project focuses on the risk assessment to the Rambla del Poyo basin (Valencia, Spain), developing firstly hazard maps, secondly, studying the vulnerability within the flooded area, and finally estimating the risk. In the second step (i.e. vulnerability analysis), it is intended to assess damages to movable assets (residential constructions and elements of public areas) and buildings (residential constructions). Moreover, damages to furniture and structures for industrial, commercial and storing uses are estimated. The ultimate purpose is to obtain the vulnerability curve (i.e. damage curve) associated with each use. This curve reflects the damage expressed in Euro to each affected use as a function of water level.

The Rambla del Poyo covers the West area of Valencia. It mainly and specifically affects to the municipalities of Chiva, Cheste, Loriguilla, Quart de Poblet, Torrent, Picanya, Paiporta and Catarroja. The analyzed municipalities to obtain the vulnerability curve are these: Alaquás, Aldaia, Alfafar, Catarroja, Massanassa, Mislata, Paiporta, Picanya, Quart de Poblet, Riba-roja del Túria, Torrente, Valencia and Xirivella.

In the same manner that damage curves were proposed to different typologies of buildings, also damage curves for vehicles were presented. Those curves were developed only for two types of vehicles: diesel and gasoline. In Figure 1b both curves are showed together with the averaged one. The scale of analysis in this case study, in order to assess the flooding risk, considers the number of cars per square meter of flooded street. In this damage assessment for vehicles, also costs related to street cleaning and drainage were taken into account.

3.3. U.S. Army Corps of Engineers Criterion

The US Army Corps of Engineers (USACE) conducted a specific study for the development of damage curves for vehicles exposed to flooding. This study is reported as a Memorandum: Economic Guidance Memorandum, 09-04, Generic Depth-Damage Relationships for Vehicles (USACE, 2009). The USACE's Water Resources Institute's "Flood Damage Data Collection Program" collects information from past floods in order to produce reliable estimations on economic damages due to flood events. As part of the surveys carried out to determine the effects of flooding on residential properties, data were also collected on the damage caused to vehicles parked in such dwellings for the ten communities that suffered the greatest floods. The baseline information for the development of such curves (Figure 1c) was therefore the data provided by the affected owners in relation to the estimation of the vehicle, the damage suffered and the depth of water that affected the vehicle. Damage curves were developed for five vehicle types (sedans, pickups, SUVs, sports, mini vans) from a sample of 640 vehicles. Such data were processed statistically to construct such curves by regression analysis.

Ultimately, the purpose of the memorandum is to provide guidelines for the generic use of damage curves developed for flood risk management studies requested by the USACE. These curves will be normally used in studies for urban flooding since in rural areas the density of vehicles is not considerable.

There are two methods to apply these curves, the first focuses on vehicles parked in residential locations and the other focuses on non-residential locations. The first requires different data: the height of the vehicle, which is assumed to be the rise of the affected residential property; an average of vehicles per property in the study area; the classification of these in the different types proposed; and finally, the percentage of vehicles that will actually be parked on the property when the flood affects that area. The memorandum offers different sources of information in the United States to obtain the data required to conduct the assessment of damage to vehicles.

The application to vehicles that are parked in non-residential locations is analogous but more specific data should be collected. In this case, sources are not provided in the memorandum. Obtaining the number of vehicles parked in shops cannot be carried out using the proposed residential method. The distribution of vehicle numbers and typology should be grouped by individual shops to accurately assess damage. However, the same generic damage curves can be used for both parked vehicles in residential and commercial areas.

4. Badalona case study (EU project BINGO)

The case study to undertake the flood damage assessment to vehicles is located in the Spanish city of Badalona. This city is one of the six areas across Europe in which the EU project BINGO (Bringing INnovation to onGOing water management - a better future under climate change (2015-2019)) is focused on: Portugal, Spain, Cyprus, Germany, the Netherlands and Norway. BINGO aims at providing practical knowledge and tools to end users, water managers, decision and policy makers affected by climate change to enable them to better deal with all climate projections, including droughts and floods.

Badalona, with more than 215,000 inhabitants within its administrative limits on a land area of more than 21.2 Km^2, is located in eastern Catalonia (Spain) and is part of the Barcelona metropolitan area (in Spanish AMB). It is located on the left bank of the Besòs River facing on the Mediterranean Sea, and backed by the Marina mountain range (Figure 2). Badalona is the third most-populated municipality in Catalonia after Barcelona and L'Hospitalet de Llobregat. The average population density of the city is around 10.000 inhab./Km^2, although this value can increase significantly in some districts of the old town and the city centre.

The morphology of Badalona presents areas close to the Marina mountain range with high gradients (4% on average) and other flat areas close to the Mediterranean Sea, around the historical centre. Quick hydrological response of these areas can generate runoff with high peak flow and significant velocities. On 14 September 1999 (Figure 3), as a result of precipitations between 50-100 mm in two rainfall events of around one hour of duration each, some ephemeral urban water courses overflowed. More than 1 million Euro was claimed to insurance companies for direct damages (e.g. underground car parks and metro stations flooded). Focusing only on vehicles damages, 136,000 Euro were claimed which was almost 14% of the total damages.

An integrated 1D sewer model (MOUSE Software) was developed in 2012 in the framework of the elaboration of the Badalona Drainage Master Plan (DMP) with a specific planning purpose, so it is not currently operative. In the framework of BINGO project, the sewer model was updated and exported to Infoworks Integrated Catchment Modelling (Infoworks ICM) provided by Innovyze. A 2D model for the overland flow simulation was coupled with the 1D sewer model. Finally, the integrated model was validated using the existent field data, 3 rain gauges covering uniformly the administrative land of the city and 17 flow depth level sensors located in the sewer network (van Alphen et al., 2016).

Four design storms have been developed for 1, 10, 100 and 500 years of return period, based on the existing rainfall IDF curves (Casas et al. 2010) developed through 5 minutes resolution time series measured in The Fabra Observatory, located in Barcelona next to Badalona. Thus, these design storms have been employed as inputs for the updated and coupled 1D/2D model and thereby obtaining, as outputs, four delimitations (i.e. one per return period considered) for the flooded area within the Badalona municipality limits. These outputs are the triangular non-structured grid cells considered for the 2D hydrodynamic calculation, and the resulting variable water depth, among others, is stored in each triangular cell. That is the starting data before the application of the methodology for the vehicular damage assessment due to flooding for each return period considered.

6. Methodology to assess the economic damage of vehicles exposed to flooding

In this section, a methodology to assess damages to vehicles exposed to flooding is proposed and implemented to the case study of Badalona. To do this, GIS tools, damage curves for vehicles and water depth maps were required as starting information in order to estimate the economic impact on vehicles. According to 2D hydrodynamic outputs, in this section damages to vehicles are estimated for floods related to four return periods (i.e. 1, 10, 100 and 500 years).

6.1 *Adequateness of the selected damage curves for vehicles*

According to the previous description of the approaches for the three damage curves founded, it is observed that the level of completeness and accuracy are quite different between them.

The HAZUS-HM damage curves were developed based on the location of critical vehicle components in passenger cars, light trucks and heavy trucks, and the floodwater depth. This development is briefly explained but it is not based on actual vehicles' damages but on the experts' opinion. The established flood levels are below carpet (damage ≤ 15%), between carpet & dashboard (15% ≤ damage ≤ 60%), and above dashboard (60% ≤ damage ≤ 100%), which take different values for each of the three types of vehicles considered. When water depth exceeds each established flood level, a significant change on slope is observed on the damage functions (Figure 1a). No ground clearance up to the vehicle floor is taken into consideration in the proposed damage functions, therefore unrealistic damages are provided even before the water depth could reach the vehicle's floor level. Although, one of these functions' positive aspects is that they were developed by considering relative damages, which allows their application in different cities or countries regardless price of vehicles.

The damage curves presented in the ERA-Net CRUE project are focused on two main types of vehicles, gasoline and diesel. No distinction of models not even if these are cars or trucks is provided, aspect which limits their application. However, these do specify a ground clearance of 15 cm, threshold up to which no damages are expected. One of their shortcomings is their development by considering absolute vehicle prices, which limits their broad application. Furthermore, a clear explanation regarding how they were developed is either not offered.

The USACE proposal, based on an empirical approach, is the most current research and all the steps for the development of the damage curves are comprehensively described. For those reasons, together with the availability of damage curves for five types of vehicles (sedans, pickups, SUVs, sports, mini vans), these curves were considered the most adequate to be adopted in this case study. On the other hand, the fact of the damage being expressed as a percentage makes that these curves can be transferred and applicable to other countries, taking into account the local price of vehicles.

As a general criticism for all three developments, it has to be noted that vehicles may lose their stability even for just 50 cm of water depth or less (Martínez-Gomariz et al., 2017; Martínez-Gomariz et al 2018) and therefore. This vehicle's instability may cause a total vehicle damage and after being washed away may collapse against other urban element, thereby increasing the damages. This issue will be addressed in future research.

In order to be applied, these damage curves, according to the methodology herein employed, must be modified from % damage to euro over square meter of affected area. According to the data provided by the Badalona City Council, 85% of registered vehicles in the municipality are Sedan style, and the rest 15% is formed by trucks and vans. In accordance with these percentages, the 15% of vehicles different from sedan style has been divided into five types of vehicles (Table 3), sedan, pickup truck, SUV, sport car and minivan, according to typologies proposed by USACE (2009). Averaged values of plan areas and prices of these types of vehicles were obtained, based on a sample of the 50 most typical Spanish vehicles. In addition, depreciation of averaged prices was considered based on both the average age of vehicles in Badalona and regulated depreciation vehicles values by Spanish Ministry of Finance (España, 2016). Therefore, the applied percentage depreciation for each type of vehicle depended on the average age of each type (Table 3), information facilitated by the Badalona City Council.

On the basis of the averaged characteristics for each group of vehicles, an average vehicle is established for each type. Therefore, a curve for each type of vehicle, based on both USACE curves and those average vehicles, can be performed as shown in Figure 4. In essence, the percentage of vehicles associated to each type is actually the probability of flood damage for each type of them (i.e. sedan style is more likely to be flooded than a van). In that sense, a unique damage curve may be representative enough if this is weighted according to the type of vehicles distribution in Badalona as formulated in equation (1) and represented in Figure 4.

$$D_w = 0.83 \cdot D_S + 0.075 \cdot (D_{PT} + D_{MV}) + 0.015 \cdot D_{SUV} + 0.005 \cdot D_{SC} \quad (1)$$

where D_w is the weighted damage, D_S is damage to sedan type, D_{PT} is damage to pickup trucks, D_{MV} is damage to minivan, D_{SUV} is damage to SUV type, and D_{SC} is damage to sport cars.

Note that the extension of the municipality is not large enough to find rather than an only average cultural scale, otherwise aspects such as richer areas where vehicles of higher quality could be found should be identified and some different weighted damage function developed.

6.2. Characterization of the vehicular occupation in Badalona

Based on aerial photographs of 25 cm resolution (Figure 5), obtained from the Cartographic Institute of

Catalonia (ICC), an assessment of vehicles presence has been conducted. The photographs resolution let to distinguish the presence of a vehicle, although it does not let to define clearly the type of vehicle. Uncertainty of vehicle types is included through the weighing of the damage curve, based on the assumption of the percentages of the different types of vehicles considered in Badalona.

Unlike static buildings, vehicle locations are spatially and temporally variable depending on the day and even the time of day. It seems reasonable to consider a workday as the most conservative period in terms of damages produced by a flood. In Figure 5 an industrial area of Badalona is shown, and two remarkable aspects must be noted: the great presence of vehicles indicates that the picture was taken in a workday and the number of vehicles circulating are negligible when compared with parked vehicles. Therefore, the instant when the photograph was taken is appropriated to carry out this study. Some other points of views could be discussed in this regard, however those are the conditions in which this study was conducted.

In order to assess the vehicular occupation in Badalona, eight analysis zones of 11,5 hectares each were considered, as shown in Figure 6 and 7, all of them representative of the existing urban patterns in Badalona. Those are zones in which every single vehicle inside the boundaries of each zone was delineated (Figure 7), thereby obtaining the number of vehicles within each zone and the approximate plan area of each vehicle. All these analysis zones have been placed in a distributed manner across the municipality of Badalona, only skipping the upper part of the municipality due to its rural character (i.e. very few vehicles are expected to circulate within this area). This distribution let us to study the vehicular occupation in enough spots to observe the diversity of presence of vehicles within the municipality. In Table 4 all the characteristics of the zones are shown. Among these characteristics, the percentage of vehicle area with respect useful area (i.e. area where a vehicle can be found, roads, car parks, etc.) was calculated too. Note the differences regarding vehicular occupation, being 2.3% the occupation within zone 6 (106 vehicles) and 9.8% (449 vehicles) within zone 1.

The vehicular occupation of each zone has been extended to a greater area called pattern (Figure 6). Therefore, each zone is considered as representative of the whole pattern and a heterogeneous distribution of presence of vehicles is defined for the whole municipality:

- **Pattern 1:** Industrial area of high vehicular occupation.
- **Pattern 2:** Residential area with high percentage of green areas and high vehicular occupation.

- **Pattern 3:** Semi-intensive urban area, with low percentage of historic centre and high vehicular occupation. Location between B-20 and C-31 motorways.
- **Pattern 4:** Industrial area of low vehicular occupation.
- **Pattern 5:** Semi-intensive urban area, high percentage of historic centre and high vehicular occupation. Location between C-31 motorway and beach front.
- **Pattern 6:** Urban area with high percentage of historic centre, high percentage of green areas and low vehicular occupation. C-31 motorway is included together with area next to the motorway and far from seafront.
- **Pattern 7:** Residential area with low vehicular occupation, including B-20 motorway.
- **Pattern 8:** Residential area with high percentage of green areas and low vehicular occupation.
- **No vehicles area:** Upper zone of the municipality, being almost entirely rural area. It includes an area located between B-20 and C-31 motorways to the East of the municipality limit.

6.3. Spatial distribution of vehicles

Two approaches can be employed when considering the spatial distribution of vehicles: complete and distributed approach. In a complete approach all vehicles must be delineated to define exactly their position (i.e. as it was conducted for the eight analysis zones) and by crossing their location with the hydrodynamic results (i.e. water depths) the weighted damage curves can be applied to each vehicle. This is the ideal approach, however the delimitation of each vehicles across the municipality is an extremely laborious work in case it is carried out manually. To give an idea of the scale, conducting a complete study for Badalona could take some days, while a distributed approach-based study would only take a few hours. Development of photogrammetry techniques to delimitate all vehicles in an automatic manner would represent a great advance in this sense, thereby avoiding manual work. Moreover, a frequent availability of satellite images would allow this process to be carried out for different time instants and to analyse variations regarding vehicular occupation depending on the instant.

Herein the simpler distributed approach has been applied because no photogrammetry or satellite techniques have been employed. Therefore, the distributed approach will take into account the heterogeneous vehicular occupation established after the study of the eight analysis zones. In that manner, each cell of the hydrodynamic results (Figure 8) is related to a pattern (Figure 6), in consequence each cell has its own vehicular occupation (%) (Table 4 and Figure 9) and water depth. Note that this approach dismisses the real location of a vehicle, although this fact is replaced by the definition of patterns of vehicular occupation. Moreover, the location is not of great importance when considering the fact that this is only a temporal situation when it comes to vehicles. By employing the distributed approach, the weighted damage curve was applied for each cell, thereby obtaining an economic cost in each cell. Thus, the aggregate of them will be the total damage within the study area for the correspondent event (i.e. 1, 10, 100 or 500 years return period).

On the other hand, both approaches (i.e. complete and distributed) were first applied only to the eight analysed zones (Figure 6) for validation purposes, thus both damage estimations might be compared. In this manner, the distributed approach, in case the comparison offers adequate results (i.e. small differences, considering the complete approach as the correct one), may be validated. In Table 5, both economic assessments are shown together at each analysis zone only for a flood related to a return period of 500 year, and a proper match can be observed. Furthermore, in Figure 11 it is observed that the tendency of damages is quite similar. Therefore, the distributed approach was considered to be appropriate to estimate damages to vehicles for all the municipality.

7. Damage mapping and Expected Annual Damage (EAD) for vehicles

The distributed approach was conducted for all considered events (i.e. 1, 10, 100 and 500 years of return period), thus, damage maps can be performed (Figure 13). Through these maps the critical areas regarding damages to vehicles can be spotted easily, even for non-experts.

Once the damage is estimated for the flooded area and for all return periods considered, the Expected Annual Damage (EAD) can be calculated. By employing the concept of risk to estimate the EAD, it can be calculated by integrating the area under the curve (Figure 14) formed after plotting the probability of occurrence of the damage and the monetary value of the damage according to expression (2) (Meyer et al. 2011).

Therefore, the EAD estimation consists of calculating the average damage of two events with probability of exceedance i, with a probability interval (ΔP_i) between probabilities of exceedance of both events. The EAD estimation was carried out for all considered events (i.e. 1, 10, 100 and 500 years of return period).

$$EAD = \sum_{i=1}^{k} D[i] \; x \; \Delta P_i \qquad (2)$$

Where,

EAD = Expected Annual Damage

$D[i] = \frac{D(P_{i-1})+D(P_i)}{2}$ $D[i]$ = Year average of two damage events $D(P_{i-1})$ y $D(P)$

$\Delta P_i = |P_i - P_{i-1}|$ ΔP_i = Interval of probability between probabilities of exceedance of both events

Beyond knowing if the estimated damage is little or much, what is worthwhile of this results is that EAD is a benchmark in order to evaluate risk reduction. Thus, initial results of EAD are an initial state of damages in Badalona in order to define mitigation actions and response to preparedness, medium-term plan in emergency management, as well as to propose public policies in this regard. Usually, within the literature this indicator has been utilized to assess damages to buildings, however in this study it has been focused only in vehicles.

In Table 6 the economic damages related to their probability of occurrence for 1, 10, 100 and 500 years of return period are shown. Such values have been obtained as the aggregated value of economic damage in each cell by applying the distributed approach and utilizing GIS tools. The graphic representation of these results is shown in Figure 14, and the EAD value was 320,983.31 €, obtained as a calculation of the area under the curve (i.e. aggregation of triangles and rectangles areas).

Actual damage data from the Consorcio de Compensación de Seguros (CCS), the re- assurance that covers the catastrophic and extreme situations in Spain, was obtained for the previously-described 14 September 1999 event and 31 July 2002 event. Among this data only tangible direct damages for vehicles were considered, adding up to a total of 136,000 € and 142,000 € respectively. The CCS damage data was compared to the estimated values.

By plotting damages to vehicles and return periods considered, a function can be fitted as indicated in Figure 12. In that manner, an estimation of damages for both considered events, which are related to a 3.3 (1999) and 1.7 (2002) years return period, can be carried out. The estimated damages, according to the fitted function (Figure 12), were of 199,240.14 € for the 14 September 1999 event and of 145,864.718 € for the 31 July 2002 event.

In order to conduct the damage assessment for all return periods it was considered a minimum limit of 500 € to be claimed for each average plan area of a vehicle (i.e. 7.51 m^2 according to Table 3). This assumption means that a vehicle's owner will not claim an amount lower than 500 €. It is consistent with the analysed real claims for the 1999 flood event, where only 5% of claims were lower than 500 €.

Even considering this assumption, as observed, the damages assessed are higher than the reported ones. Although this might seem inaccurate, especially for the 14 September 1999 event, some reasons can explain such differences:

- Vehicle distributions at the time of these actual events were different to the distribution used from the single aerial photo.
- Some of the flooded vehicles may have not reported their damages to the CCS (Velasco et al., 2015) because they were low (even higher than 500 €), or they were not aware that they could be compensated. Similar situations are observed elsewhere: in a study undertaken in the US (Cummins et al., 2010), it was found that for several natural hazards, the ratio between insured and total losses was on average smaller than 50%.
- The spatial distribution of the rainfall is essential when assessing damages for a larger area such as the municipality of Badalona. The design storms for each return period have been considered as uniform for the whole catchment. Therefore, only a part of the municipality might has been affected by the real 1999 flood event. No rainfall data in this regard is available for this event.
- Vehicles are movable elements within urban areas, thus, when owners are aware of the possibility of a hazardous event such as flooding, those could be moved to more secure areas. In the present simulations vehicles are considered to be placed at the same spot and damaged may be higher than in a real situation.
- Actual damages occur also in underground car parks, which have not been considered within this study but will be in future studies. The great amount of private underground car parks precludes to the municipality to have a database of their locations and characteristics. Moreover, the CCS does not know if vehicles were either damaged on surface streets or in underground car parks. Further research must be conducted in this regard.

8. Conclusions and future developments

Within cities there is a great diversity of vehicles and its number seems to increase worldwide. Although, particularly in Badalona its number has decreased (mainly due to economic crisis) over the last years. Traditionally, most studies undertaking flood damage assessment in urban areas focus on buildings, and the basic tool to carry out this task are the so-called flood damage curves or functions. However, floods, especially in urban areas, can generate significant tangible direct damages to vehicles themselves and to urban elements in case of loss of stability and collision, which cannot be neglected.

In this study, after a state-of-the-art review for damage curves for vehicles, a methodology to assess the direct economic impact for vehicles exposed to flooding has been described and applied within the BINGO H2020 EU Project framework. Only three different studies focused on damages to vehicles in contact with floodwater have been found. Contrasting damage curves for vehicles are found when comparing the three approaches, however the ones proposed by the USACE offer a high level of completeness and accuracy. Moreover, USACE's development is the most current research and all the steps for the development of the damage curves are comprehensively described. For those reasons, together with the availability of damage curves for five types of vehicles, these curves were considered the most adequate to be adopted in this case study. On the other hand, the fact of the damage is expressed as a percentage makes that these curves can be transferred and applicable to other countries, taking into account local prices of vehicles. Finally, after the description of a detailed methodology for flood damage mapping for vehicles, a procedure to evaluate the Expected Annual Damage for vehicles is offered. The obtained value of the EAD for the Municipality of Badalona was 320,983.31 €.

Regarding future research, there is a clear necessity of development of photogrammetry techniques to facilitate the delineation of all vehicles within the study area. Moreover, in that manner, the weighted damage curve could be applied directly on each vehicle, instead of employing the proposed distributed approach. This would allow a spatial assessment of the damage in the city. A frequent availability of satellite images, together with an appropriate photogrammetry technique, would allow to analyse the vehicular occupation for different time instants along the day.

In addition, the development of damage curves specifically for European typical vehicles would be a significant contribution. Moreover, only water depth has been considered as unique variable that affects to damages to vehicles, however some others such as velocity, flooding duration, the polluting or sediments load conveyed by water can affect also and should be studied. Finally, the applicability of damage curves is only when the vehicle remains stable, thus once the vehicle becomes unstable the damages should be assessed in a different manner. Note that when applying damage curves the assumption of vehicle stability is considered regardless the watertight level of the vehicle and the velocity of water, critical aspects when considering vehicles stability. Therefore, a more challenging research may be conducted by relating the vehicle's stability functions with the damage curve, thereby putting aside the assumption that vehicles remain stable when applying damage curves.

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Table 1. Summary of the depth damages curves identified in the state of the art review (Martínez-Gomariz, 2016)

Ref.	Model	Country	Development	Damage	Types of vehicles	Initial Cost	Analysis Approach
(FEMA, 2015; Scawthorn et al., 2006)	HAZUS-MH (FEMA)	EEUU	Synthetic	Relative (%)	Car Light Truck Heavy Truck	New or used applying 50% of new one price	Individual Objects
(Francés et al. 2008)	CRUE	Spain	Synthetic	Absolute (€)	Gasoline Diesel Averaged	No specified	Individual objects every 100 m2 affected
(USACE, 2009)	USACE	EEUU	Empirical-Synthetic	Relative (%)	Sedan Pickup Truck SUV Sports Car Mini Van	Market value	Individual Objects

Table 2. Percentage of damage related to water depth per each vehicle type (adapted from USACE (2009))

Sedan		**Pickup Truck**		**SUV**		**Sports Car**		**Minivan**	
									
Depth (m)	**Damage (%)**	**Depth (m)**	**Damage (%)**	**Depth (m)**	**Damage (%)**	**Depth (m)**	**Damage (%)**	**Depth (m)**	**Damage (%)**
0	0	0	0	0	0	0	0	0	0
0.15	7.6	0.15	5.2	0.15	0	0.15	1.4	0.15	0
0.30	28.0	0.30	20.3	0.30	13.8	0.30	29.2	0.30	17.8
0.61	46.2	0.61	34.4	0.61	30.6	0.61	52.8	0.61	38.3
0.91	62.2	0.91	47.5	0.91	45.8	0.91	72.2	0.91	56.8
1.22	76.0	1.22	59.6	1.22	59.4	1.22	87.4	1.22	73.3
1.52	87.6	1.52	70.7	1.52	71.4	1.52	98.4	1.52	87.8
1.83	97.0	1.83	80.8	1.83	81.8	1.83	100	1.83	100
2.13	100	2.13	89.9	2.13	90.6	2.13	100	2.13	100
2.44	100	2.44	98.0	2.44	97.8	2.44	100	2.44	100
2.74	100	2.74	100	2.74	100	2.74	100	2.74	100
3.05	100	3.05	100	3.05	100	3.05	100	3.05	100

Table 3. Averaged characteristics for the different types of vehicles considered

Type of Vehicle	**Average plan area (m^2)**	**Average price (€)**	**Average Age (years)**	**Depreciation (%)**	**Depreciated average price (€)**	**% in Badalona**
Sedan	7.31	18,253 €	12	87	2,373	83
Pickup Truck	7.54	17,599 €	13	90	1,760	7.5
SUV	8.80	58,337 €	13	90	5,834	1.5
Sports Car	8.80	103,949 €	12	87	13,513	0.5
Minivan	9.35	29,961 €	13	90	2,996	7.5

Table 4. Characteristics of analysed zones and occupancy percentage of vehicles within each one

	Zone							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Area (m^2)	114,566.99	114,566.99	114,566.99	114,566.99	114,566.99	114,566.99	114,566.99	114,566.99
Usable area (m^2)	30,487.83	35,522.64	27,172.37	23,439.16	37,327.20	27,892.59	49,376.99	37,601.37
% area of the total	0.54%	0.54%	0.54%	0.54%	0.54%	0.54%	0.54%	0.54%
Number vehicles	449	418	355	202	515	102	196	295
% of the total	0.46%	0.42%	0.36%	0.21%	0.52%	0.10%	0.20%	0.30%
m^2 vehicle	2994.21	2777.02	2288.77	1289.96	3122.94	639.16	1191	1837.11
m^2vehicle/m^2 usable area	9.8%	7.8%	8.4%	5.5%	8.4%	2.3%	2.4%	4.9%

Table 5 Comparative of economic assessment of distributed method against the complete one

500 years	Zone							
Method	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Complete	30,311.87 €	32,811.38 €	8,686.23 €	2,482.04 €	8,872.70 €	261.79 €	41,424.83 €	32,621.32 €
Distributed	24,914.40 €	26,963.44 €	13,938.91 €	1,575.10 €	15,231.68 €	1,381.00 €	58,927.77 €	25,622.86 €

Table 6 Probabilities and damages for floods resulted from the different design storms considered

Return Period (years)	1	10	100	500
Probability	1	0.1	0.01	0.002
Damage (€)	93,604.34 €	450,767.72 €	1,000,823.20 €	1,672,750.33 €

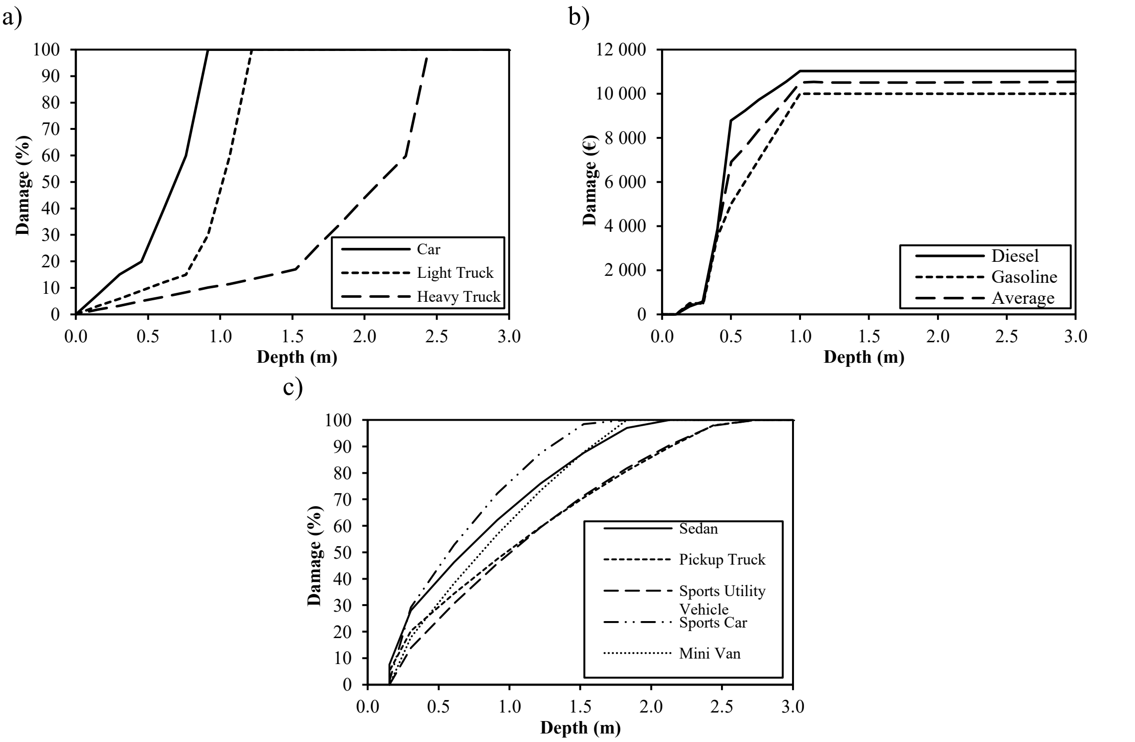

Figure 1. Depth damage curves per type of vehicle proposed in a) HAZUS-MH, b) CRUE project, and c) USACE

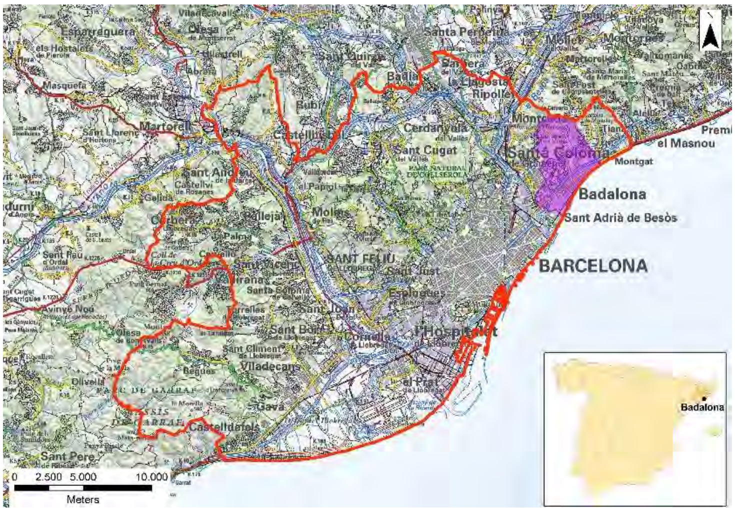

Figure 2: Map including Badalona location and AMB administrative limits (in red)

Figure 3: Jornet river flooding in Badalona during the event of 14/09/1999 (Source: Gregori Muñoz-Ramos Trayter, biologist and head of service of the environmental and sustainability of the Badalona city council)

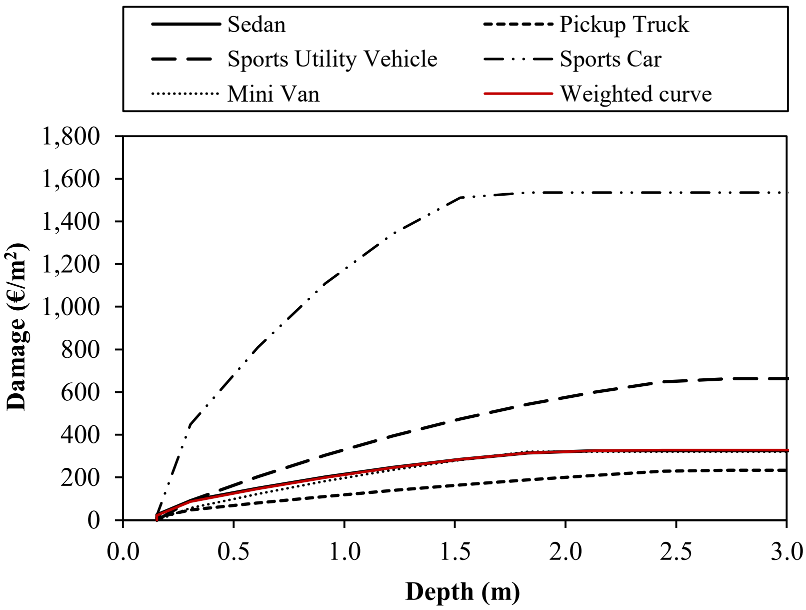

Figure 4: Weighted damage curve according percentage of types of vehicles in Badalona

Figure 5. Badalona detail area. Aerial photograph of 25 cm resolution

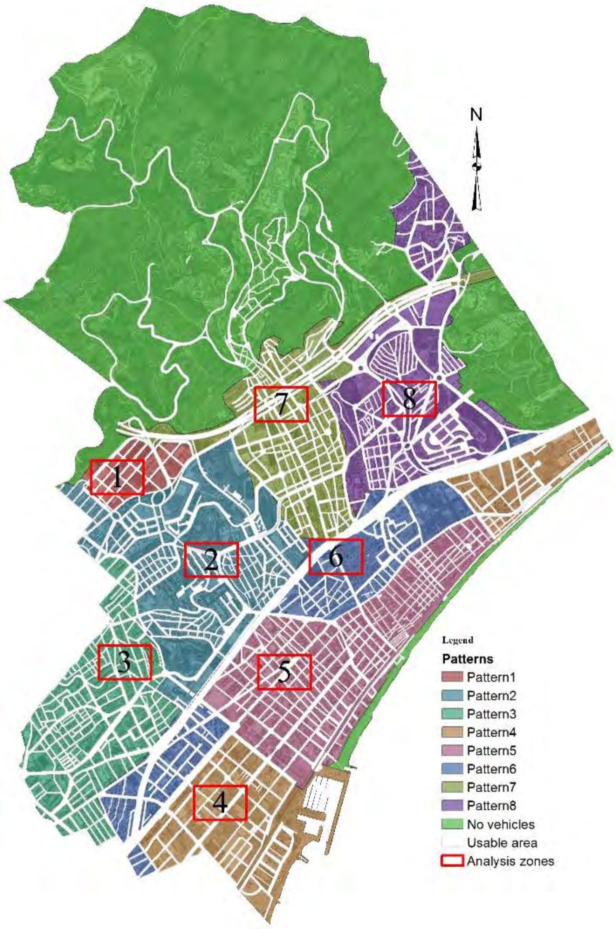

Figure 6. Location of the eight analysis areas and patterns of vehicular occupation

Figure 7. Detail of first four study zones in Badalona and delimitation of existing vehicles

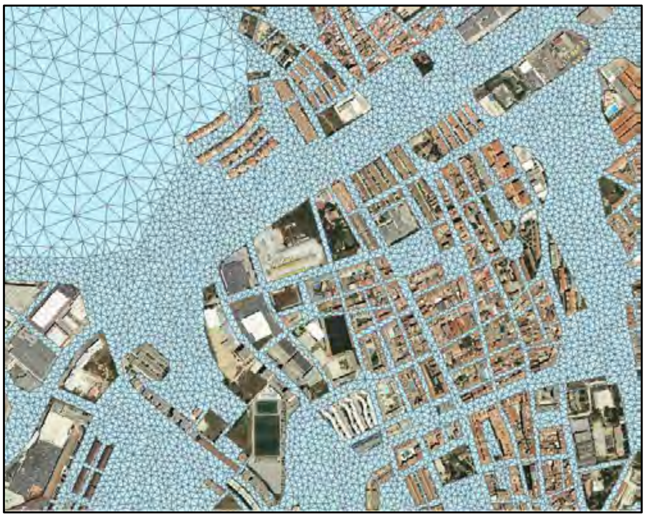

Figure 8. Triangular cells, output of the two-dimensional hydrodynamic calculations. Each cell stores hydraulic information, specifically water depth

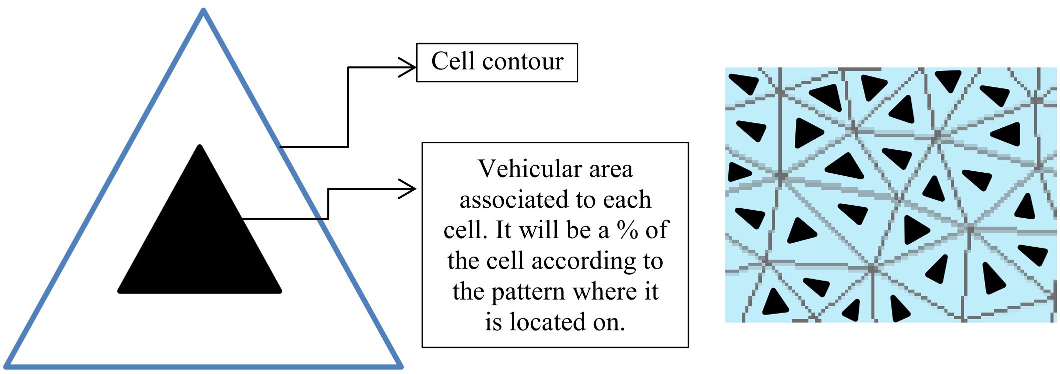

Figure 9. Vehicular area associated to a cell to apply the distributed method

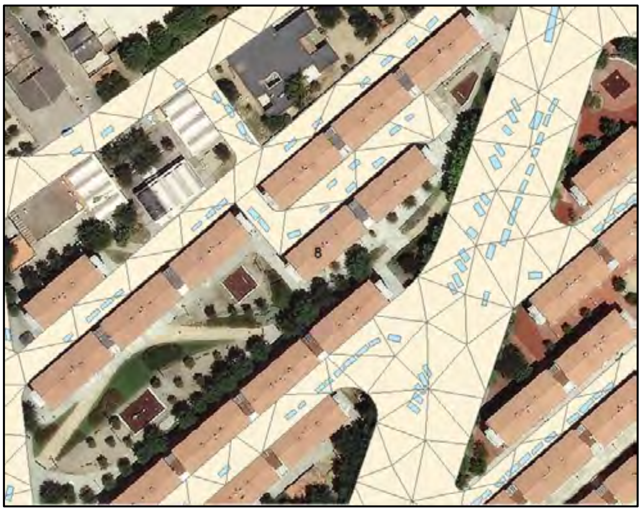

Figure 10. Crossover of vehicular delimitation with cells which store water depths

a) b)

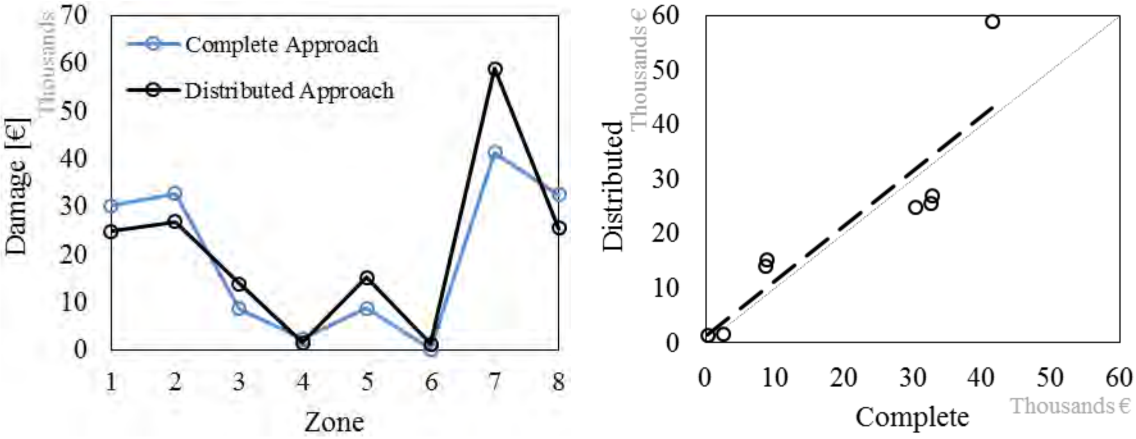

Figure 11. Comparison between damages of complete and distributed approach within the eight analysed zones.

a) b)

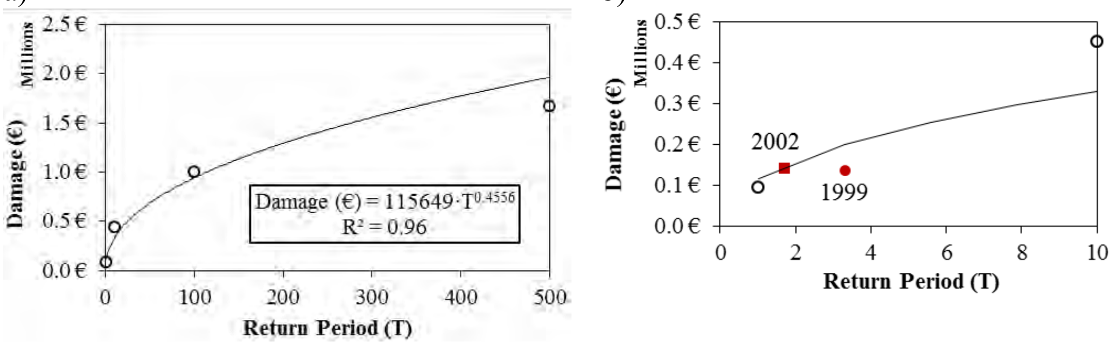

Figure 12. a) Damages to vehicles versus return period of the design storm plot and fit equation, and b) 1999 and 2002 actual events values represented in a zoomed area

a) b)

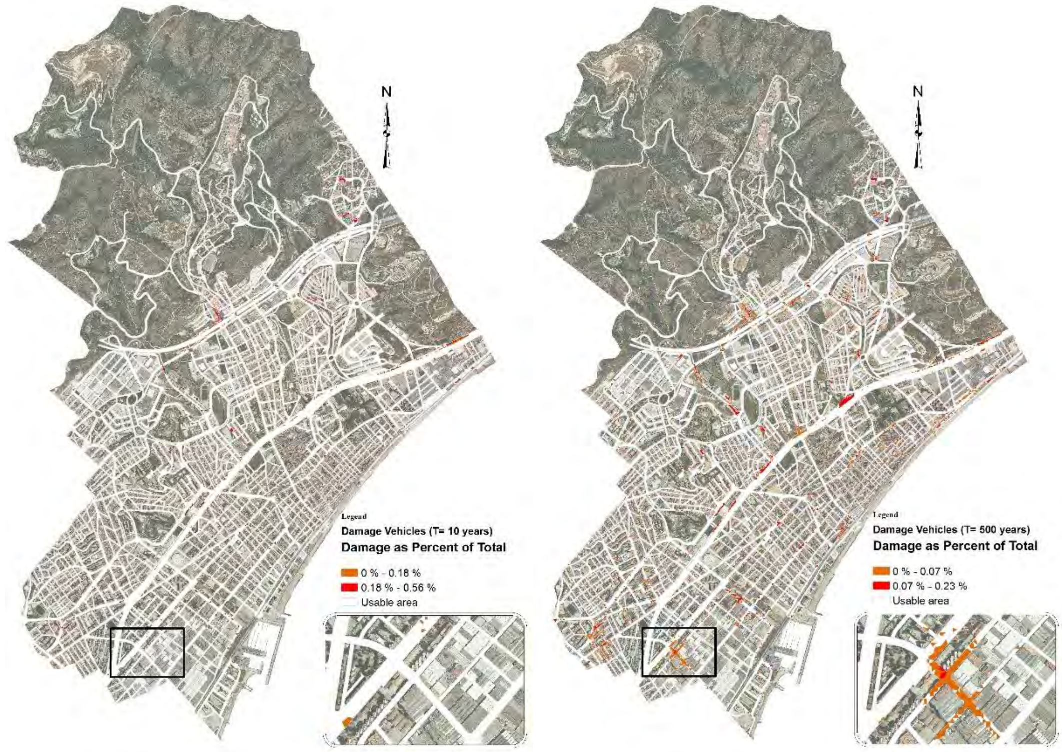

Figure 13. Damage maps for vehicles related to a) 10 and b) 500 years return period.

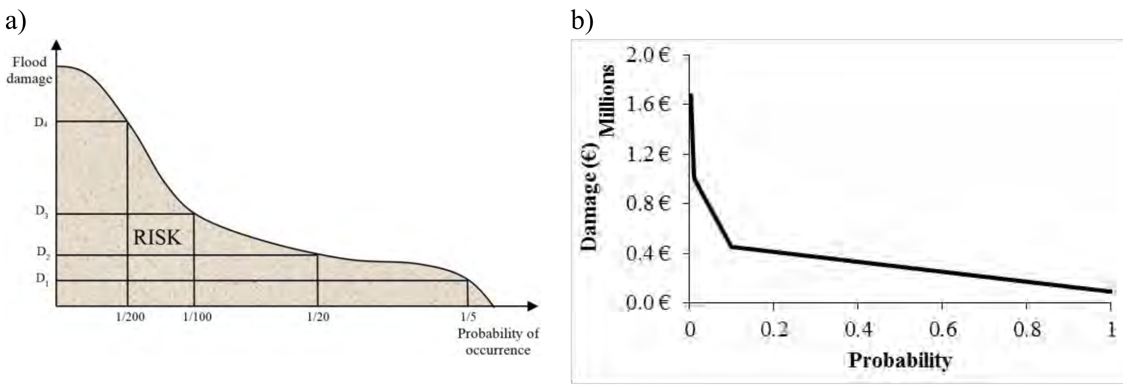

Figure 14. a) Descriptive curve of flood risk (Meyer et al. 2009), and b) Damage-Probability curve for the municipality of Badalona. The area under the curve represents the Expected Annual Damage (EAD)