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A novel expert opinion-based approach to compute estimations of flood damage to property in dense urban environments. Barcelona case study

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Abstract: A certain acceptable level of risk in major drainage system must be established since urban areas cannot be made entirely free from pluvial flooding. Among the diversity of flood risks in urban areas, direct damage to property has been extensively studied. A novel model approach (SFLOOD) to estimate flood damage to property in urban areas has been developed and presented herein. The model was conceptualised according to the knowledge of an insurance surveyor, acquired over many years on flood economic losses appraisals. It is a micro scale-, depth-damage- and GIS-based model where water depth is the only hydrodynamic variable considered as a damage driver. The model testing has been conducted through the direct comparison of computed damage and damage appraisals provided by the Spanish public insurance company, Consorcio de Compensación de Seguros (CCS), for three actual flood events occurred in Barcelona (Spain). Although a variety of uncertainties related to the flood damage estimates have been revealed here, the model is able to predict the order of magnitude of the actual damages according to the results obtained.

Keywords: pluvial flooding; damage assessment, insurance; Barcelona.

- A flood damage model has been developed and presented herein
- It will allow predicting a reliable damage distribution in cities
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1. Introduction

Decision-making in a flood risks context requires reliable tools to select the most effective adaptation measures to face current hazards but also the challenges of climate change. The reported economic losses caused by climate-related extreme events in Europe amounts to EUR 453 billion for the period 1980–2017, whereof an 8% corresponds to Spain. Two-thirds of these damages are derived from flood impacts. The total damage costs may increase as a consequence of more frequent and intense rainfall events in many regions due to rising temperatures that are expected to alter the hydrological cycle (European Environmental Agency (EEA), 2016).

Urban environments are extremely vulnerable to floods from different sources, mainly pluvial and fluvial (Chen et al., 2010). However, pluvial flooding is a global challenge for all cities, not only those located in riverine floodplain areas. An urban drainage system deals with stormwater, and two subsystems form it; major (overland flow paths), and minor (pipes) (Butler et al., 2018). Heavy rainfall may lead to pluvial floods in many cities once the minor drainage system exceeds its capacity. Although fluvial floods tend to be more calamitous, they do not occur that often as pluvial ones (Ootegem et al., 2015). The higher frequency of pluvial floods results on relevant aggregated damage over the years. Also, growing urbanisation leads to a higher volume of runoff, due to decreasing of infiltration, thereby exacerbating flooding consequences. The already vulnerable situation of urban areas and their drainage systems is forecasted to worse due to climate change. Changes in precipitation patterns will lead to more frequent sewer surcharging (Arnbjerg-Nielsen et al., 2013; Zhou et al., 2012).

Therefore, more frequent pluvial urban floods are expected and, both residents and assets will be exposed to them. For this reason, a comprehensive risk assessment is paramount from a social and economic point of view. Although the complexity of flood risk assessments in urban areas is added. Factors that may potentially influence the severity of flooding can be topography, building and household and urban drainage characteristics, and spatial distribution of rainfall (Spekkers et al., 2013). Land-use planning that does not pay attention to potential flooding and climate change effects may contribute to increase risks.

As urban areas cannot be made completely free from flooding (pluvial), a certain acceptable level of risk (Dickson et al., 2012) in major drainage systems has to be established. Among the diversity of flood risks in urban areas, direct damage to property has been extensively studied. A variety of flood damage assessment methodologies approaches can be found globally. Nevertheless, they share the aim of prioritising adaptation measures according to their effectiveness in terms of economic direct damages reduction.

Pluvial flooding acts on a different scale than fluvial flooding, where mechanisms and characteristics are functionally different. A variety of flood loss estimation models exist worldwide (Galasso et al., 2020)and a particular distinction can be made between those based on aggregated land use data (e.g. CORINE) and those focused on individual objects (Jongman et al., 2012; Merz et al., 2010). Both types are generally applied through GIS techniques. The first is usually employed when assessing damages at meso- and macro-scales (fluvial floods), and the second is more appropriate at a micro-scale level (pluvial urban floods) (Merz et al., 2010). Object-based models require a high complexity rather than simplicity linked to the ones based on aggregated land use. These characteristics lead to different advantages for each type of model. Land use-based models provide with a rapid calculation, and object-based models offer a detailed building distribution within the study area.

Notwithstanding, object-based models use a large number of object types and corresponding flood damage characteristics (IBI Group, 2015). An additional classification for damage models may be done according to their data source, distinguishing between empirical and synthetic. While the first can be accurate when applied to similar studies, the second group provides an unreliable application to another region.

Different factors contribute to cause damages to property, such as the time of the year the flood occurs, flood duration, water velocity, suspended debris, or warning time (Kelman, 2007;

Kreibich et al., 2009; Merz et al., 2004). Based on the number of factors considered, another classification can be established, by defining bivariate models as those considering only floodwater depth as the primary driver of damage, and multivariate as those encompassing a variety of factors (Ootegem et al., 2015). The first relies on the so-called depth-damage curves that represent the vulnerability of elements at risk. These are functions that relate a floodwater depth to its corresponding damage in relative or absolute terms (Velasco et al., 2016). Although there is an intrinsic uncertainty to depth–damage approaches (Jongman et al., 2012) these tend to be widely used in many damage models. Jongman et al. (2012) compared seven flood damage models developed for different European regions and the United States. An intrinsic characteristic of flood damage models is their limitation in terms of transferability in space and time (Thieken et al., 2008). Damage models based on depth-damage curves require the flood extent as input which is obtained through hydrodynamic coupled 1D/2D models in urban environments. The damage assessment process is conducted through the overlaying of flood inundation, buildings, and their corresponding depth-damage curves.

Recently, Jamali et al. (2018) proposed an integrated hydrodynamic and pluvial flood damage assessment model. The first was developed as a rapid inundation model coupled to a 1D drainage network model to reduce computational efforts and thus computing time. The flood damage assessment module uses monetised (€/m^2) depth-damage curves for Australia. Only two types of property use are considered, residential and commercial. An example of a multivariate flood damage model is the one proposed by Ootegem et al. (2015). It includes non-hazard indicators (i.e. properties flooded without related damage) based on a survey conducted in Flanders (the northern region of Belgium). Some other indicators used were building characteristics, victims' behavioural predictors (e.g. risk awareness) and properties income. Damage functions were constructed not only based on water depth (i.e. depth-damage functions) but also for various categories of specific hazard indicators. It is explicitly said that no consideration is made regarding the place where the water enters the building. Although it is a comprehensive model, it is not supported by a GIS platform, and thus damage distribution is not predicted. This type of models generally does not account for the enhancements of the drainage network over the considered time period of damaging events analysed. Likely, a variety of interventions have been conducted over this period which may bias the model outcomes. However, the advantage of these models is that they do not require a previous hydrodynamic simulation. There exist also approaches focused on specific types of buildings, such as the study of Milanesi et al. (2018) that considers building' structure stability against floods occurred in mountain areas. Namely, the model encompasses only masonry building and considers masonry walls' impact by flow under different building configurations. Although the purpose of the study is to identify potential structural damages, no monetisation is considered.

Merz et al. (2010) expounded the scarcity of damage data and the overall crudeness of damage assessment models. This statement is still current, and due to this lack of damage data and damage assessment models are transferred in time and space without sufficient justification. The concern takes on particular relevance when it comes to dealing with the complexity of assessing economic damage to property caused by pluvial floods in urban environments.

On the other hand, the EU Floods Directive (The European Parliament and the Council of the European Union, 2007) requires the Member States to develop, adopt, and implement flood risk management plans. In Spanish plans, measures aiming at reducing the building's vulnerability (Manrique et al., 2017) have been proposed, but the plans take into consideration mainly riverine and coastal floods. Sewer flooding though should not be undervalued since worldwide urban environments, to a greater or lesser degree, are exposed to this threat. Pluvial flooding is also expected to become more frequent due to the effects of climate change (Arnbjerg-Nielsen et al., 2013), increasing risk, damage, and disruptions to citizens. Therefore, pluvial flood risk assessments for urban areas should be considered as one of the main challenges for the implementation of the EU Floods Directive by EU member states (Kellens et al., 2013). A comprehensive framework, like the proposed by Zhou et al. (2012), may be adequate for future Flood Risks Directive updates.

This paper presents the development of a comprehensive pluvial flood damage model to predict economic losses to property in dense urban environments. The model has been termed SFLOOD that stands for Stormwater FLOOding Damage. For simplicity, although a variety of variables contribute to causing damages when a pluvial flood occurs (Ootegem et al., 2015), the proposed approach herein only considers floodwater depth as the primary damage driver. The lack of tools to estimate pluvial flood damages in Spanish urban areas led to the need in defining this model and their related tools presented herein. In despite of its tailored approach for Spanish urban environments, this model may be adapted to similar city landscapes and property layout out of Spain. It is especially adequate for large cities with complex drainage networks, for which these tools are of major importance (Ashley et al., 2005). According to previous descriptions, our development can be classified as a micro scale-, depth-damage- and GIS-based model.

The model and tools presented herein will contribute to a common pluvial flood risk mitigation framework in Spain, thereby complementing a previous work on nationwide depth-damage curves (Martínez-Gomariz et al., 2020). The model will allow predicting overall damage at the municipal level but also providing a reliable damage distribution, thereby identifying risk hotspots in cities. It will be a tool to assist institutions dealing with urban drainage management, to prioritise adaptation scenarios (i.e. a set of measures) according to their effectiveness in terms of risk (i.e. direct tangible damages) reduction. Therefore, it will be a decision-making tool in terms of local investments (e.g. regional Master Drainage Plans). Standardisation of the use of this tool at a national level would allow comparing the Expected Annual Damage (EAD) of different regions. The EAD is an aggregated value of the damage model outcomes (Zhou et al., 2012), and tend to be used as a risk indicator in monetary terms.

In terms of policy implications, these new tools to predict pluvial flood damages in urban areas may lead to consider pluvial flood risk assessments in future updates of the EU Floods Directive (2007/60/EC). Tools developed in the present work align well with the framework proposed by Zhou et al. (2012) and can contribute largely to the implementation of Floods Directive in Spanish urban areas. In alignment with this, providing these tools will contribute to new approaches of risk-oriented (Merz et al., 2004) Master Drainage Plans at a municipal level.

Finally, this development is expected to contribute to the Spanish insurance market. After a pluvial flood event, the Spanish Insurance Compensation Consortium (CCS, for its acronym in Spanish) receives an uncertain number of claims. Accordingly, these claims amount to an unknown payout quantity, which does not allow CCS to anticipate the disbursement of existing funds. The compensation payout process is complex and slow enough to allow a quick damage assessment in just a few hours (e.g. 24 to 48 hours).

Following sections of this paper include: 2) methods and materials; 3) results and discussion; and 4) conclusions. Section 2 (methods and materials) presents the description of the case study, the urban drainage model and a comprehensive explanation of the approach taken for the pluvial flood damage model. Section 3 (results, limitations of the method and discussion) encompasses the flood risk assessment carried out for Barcelona. This assessment is only based on the economic damage to property estimations, carried out through runs of the damage assessment model presented herein. As the damage model is the main aim of this paper, its accuracy is analysed too. Discussion about uncertainties and further research necessities is provided. Finally, section 4 (conclusions) gathers some take-home messages, and the main benefits of the presented research are recalled.

2. Methods and materials

2.1. The case study description: Barcelona

Barcelona (Figure 1) has a population of 1,620,943 inhabitants and a municipal area of 101.4 km^2. The city is located in Catalonia, Spain, on the Northeast coast of the Iberian Peninsula and is facing the Mediterranean Sea. It is highly urbanised, and most of the urban area is located on a rather flat area few tens of meters above mean sea level and surrounded by the mountain range of Collserola, the Llobregat River to the south-west and the Besós River to the northeast. The average population density of the city is 15,985 inhab./km^2 with higher values on the city centre and lower ones on the surrounding hills.

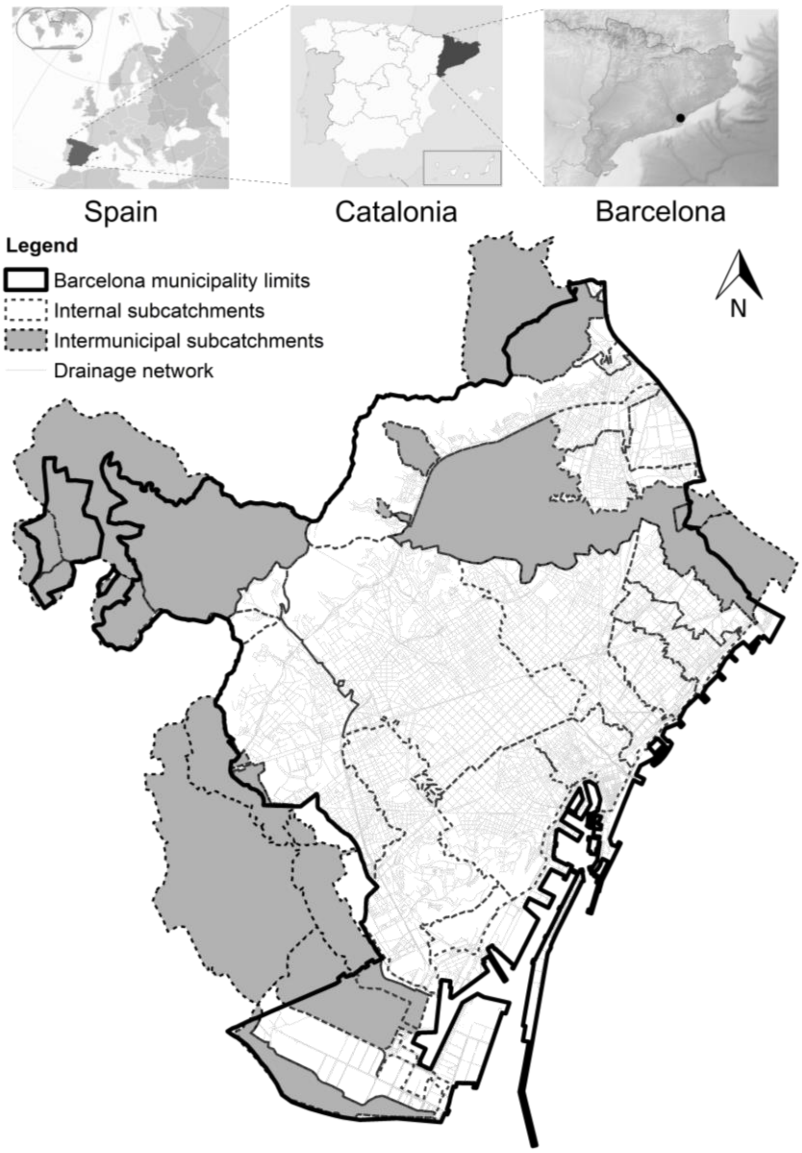


Figure 1. Barcelona limits, subcathments, and drainage network

Barcelona has a Mediterranean climate with mild winters and warm summers, experiencing heavy rainfalls of high intensities and flash floods events. The yearly average rainfall is approximately 600 mm, the maximum 5-minutes rainfall intensity corresponding to a return period of 10 years is 204.7 mm/h (Russo et al., 2015), and it is not rare that 50% of the annual precipitation occurs during two or three rainfall events. This rainfall patterns, together with the old and mostly combined drainage system, the high degree of imperviousness and the terrain slopes, cause urban pluvial floods and combined sewer overflows. The degree of imperviousness is estimated to be approximately 70% of the whole municipal area with higher percentages in the urban areas and lower ones on the surrounding hills.

The morphology of Barcelona presents areas close to Collserola mountain with high gradients (with an average of 4% and maximum values of 15–20%) and other flat areas near to the Mediterranean Sea with mild slopes (close to 0–1%), and there are also local low-lying areas susceptible to floods. During heavy storm events, Barcelona suffers critical flooding with significant impacts in terms of economic damage and possible service interruptions (transport, energy, etc.).

2.2. Urban drainage model of Barcelona

The pluvial (or urban) flood model of Barcelona is used to simulate spatially distributed maximum flood depth on the urban areas that are used as an input for the flood damage model. The pluvial flood model is a 1D/2D (sewer/overland flow) model that can continuously simulate the spatial and temporal distribution of both sewer and surface flood processes and their mutual interaction. This model was calibrated and validated using historical observation data during different rain events. Data such as water level measurements in the sewer network, rainfall intensities from local rain gauges and photos and videos of urban floods during different past rain events were used for calibration and validation.

The 1D/2D hydrodynamic model was developed with InfoWorks ICM®. The model includes 2041 km of pipes, 85 834 maintenance holes, 980 weirs, 44 sluice gates, 75 pumps and 285 storage nodes representing diverse kinds of chambers and 10 detention tanks with a total volume of more than 400 000 m^3. The 2D overland flow model covers the whole administrative land of the city and all the upstream catchments discharging into the Barcelona sewer network. The 2D domain includes 1,361,324 cells. The 1D/2D model is made of different sub-models continuously interacting with each other:

- A rainfall-runoff model that simulates rainfall-runoff processes for each of the approximately 85,000 sub-catchments. Sub-catchments were created using Thiessen polygons applied to each drainage network node except for the upstream undeveloped areas where sub-catchments were delineated with GIS hydrological tools applied to the DTM model. Each sub-catchment has a GIS estimation of both pervious and impervious areas. Continuous hydrological losses were associated only to pervious areas and were simulated using the Horton infiltration model. Initial losses up to few mm were specified for both pervious and impervious areas. Initial losses usually have a minor impact on urban flooding. The routing model was based on a non-linear reservoir with a kinematic-wave equation. For each sub-catchment, the flow rate resulting from the rainfall-runoff model is diverted into the corresponding 1D model node representing a sewer manhole.
- A 1D hydraulic model of the drainage network that solves the 1D Saint-Venant equations to simulate the spatial and temporal distribution of flow velocities and depth in the network.
- A 2D overland flow model made of an unstructured grid to simulate overland flow over floodable urban areas. This 2D grid was generated from a digital terrain model (DTM) of 2.25 m^2 resolution obtained from LIDAR data of 15 cm precision. The 2D cells have variable areas that can vary from a minimum of 25 m^2 in the streets of Barcelona up to a maximum of 100 m^2 in the less urbanised and hilly upstream areas.

The 1D/2D coupled model was conceived as a semi-distributed model, commonly applied in urban stormwater modelling, that is based on subcatchment units where rainfall is applied, while runoff is estimated and routed according to specific hydrological losses and rainfall-runoff transformation methods. 2D overland flow module is activated only in case of flooding produced by surcharged sewer pipes, causing overflow on the urban surfaces (Russo et al., 2020).

2.3. Pluvial flood damage model approach

2.3.1. The role of an insurance surveyor in flood claims in Spain

Risks posed by natural hazards are among the so-call extraordinary risks covered by the Spanish Insurance Compensation Consortium (CCS, for its acronym in Spanish). This is a government institution attached to the current Ministry of Economy Affairs and Digital Transformation, which is subject to the private insurance rules. In Spain, the receipts of private insurance policies include a surcharge to the endowment of a CCS common fund. Generally, the CCS will be responsible for flood damages compensations, unless this specific risk is covered by the private insurer. In any case, a policyholder will be only entitled to compensation once an insurance surveyor (or more) appraises the damaged property. Focusing on pluvial floods in urban areas, when these occur, the CCS sends one or more insurance surveyors to provide them with a first evaluation of damages. This first damage evaluation, according to the CCS, tends to be accurate and is extremely useful for the insurer to forecast the total payouts to be finally compensated. This fact denotes significant knowledge of these experts. The expert opinion was already taken into consideration in the British Multi-Coloured Manual (Penning-Rowsell et al., 2010), which was developed mostly through a synthetic analysis and using of expert judgment (Jongman et al., 2012).

Therefore, flood insurance surveyors well know the characteristics and behaviour of pluvial urban floods. Besides, it is not clear to what extend property owners may remember the amount of the damage or the floodwater depth inside the property (Ootegem et al., 2015). However, fortunately, a flood insurance surveyor has records of this valuable information. We have put this knowledge into practice by depicting a conceptual model of water intrusion into properties and developing tools to predict pluvial flood damages.

2.3.2. A conceptual model of the floodwater transfer from outside to inside a property

Depth-damage curves are the most established approach to estimate flood damages. When it comes to a detailed study in urban areas, the water level to consider must be the one inside the property. Typically, floodwater depths surrounding the parcel or building are applied to estimate the damage for a specific property. This assumption could be acceptable for a riverine flood, which residence time could be considered enough to let water level inside the building reach the outside level. However, the low residence time of pluvial floods cannot allow taking such an assumption. Water contact damage is the damage caused by material getting wet, not by any physical force applied by the water (Kelman, 2007). This study focuses on property use rather than building or material type because when it comes to urban pluvial floods damage to contents is especially relevant.

As stated by Merz et al. (2010), flood damage assessment can be performed on three different scales: macro, meso and micro. The main differences between spatial scales relate to the spatial accuracy of potential damage analysis. When the assessment focussed on an urban area, it should be considered as a micro-scale; thus, aspects such as the relations between water depths outside and inside must be considered. Therefore, a conceptual model based on discussions with an insurance surveyor expert in flood damages is proposed here to understand the transfer of water from outside to inside the building. Buildings are naturally leaky, and it is difficult to be entirely certain of keeping all water out of all possible entry points (Kelman, 2007). There are two main ways for floodwater to access into the property: a) overland flow into the building, and b) surcharge of the drainage system. Sinks and toilets are many times connected by gravitational flow to the sewers. It makes basements and lower ground floors vulnerable to surcharged flow that may reverse up the combined building drains and be forced backward through the household appliances into the properties during heavy rainfall (Sörensen and Mobini, 2017). A depth differential between the inside and outside of the property occurs when floodwater rises outside property without rising at the same rate on the inside of the property (Kelman, 2007). These situations may lead to structural failures, mainly in the case of riverine flooding and sealed properties. However, no structural stability problems are expected when it comes to stormwater flooding in urban areas. The basis of this statement refers to the available historical flood damage records in Barcelona. Experimental and numerical studies have been conducted to estimate flow intrusion towards buildings within highly urbanised areas (Mignot et al., 2020) or isolated buildings (Gems et al., 2016). Nevertheless, these studies consider closing systems open by themselves after being submerged and thus become damaged or entirely removed. These situations are more likely to occur during riverine flooding. According to our experience and records in Barcelona, closing systems do not tend to be damaged or removed during stormwater flood events. For this reason, in the present approach, we consider all closing systems are closed during a flood event, which although does not guarantee entirely sealed properties.

The existing front steps to enter the properties act as flood protection and reduces the water depth on the pavement ($\bar{y}$, Figure 2) to a lower depth (y_o, Figure 2). It has to be noted though that commercial uses do not present these front steps or it is very low-lying to facilitate customers to enter, thereby providing none or little flood protection (Figure 3). Fieldwork has been conducted in the city of Barcelona (Spain) in order to obtain an average height value for these steps according to a variety of property uses. This work consisted of the visit and measurement of step heights from around 50 properties of different uses located in the neighbourhoods that historically have been more affected by floods: El Raval, Poblenou and Poble Sec.

Therefore, depending on the water depth acting on the entrance from the property (y_o, Figure 2), a greater or lesser water ingress into the property will occur. As the flood residence time is expected to be low for pluvial floods (Chen et al., 2010), the depth inside will be likely lower than the outside one. According to this approach, the conceptual model of water ingress into properties depicted in Figure 2 is proposed here. This scheme considers different layouts of buildings: 1) only ground floor, 2) ground floor and one basement, and 3) ground floor and two basements. Moreover, these layouts consider the presence of car parks, which means that six possible layouts are considered in this model, which would cover the vast majority of layouts that can be found in Spanish urban areas. When a property does not present any basement, the water depth could reach the outside water level. However, the existence of one or more basements would cause the water to flow down to lower stories (i.e. basements) thus not allowing the water to exceed a certain maximum level (Max depth, Figure 2), lower than the outside one. Basements act as small water storage tanks and water depths could even become higher than those present on the streets. There may be several connections to let the water leak from one floor to the other, but stairwells are supposed to be the main ones. Therefore, the maximum damage on a floor with an underneath level will be related to the *maximum depth*. It may also be accepted a *residual depth* because a certain amount of water will remain on the ground floor without flowing down to the basements. In case of the existence of a car park, a water leak will occur from one floor to other but also from the street, due to the entrance gate to the car park, which is in contact with the water depth outside the building. If this approach is accepted, depth-damage curves should be applied to the depths inside the property (y_{GF}, y_{B1}, y_{B2}, Figure 2). Closing systems such as doors and windows are the spots through which water could enter the property. During a flood event, these closing systems are expected to be closed, but even then, water may percolate since their sealing capacity is not fully guaranteed (Figure 4).

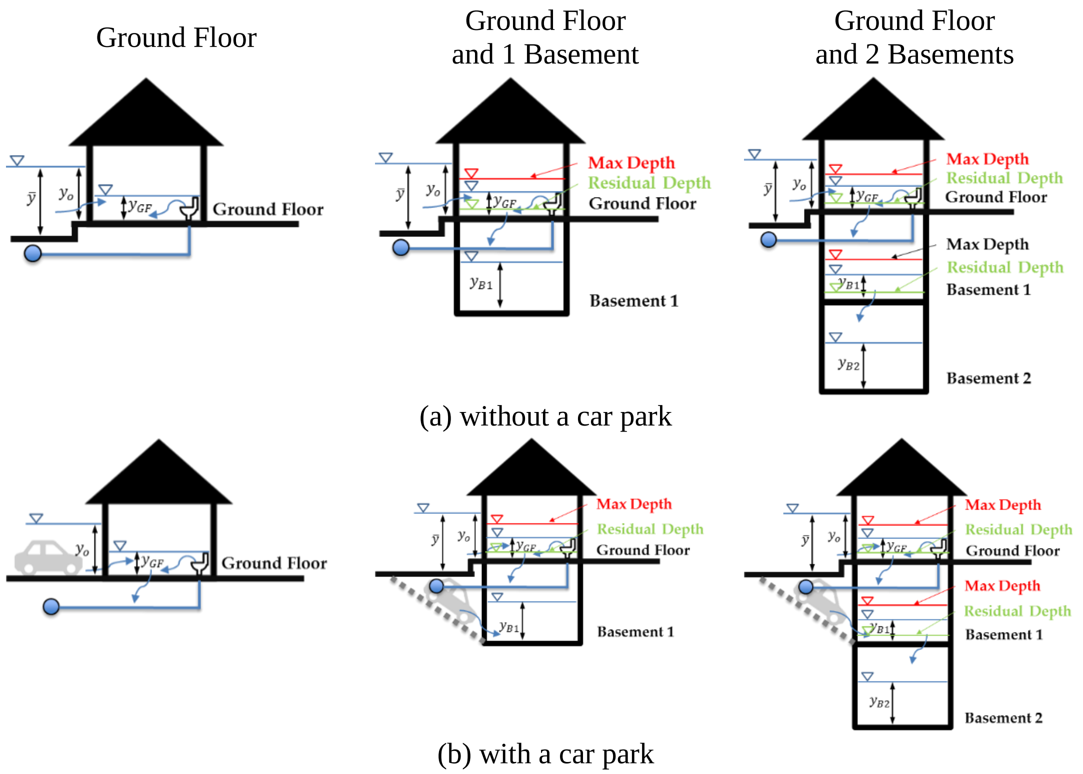


Figure 2. Conceptual model of the water transfer from outside to inside the property during pluvial floods in urban areas.

The main idea in this approach is that a "Permeability Coefficient" (P_C) will determine the difference between the water depth outside and inside ($P_C = y_{GF}/y_o$). The higher is the water depth outside, the higher is the Permeability Coefficient (P_C). In other words, when the water depth outside is high enough, the water depth inside the building is expected to be the same that the outside one (P_C = 1). The Permeability Coefficient is a function of the water depth outside but also depends on the type of property. Tailored relations between water depth outside and inside the buildings have been developed for 14 property uses considered. Diverse types of closing systems and number of toilets (another source of water ingress) have been considered for each property use.

Figure 3. Entrance to trades in Barcelona with a nearly inexistent front step height.

Figure 4. Signals of floodwater level inside and outside the property.

On the other hand, this conceptual model fits with properties with a reduced floor area, because large floor areas are usually not entirely covered by water. According to this, it might be distinguished between total floor area and flooded floor area. The most conventional trades usually have floor areas not exceeding 250 square meters. Therefore, for small floor areas (Figure 5a) total floor areas correspond to the flooded area, unlike large floor areas (Figure 5b), which use to be partially flooded.

Although flood recurrence can be relevant (Elmer et al., 2010) in terms of self-protection measures, the changes in small business' ownership, the most affected by pluvial floods in highly dense urban environments like Barcelona, is extremely frequent in recent times. For this reason, the fact of non-considering property's self-protection is not assumed as a model's shortcoming.

(a) (b)

Figure 5. Entrance to properties with a) small floor areas, and b) large floor areas.

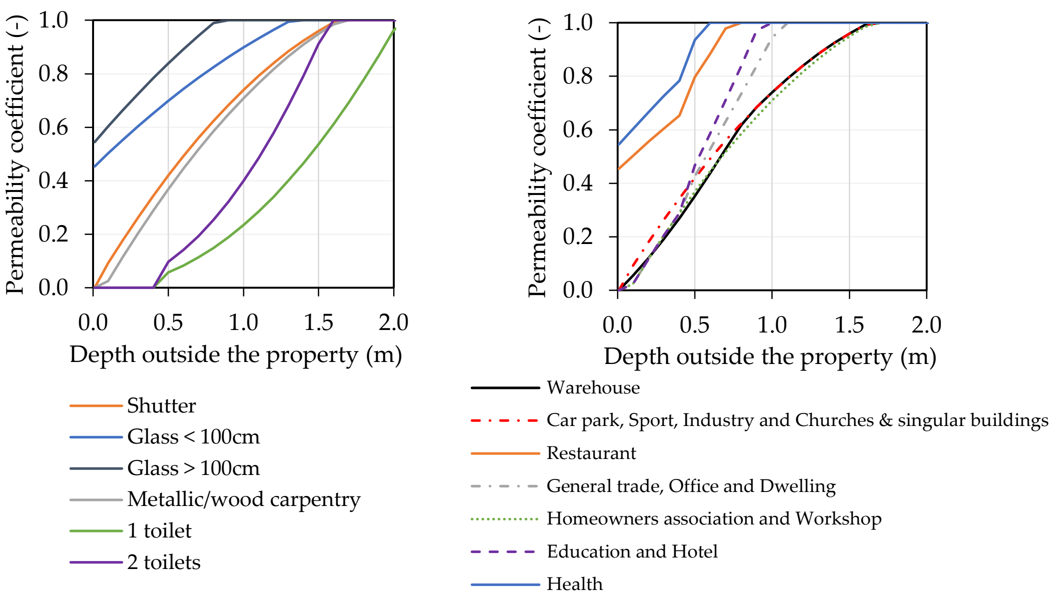
2.3.3. Functions of permeability coefficients

Although water depth inside a property damaged due to flooding is part of the recorded data from a damage survey, the water level on the street is not usually registered. However, an experienced flood surveyor can estimate this water level. Therefore, the permeability coefficient for different water depths has been estimated based on the experience of one of the authors of this piece of work. Initially, these values have been related to specific water entry points, such as closing systems and number of toilets (drains and traps). For instance, a property with glass closing systems, without aluminium carpentry, would allow the water entry in an easier manner than a property with closing systems with any carpentry.

Moreover, it is expected that these coefficients will vary with the existing water depth on the street since the higher is the water depth on the streets a higher flood residence time is assumed. Therefore, functions that depend on water depth on the streets and the type of closing system and the number of toilets have been derived first (Figure 6a). A certain number and type of closing systems, as well as the number of toilets (Table 1), have been related to each type of property considered. By aggregating per type of property, the effects of single water entry elements total functions of permeability coefficients per type of property have been developed (Figure 6b). There exist a discussion about the dilemma of to seal or not seal an individual property (Kelman, 2007). However, the fact is that most residents tend to seal their properties to prevent floodwater infiltration. The concept of indoor water depth was also considered by Chen et al (2019), who assumed that floodwater flows into the buildings through doors with known location and it follows the fluid mechanics of discharge over a rectangular weir.

Table 1. Closing systems and toilets related to each type of property.

Type of property	Combination of closing systems and number of toilets
Warehouse	Shutter and glass > 100cm
Car park	Shutter
Restaurant	Glass < 100cm and two toilets
General trade	Metallic/wood carpentry and one toilet
Homeowners associations	Metallic/wood carpentry
Sport	Shutter
Education	Metallic/wood carpentry and two toilets
Hotel	Metallic/wood carpentry and two toilets
Industry	Shutter
Office	Metallic/wood carpentry and one toilet
Health	Glass > 100cm and two toilets
Workshops	Metallic/wood carpentry
Dwelling	Metallic/wood carpentry y one toilet
Churches and singular buildings	Shutter

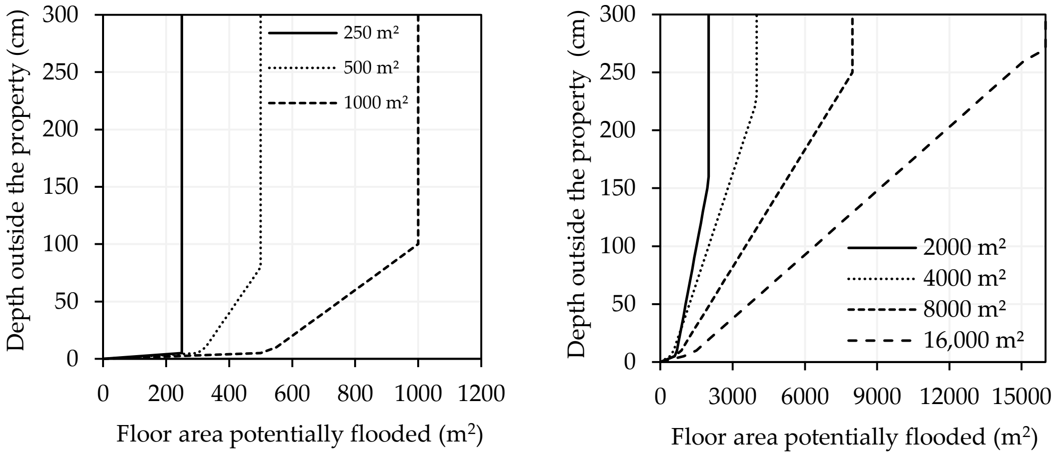


(**a**) (**b**)

Figure 6. Permeability coefficient functions according to a) a specific water entry element and b) different property types.

2.3.4. Functions of floor area potentially flooded

These functions allow estimating the flooded floor area of each type of property depending on the water depth outside the property (Figure 7). By way of illustration, a 1000-square-meter property is not expected to be entirely flooded until the water level on the street reaches one-meter depth according to the functions proposed. Water depths lower than one meter are assumed to increase lineally up to reach a one-meter depth when the floor area would be entirely flooded.



(**a**) (**b**)

Figure 7. Floor area potentially flooded functions versus depth outside the property according to the total floor area: a) up to 1000 m^2, and b) up to 16,000 m^2.

2.3.5. Flood depth-damage curves for Barcelona

Semi-empirical flood depth-damage curves for 14 different property uses have been derived for the city of Barcelona (Figure 8). This development has been based on a sample of actual flood damage records. These were taken by an insurance surveyor, who is included among the authors of this work, during his flood damage appraisal processes. The depth-damage curves construction relied on statistical data analysis; however, in case of lack of data the curves were adjusted according to expert opinion. For instance, in case we did not have data between 50cm and 1m water depths, the insurance surveyor proposed the expected damage according to his own experience. Details of this development can be found in Martínez-Gomariz et al. (2020), a study which, moreover, provides with a methodology to obtain nationwide depth-damage curves. Therefore, both the present and the previous studies will contribute to a common pluvial flood risk mitigation framework in Spain.

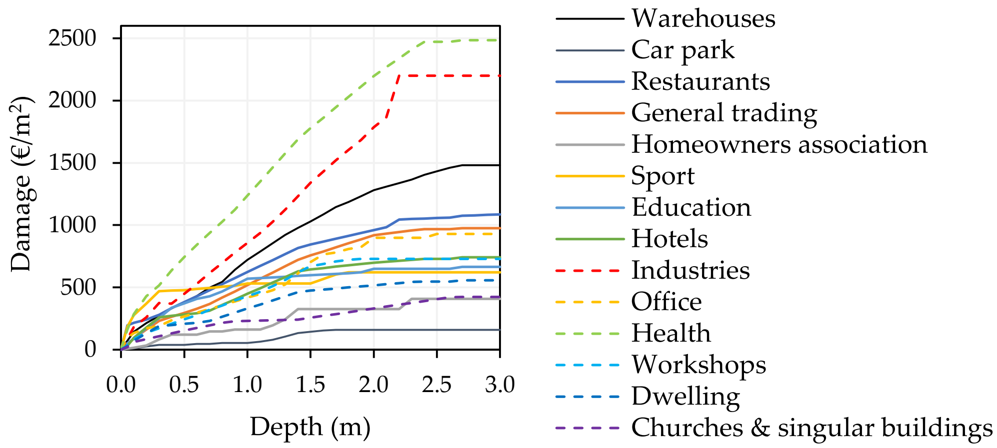


Figure 8. Semi-empirical depth-damage curves for Barcelona.

2.3.6. GIS toolbox

The main output of the SFLOOD model is a map of the municipality and the expected flood damage distribution among the parcels (i.e. a risk map). Also, the overall flood damage is provided as an aggregation of damages from individual properties. To obtain this, a GIS-based tool (i.e. SFLOOD model), which allows automating the flood damage assessment process, has been built up. The steps to be conducted are listed following and inputs and outputs of the tool are depicted in Figure 9.

1) Initially, both the city parcels and the cadastral information database must be downloaded. These files are freely downloadable from the Spanish Cadastre website (www.sedecatastro.gob.es). This database contains the use of each property, among other information. Thus, both files should be provided to the tool as a first step. The tool will select from the database only the information required to conduct the process, and the property uses will be transformed into the 14 categories proposed here.

2) Secondly, a shapefile with the floodwater depths of the flood event to analyse must be provided to the tool. This file must be obtained from different software. In this case, Infoworks ICM® has been employed to obtain the flooding dataset.

3) Water depths, resulting from the 2D hydrodynamic model, within a property influence area specified by the user, are averaged to obtain a single water depth on the pavement ($\bar{y}$, Figure 2). This water depth will be reduced initially according to the front step related to the type of property exposed (y_o, Figure 2) and following it will be multiplied by the corresponding Permeability Coefficient, thereby obtaining the expected water depth inside the building (y_{GF}, y_{B1}, y_{B2}, Figure 2).

4) Small flooding areas resulting from the hydrodynamic model were observed to mislead the damage model to unrealistic damaged properties. For this reason, a parameter to eliminate these small flooded areas is included in the tool. Therefore, a minimum threshold of flooding area to cause damages must be indicated by the user. This parameter can also be considered in the calibration process.

5) Two parameters must be indicated within the tool, maximum water depth and residual depth inside the property (Figure 2). The water depth inside each story of a property (y_{GF}, y_{B1}, Figure 2) with a possible underneath level will be related to the maximum depth unless the water depth obtained in the previous step is lower than the maximum. In this case, the previous water depth will be kept. Maximum and minimum water depths are calibration parameters of the model.

6) A database of depth-damage curves for Spanish municipalities is contained in the tool (Martínez-Gomariz et al., 2020). Therefore, the municipality aim of the study must be indicated to the tool, and its corresponding depth-damage curve will be automatically used in the damage assessment process. Depth-damage curves are applied by relating the water depth inside the building (y_{GF}, y_{B1}, y_{B2}, Figure 2) and the type of affected property. This step provides the economic losses per square meter of property (€/m^2).

7) Functions of floor area potentially flooded are applied in this step. The floor area is reduced when required before being multiplied by the economic losses per unit area determined previously. The total economic losses per story of each property are calculated in this step.

8) Once all input data is provided to the tool, the tool can be run. The conceptual model depicted in Figure 2 is carried out through a python code included in the GIS-tool.

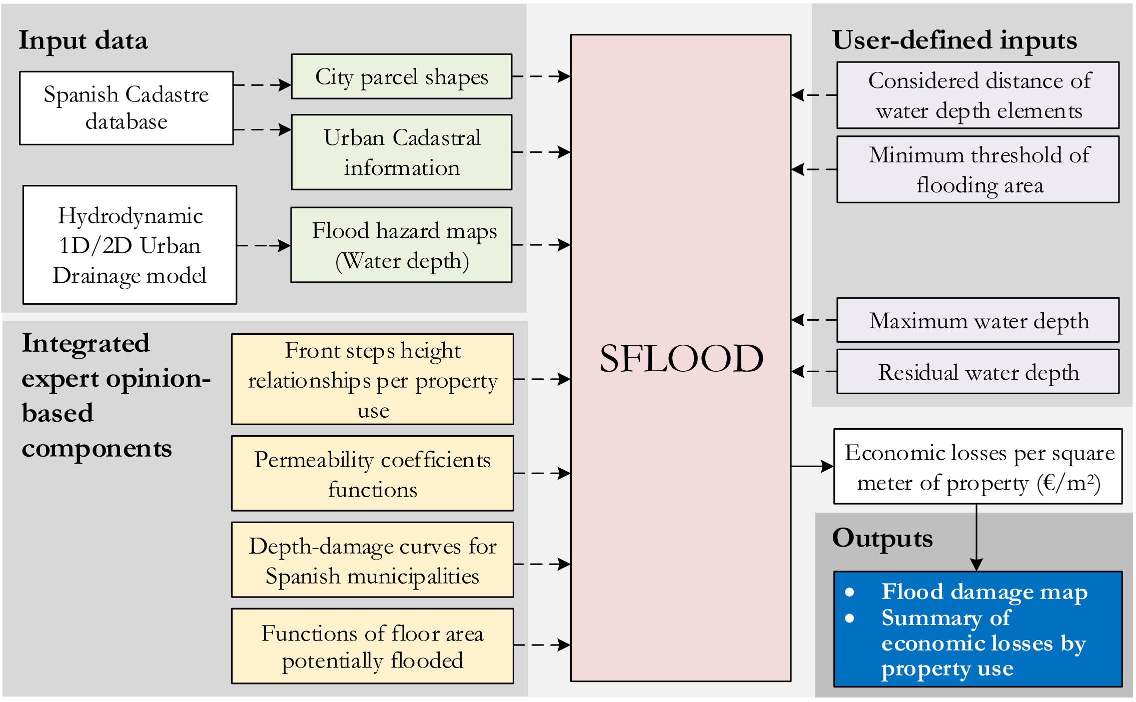


Figure 9. GIS toolbox: inputs-outputs.

Pluvial flood damages were already assessed in Barcelona in the framework of the EU funded CORFU project (2010–2014). To do this a GIS-based toolbox was developed (Hammond et al., 2014) and its process to assess flood damages can be summarised in three steps: 1) Assign a water depth to each building; 2) Interpolate this value in the stage-damage curve to obtain the relative cost, and 3) Multiply the relative cost by the area, obtaining the total damage value per each block. Unlike the CORFU tool in the present development it is considered the water depth inside the property to assess damages. This can be considered the key difference between both models, which can be understood as a more realistic approach.

2.3.7.Model testing and accuracy

2018 was a very damaging year with more than 4.5 M€ of insurance compensations due to damages to property caused by pluvial floods in Barcelona (Figure 10). A single flood event originated most of these damages on the 6th of September which compensations amounted to 3.5 M€. On the 17th of August of the same year, another intense rainfall hit Barcelona, causing extensive flooding which led to the CCS to compensate nearly 0.5 M€ due to damages to properties. In 2011, on 30th of July, a heavy rainfall event also hit Barcelona leading to more of 2 M€ of CCS payouts. These three flood events have been selected to test the damage model presented herein. Rainfall main characteristics and damages produced by these three flooding events are presented in Table 2.

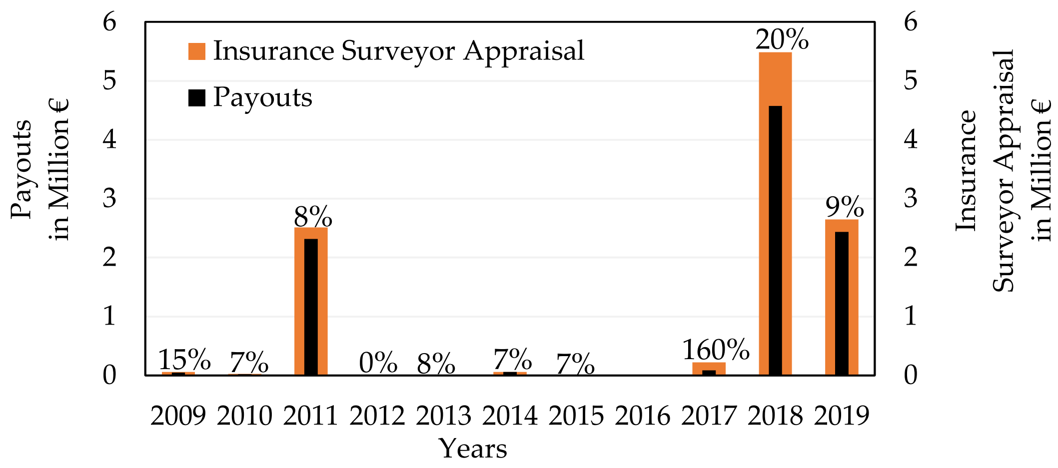


Figure 10. Yearly payouts and appraisals due to pluvial flood damages to properties in Barcelona within the period 2009-2019.

Table 2. **Rainfall characteristics and economic damages related to the selected flood events**

	Rainfall					Damage	
Date	Maximum accumulated rainfall (mm)	Start time	End time	Duration	Weekday	Appraisal	Payout
30/07/2011	58.6	14:45h	16:00h	1h 15’	Saturday	2,263,750.22 €	2,089,426.79 €
17/08/2018	64.8	11:50h	14:30h	2h 40’	Friday	487,999.38 €	444,966.78 €
06/09/2018	89.1	00:25h	02:40h	2h 15’	Thursday	4,323,259.13 €	3,498,118.48 €

It must be noted the difference between the insurance surveyor appraisal and the final CCS Payouts. This difference is due to the deductible (7% for most of the cases) and the underinsurance in some cases. Therefore, the appraisal figures have been considered as the reference values, instead of CCS payouts, because they are assumed to be closer to the actual flood damage. The testing process has been conducted based on the comparison of computed damage and the economic appraisal carried out by the insurance surveyor after the policyholders' claims. It has been used the term "testing" because of the particular inaccuracy of the term "validation" in this case since the actual damages are unknown and the comparison of model's outcomes is made with the insurance surveyor appraisal.

As stated by Zischg et al. (2018), insurance claims constitute a potential validation dataset because of their consistent and relatively homogeneous records over time; however, the data availability constrained by privacy protection is a critical point. To solve this concern, the CCS provides unconditionally with aggregated economic compensations at a larger scale than that of individual properties. For the present study, the CCS provided a single value for both payouts and appraisals at a census district-scale as can be observed in Figure 11, where CCS payouts are distributed per census district for the three selected flooding events. Also, in the same figure, it is shown the spatial distribution of the accumulated rainfall that caused each flooding event.

The accuracy of the model relies not only on the aggregated computed economic damages but also on the damage distribution within the studied area. For this reason, a census district-scale comparison approach was conducted. To test the accuracy of the model, economic damage was compared between computations and insurance data. However, it must be noted that the damage model outcomes are strictly dependent on the accuracy of the hydrodynamic model since the latter's outputs are damage model input. For instance, if the drainage model does not reproduce the flood extent correctly, the flood damage model will not provide any damage to properties that, according to the drainage model, are not in contact with floodwater.

The accuracy of the model was analysed taking into account the four calibration parameters (see user-defined inputs in Figure 9): a) minimum threshold of flooding area to cause damages, b) distance of water depth elements (property influence area), c) maximum depth, and d) residual depth. The 2011 flooding event was used to analyse the model outcomes by varying these four parameters. The parameters combinations (63) are presented in Table 3.

Table 3. Combinations of user-defined parameters considered

# Combination	Distance of water depth elements (m)	Maximum depth (cm)	Residual depth (cm)
1	1	20	5
2	1	20	10
3	1	10	5
4	3	20	5
5	3	20	10
6	3	10	5
7	5	20	5
8	5	20	10
9	5	10	5
10	7	20	5
11	7	20	10
12	7	10	5
13	10	20	5
14	10	20	10
15	10	10	5
16	15	20	5
17	15	20	10
18	15	10	5
19	20	20	5
20	20	20	10
21	20	10	5

Three minimum thresholds of flooding area to cause damages were proposed 500, 1000 and 1500 m^2. For each threshold, 21 combinations of the other parameters have been proposed (Table 3). Distance of water depth elements (property influence area) has been tested from 1 to 20 meters, although the lower is this distance, the more realistic is the physical process. Two values for maximum (10 and 20 cm) and residual (5 and 10 cm) depths have been proposed too. The ranges of parameters' values were established based on the insurance surveyor opinion.

The Normalised Root Mean Square Error (NRMSE) [1] was used to assess how accurate was the output of the model when compared with the insurance surveyor appraisal per census district. Therefore, the differences are accounted within the entire study area at a census district level. The minimum NRMSE obtained for a model run indicates that the selected parameters provide the most accurate estimation. The NRMSE variance will indicate the model accuracy. We are using the term “error” inaccurately since the comparison was made between computed damage and insurance surveyor appraisal, which is different from the actual damage to a greater or lesser extent.

$$NRMSE = \frac{\sqrt{\frac{\sum_1^n (C_{Di} - D_{Ai})^2}{n}}}{D_{Ai,max} - D_{Ai,min}} \quad [1]$$

where n is the number of census districts (n=1068), C_{Di} and D_{Ai} are the computed damage and the damage appraisal in the census district i, and $D_{Ai,max}$.and $D_{Ai,min}$ are the maximum and minimum damage appraisal respectively within the 1068 census districts. $D_{Ai,min}$ is always 0 because not all census districts are damaged when a flood event occurs.

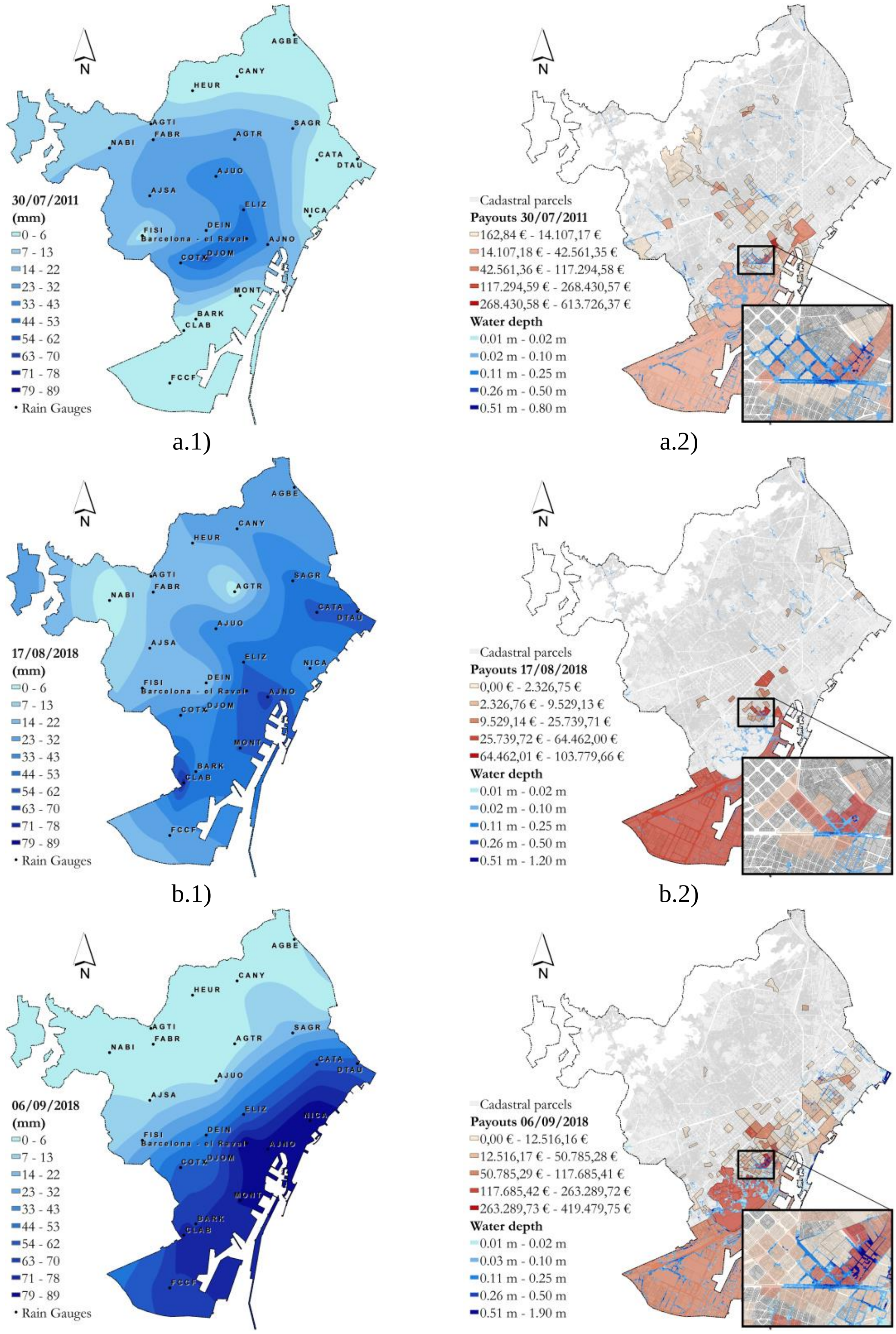


Figure 11. Geospatial distribution of accumulated rainfall volume and CCS payouts in Barcelona for different events: a) 30/07/2011, b) 17/08/2018, and c) 06/09/2018.

3. Results and discussion

3.1. Model accuracy for the selected flood events

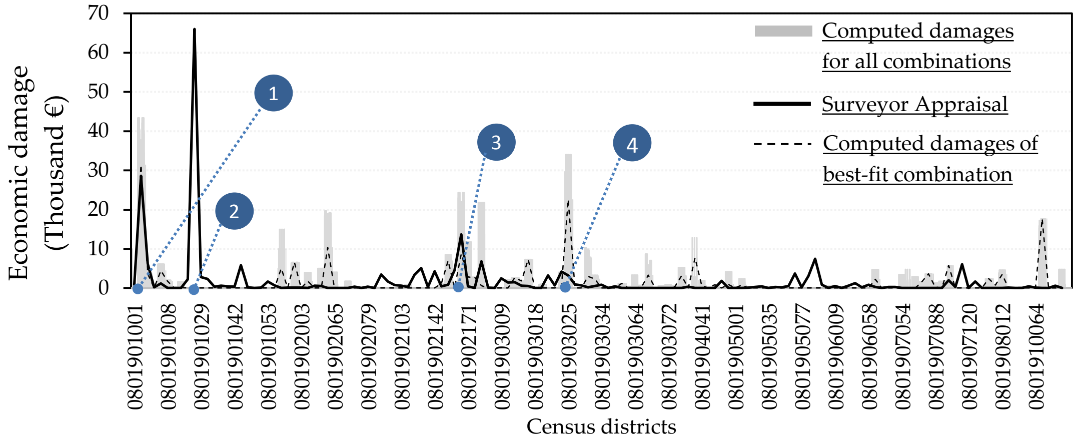
The flood damage model (SFLOOD) was run 189 times to obtain computed damage for 63 parameters' combinations and three flood events (30/07/2011, 17/08/2018, and 06/09/2018).

Figure 12 presents plots with the overlapping of the damage appraisal and the computed damages resulting from 63 model runs, per census district. The continuous line indicates the aggregated damage appraisal per census district and the dashed line represents the computed damages that presented the lowest NMRSE for each flood event. The shadowed data series represent the other model's outputs for the rest of the parameters' combinations. The observation of these plots provides a qualitative overview of the model accuracy. All model outputs provided a similar damage distribution pattern across the census districts, which is basically flood extent dependent. However, the model response was not evenly accurate across all census districts. Focusing on the 2011 event (Figure 12a), it can be observed how some damaged census districts (points (2) and (4)) according to the insurance surveyor appraisal are not represented accurately. While point (2) marks a non-damaged census district, point (4) shows how the model overestimates damages. On the contrary, point (1) and (3) show an excellent correspondence with the insurance surveyor appraisal. As said before, the accuracy of the damage model also depends on the output of the hydrodynamic model, mainly the flood extent. In this regard, the damage model cannot predict any damage to census districts that are not flooded (point (2)), according to the hydrodynamic model.

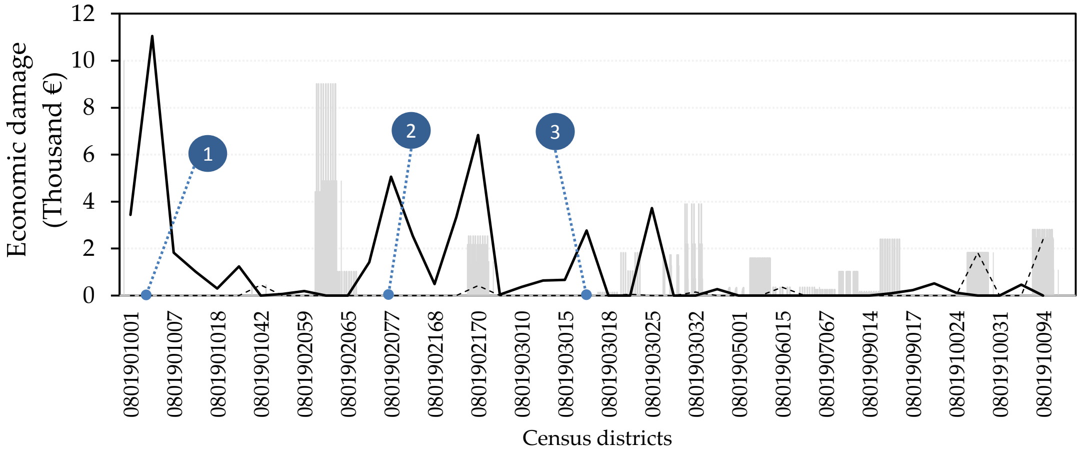
This fact is generally observed in the results obtained from the second flood event (Figure 12b) where the most damaged census district was predicted as non-damaged (points (1), (2) and (3)). The results for this second flood event are weak in terms of damage distribution; however, as could be observed in Figure 11b.2 the flood extent does not fit accurately with the parcels damaged. This means that the hydrodynamic model seems not to reproduce the actual flood event accurately, thus, we cannot state a wrong behaviour of the damage model.

Finally, the computed damage distribution fit much better with the insurance surveyor appraisal for the third flood event (Figure 12c). The census district with major damages (point (1)) is well represented, although the model does not identify damages in others (point (3)) with relevant actual damage. Some other census districts' damages are correctly identified (points (2) and (4)), providing though considerably more damage. This may not mean an inaccuracy since actual damage is expected to be greater than or equal to the insurance surveyor appraisal.

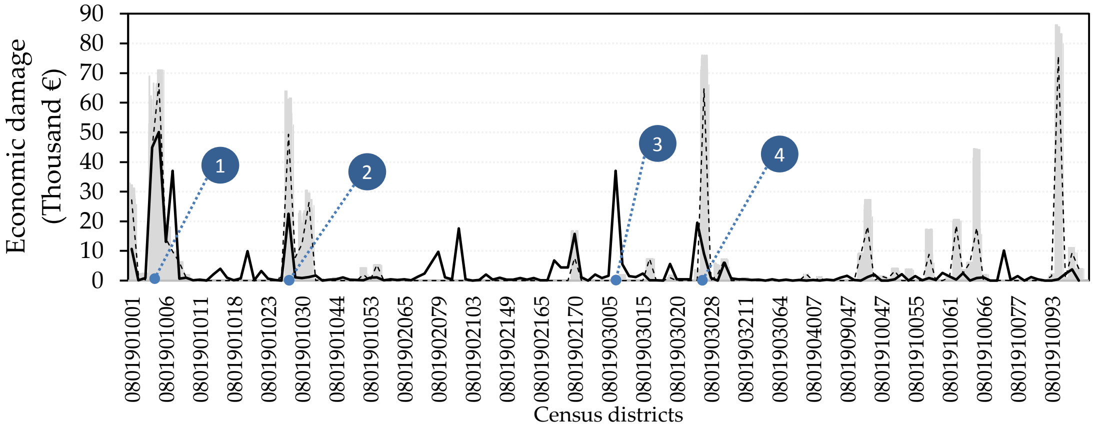
In Figure 13 it is shown the variance of the NRMSE for each simulation. The simulations conducted for the 2011 event provided an NRMSE mean of 3.75% with a maximum of 3.91% and a minimum of 3.55%. It means an error variance of 10%. In the case of the second event (17/08/2018), the NRMSE mean was 16.71%, and the maximum and minimum were 18.51% and 14.85% respectively. It means an error variance of 25%. Regarding the third event (06/09/2018), the NRMSE mean was 38.99%, and the maximum and minimum were 41.13% and 36.18% respectively. It means an error variance of 14%. Therefore, the error variability is considered low for the proposed parameters' combinations, especially for the first flood even which hydrodynamic simulation fits better with the parcels damaged (Figure 11a.2). Therefore, due to the low error variability proven, the selection of the user-defined parameters, as long as they fall in the ranges proposed by the expert opinion, is not considered as critical. On the contrary, an inaccurate flood extent obtained through the hydrodynamic model considerably mislead damage model outputs.



a)



b)



c)

572 **Figure 12.** Comparison of damage distribution per census district between surveyor appraisal and
573 damage model output for the three selected events: a) 30/07/2011 (# combination 19 and a
574 threshold of 500 m^2), b) 17/08/2018 (# combination 17 and a threshold of 500 m^2), and c)

06/09/2018 (# combination 17 and a threshold of 500 m^2). Circled numbers indicate locations to be discussed within the text.

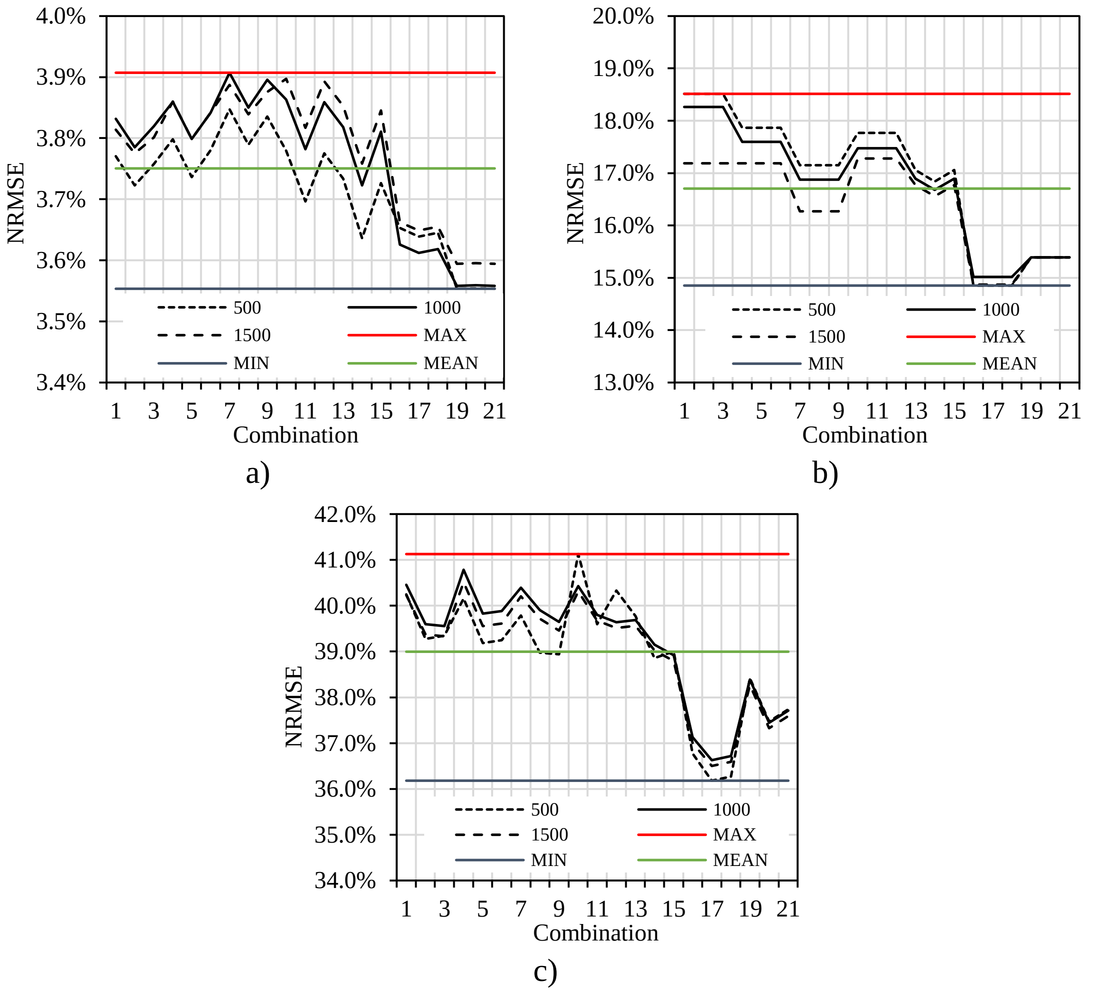


Figure 13. Normalised Root Mean Square Error (RMSE) for each parameters' combination and each flood event: a) 30/07/2011, b) 17/08/2018, and c) 06/09/2018.

3.2. Pluvial flood damage estimates

The aggregated estimate damage at the municipal level for the three selected flood events is presented in Table 4.

Table 4. Flood damage estimations for the three selected events

Date	Maximum accumulated rainfall (mm)	Appraisal	Payout	Combination Id	Computed damage (€)	Difference against appraisal	Difference against payouts
30/07/2011	58.6	2,263,750.22 €	2,089,426.79 €	50019	1,973,940.42	14.68%	5.85%
17/08/2018	64.8	487,999.38 €	444,966.78 €	50017	56,755.00	754.84%	684.01%
06/09/2018	89.1	4,323,259.13 €	3,498,118.48 €	20017	5,503,679.16	21.45%	36.44%

As Merz et al. (2007) stated, the spatial description of the risk plays an important role when trying to communicate the results of risk analyses and to sensitise people at risk. In accordance with this, Figure 14 presents the computed damage at a census district scale for the three selected flood events.

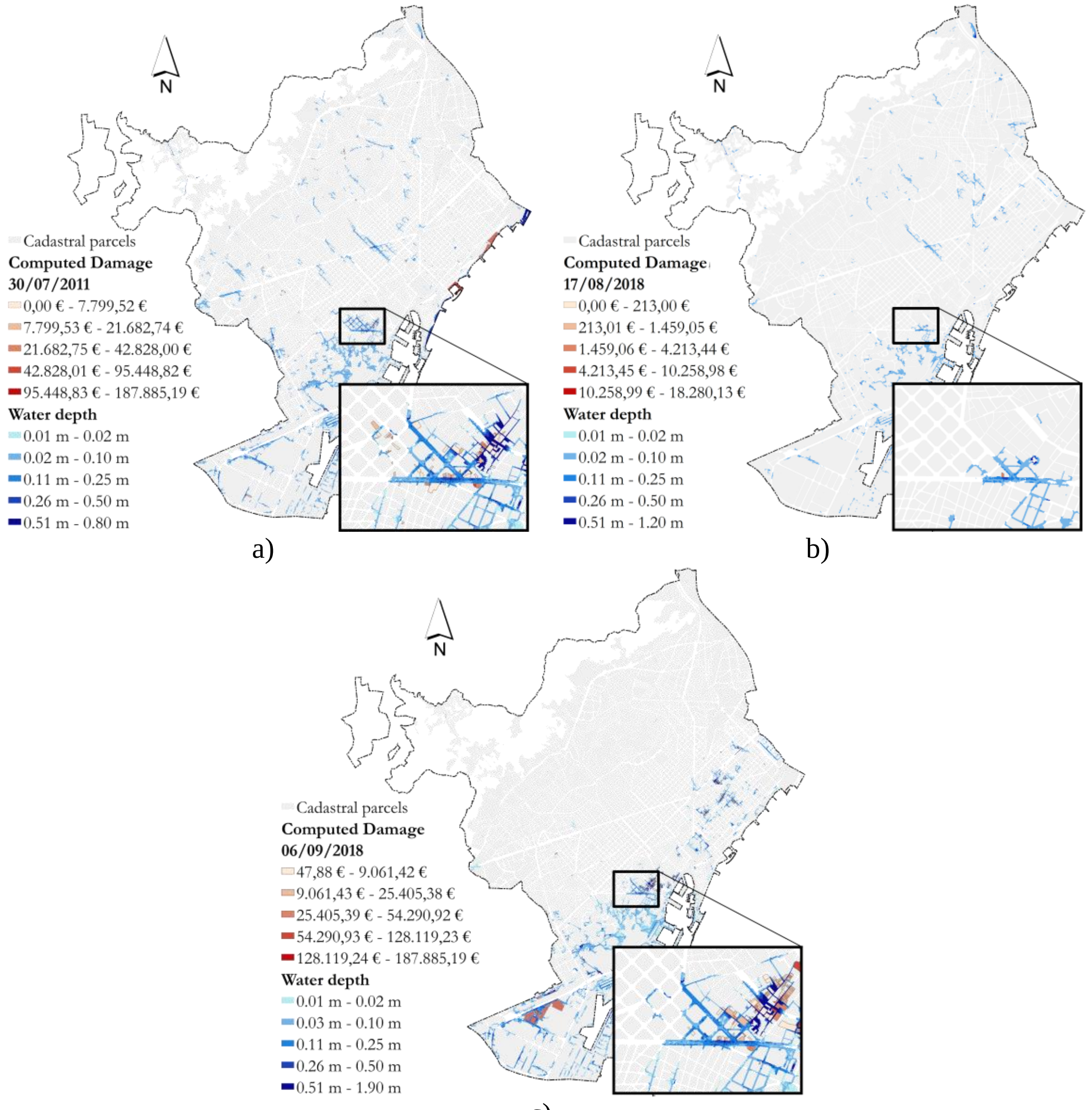


Figure 14. Computed damage maps for the three selected events: a) 30/07/2011 (combination id: 50019), b) 17/08/2018 (combination id: 50017), and c) 06/09/2018 (combination id: 50017)

3.3. Limitations of the method

We do not certainly know how far the insurance appraisal could be from the actual flood damage; thus, there is significant uncertainty in the results (Velasco et al., 2016). For this reason, it cannot be stated that a lower difference between computations and appraisals indicates a more accurate result. Some aspects to consider between these differences are described following:

1. Flood recurrence. If a property was flooded two or more times in a brief period, the second and subsequent damage appraisals only consider new damage, different from the one caused by the precedent event. It would be in this way if the property owner or tenant did not have time enough to replace the flooded assets.

2. Date and time of the flood event. The flood event may occur at any day and daytime hours. When it occurs at night or non-working days, the property owner or tenant cannot act to avoid or restrict the water ingress. Self-protection measures may reduce damages significantly, but they are usually applied only during working days and work hours. The model does not consider self-protection measures.

3. The consideration of only floodwater depth as the primary damage driver. As discussed in the introduction section, different factors contribute to cause damages to property, such as the time of the year the flood occurs, flood duration, water velocity, suspended debris, or warning time (Kelman, 2007; Merz et al., 2004). Therefore, part of the total flood damage may be due to those other factors, which are not considered in our model.

4. Areas frequently flooded. Property in these specific parts of a city is widely insured, unlike those zones where flooding is not frequent. This means that flood damage appraisal is expected to be closer to the actual damage in those areas that are frequently flooded.

5. Hydrodynamic model assumptions and simplifications. Before, the relevance of an accurate flood extent was highlighted as an essential aspect for the flood damage model to provide more accurate estimates. However, there are other aspects related to the drainage model that may influence on the damage model outcomes. The first is the establishment of maximum water depths over the simulation time across the entire model domain. The hydrodynamic variables (e.g. water depths) in each grid cell vary over time,

but maximum values were used as input data for the damage model. Since the 2D overland flow module is activated only in case of flooding produced by surcharged sewer pipes, it cannot generate flooding before entering a manhole or a gully. It means that the computed overland flow may be slightly different from reality, thereby misleading somehow the damages computation.

6. On the other hand, when a real flood event occurs, the public institution responsible for managing the drainage network carries out several operations of opening and closing of retention tanks. These operations are not considered in the hydrodynamic model, which also may cause some differences between actual and computed floods.

7. Sinks and toilets connections to the sewers. Although no overland flow may be observed in certain areas, damage to property could occur due to backflow if the property's sinks and toilets are connected to the combined sewer. This is especially relevant for basements and lower ground floods that can be flooded due to reverse flow from surcharged combined sewers.

3.4. Discussion

This section provides a discussion regarding various aspects of the flood damage estimation carried out in this study: 1) The damage model, 2) the insurance data, 3) the hydrodynamic 1D/2D model and, 4) statistical or multivariate damage models.

The damage model: it was developed based on the knowledge of an insurance surveyor and can be classified as a micro scale-, depth-damage- and GIS-based model. Usually, the vulnerability of properties is related to their corresponding depth-damage curves. Nevertheless, the proposed conceptual model considers property's vulnerability as the combination of both their permeability and the damage rate for the water level rising (i.e. depth-damage curves). This point arises from the fact that we apply depth-damage curves to the floodwater level inside the property. We acknowledge the scientific weakness of the permeability and floor area potentially flooded functions. Thus, an experimental campaign to validate the tools provided herein will be necessary

(Mignot et al., 2020), thereby reducing uncertainty to the model. Some limitations of this model are the non-consideration of self-protective measures and damage to property related to reverse flow from surcharged combined sewers. According to Jongman et al. (2012), uncertainty in depth-damage curves is higher than uncertainty in maximum damage values. However, the development of site-specific depth-damage curves was demonstrated by Albano et al. (2018) to reduce the epistemic uncertainty considerably. Even being a detailed model with which less uncertain is expected, a certain degree of it cannot be avoided. The decision-making process based on uncertain predictions can have a huge economic impact. In this regard Bhola et al. (2020) proposed a methodology for obtaining a multi-model combination as an effective alternative to the traditional best-model approach for producing detailed hazard maps. Their novel approach can be included into the process of decision making to complement the use of the SFLOOD tool. Finally, aspects such as the dependence of computational cell size of the hydrodynamic model on the distance of water depth elements parameter (i.e. property influence area) require further analysis.

The insurance data: it was used to calibrate and validate the damage model through a direct comparison between insurance surveyor appraisals and compute damage for selected actual flood events, at a census district scale. The fact of basing the model validation on the comparison of appraisals and computed damage may lead to inaccurate estimates. For instance, an area containing a high percentage of insured buildings will likely result in a larger total number of claims than an area with less buildings insured (Gradeci et al., 2019). According to this, the model must guarantee a computed damage greater than or equal to the insurance surveyor appraisal. It is worthy of mention that resilient reinstatement (Kelman, 2007) is not mandatory for receiving CCS compensations. This means that residents are not obliged to implement resilience measures to reduce damage for the next flood. Otherwise, the model will present another limitation, but Spanish cities would be more flood resilient. For areas not frequently flooded, insurance coverage tends to be less extensive. For this reason, insurance surveyor appraisals may vary significantly among census districts.

The hydrodynamic 1D/2D model: unlike statistical (i.e. multivariate) damage models, the GIS-based development presented herein requires from the flood extent and floodwater depths obtained through a hydrodynamic model. It means that the damage model inherits the uncertainty related to the hydrodynamic model. For instance, the unrealistic fact that the 2D overland flow module is activated only in case of flooding produced by surcharged sewer pipes can be considered as a limitation of the hydrodynamic model, and thus another uncertainty to account for. Ideally, uncertainty should be reduced jointly between both models. In the present study, the drainage model was borrowed from the municipal water cycle company responsible for the drainage network management, which means that the joint uncertainty reduction was not possible. Also, ideally, the validation process of both models should be conducted under the same criterion. In this case, the validation of the hydrodynamic model based on the actual parcels damaged according to the insurance data (Zischg et al., 2018), would have allowed obtaining a more accurate flood extent and thus the exposed element. Zischg et al. (2018) stated that the selection of the flood model validation technique should be based on the type of flood analysis conducted. When it comes to flood exposure and risk analyses, accurate results at locations of interest for risk assessment are required.

The needed simplifications, limitations and assumptions of the hydrodynamic model also affect the damage model results. Previously was already mentioned the consideration of maximum water depths over simulation time in each grid cell and the non-consideration of opening and closing operations of retention tanks, but some other aspects may affect the damage estimates. Mignot et al. (2020) highlighted the importance of considering largest obstacles, such as parked cars, in operational numerical models that calculate urban floods for an accurate estimation of the intrusion discharge. Forero-Ortiz et al. (2020) analysed flood risks posing potential Barcelona metro disruptions due to a substantial amount of water flowing down to the underground metro system. None of these aspects was considered in the hydrodynamic model used herein, which implies an added uncertainty to the damage assessment process.

Statistical or multivariate damage models: these are a different approach from the one presented herein since these do not require a hydrodynamic model. Instead, these models establish relations among several explaining variables and flood damage. Although these models seem to be more advantageous than those GIS-based, they can mislead estimates if, for instance, interventions (improvements) to the drainage network are made. Gradeci et al. (2019) conducted a comprehensive review of studies that proposed relationships between different explaining variables and flood damages in urban areas. The authors gathered all explaining variables found in the literature and groped them into four categories: meteorological, geographic, demographic, and building. Part of the variance will always remain unexplained if no account is taken of variables from any of the identified categories. The spatial and temporal perspectives of the rainfall are paramount to the flood-related damages (Gradeci et al., 2019). However, although rainfall is agreed to be the most relevant factor to explain damages, its single consideration is not enough to explain observed variance. The selection of the explaining variables also depends on the working scale. The explaining variables are interminable: binary variable depending on whether the event occurred during the day shift or night shift, urban exposure, the permeability of surfaces, property value, household income, age and education of breadwinner or fraction of homeowner, urban drainage system properties (drainage capacity, age of infrastructure, percentage of surface water), level of urbanisation, socioeconomic indices (household income and property value), district-related parameters (percentages of low-rise and high-rise buildings, percentage impervious surface), weather conditions prevailing during preceding days, green spaces, self-protective behaviour, precautions, external response and early warning, building condition, age of residents, willingness to pay for insurance, presence during occurrence of the event. This denotes the great uncertainty behind flood damage estimates.

4. Conclusions

A comprehensive pluvial flood damage model (SFLOOD) to predict economic losses to property in dense urban environments has been developed and presented herein. It is a micro scale-, depth-damage- and GIS-based model where water depth is the only hydrodynamic variable considered as a damage driver. Although a variety of uncertainties related to the flood damage estimates have been revealed here, the model is able to predict the order of magnitude of the actual damages according to the results obtained. Assumptions and limitations of the hydrodynamic 1D/2D model may influence largely to the damage predictions. A correct flood extent is one of the major aspects to ensure more accurate damage estimates.

The model's primary design purpose was to predict pluvial flood damages in Spanish urban environments; however, it could be used for predicting damages caused by fluvial flooding and adapted to be applied in urban areas out of Spain. Nevertheless, it is of interest to tackle the lack of tools to estimate flood damages in Spain and to contribute to a common pluvial flood risk mitigation framework nationwide. This tool will benefit institutions dealing with urban drainage management, to prioritise adaptation scenarios according to their effectiveness in terms of risk reduction. Besides, it is expected to lead to policy implications by contributing to future updates of the EU Floods Directive in Spain. The Spanish insurance market can be benefited from this tool too; in particular, the CCS, which could anticipate the disbursement of existing funds.

Acknowledgments

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A novel expert opinion-based approach to compute estimations of flood damage to property in dense urban environments. Barcelona case study

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Abstract: A certain acceptable level of risk in major drainage system must be established since urban areas cannot be made entirely free from pluvial flooding. Among the diversity of flood risks in urban areas, direct damage to property has been extensively studied. A novel model approach (SFLOOD) to estimate flood damage to property in urban areas has been developed and presented herein. The model was conceptualised according to the knowledge of an insurance surveyor, acquired over many years on flood economic losses appraisals. It is a micro scale-, depth-damage- and GIS-based model where water depth is the only hydrodynamic variable considered as a damage driver. The model testing has been conducted through the direct comparison of computed damage and damage appraisals provided by the Spanish public insurance company, Consorcio de Compensación de Seguros (CCS), for three actual flood events occurred in Barcelona (Spain). Although a variety of uncertainties related to the flood damage estimates have been revealed here, the model is able to predict the order of magnitude of the actual damages according to the results obtained.

Keywords: pluvial flooding; damage assessment, insurance; Barcelona.

1. Introduction

Decision-making in a flood risks context requires reliable tools to select the most effective adaptation measures to face current hazards but also the challenges of climate change. The reported economic losses caused by climate-related extreme events in Europe amounts to EUR 453 billion for the period 1980–2017, whereof an 8% corresponds to Spain. Two-thirds of these damages are derived from flood impacts. The total damage costs may increase as a consequence of more frequent and intense rainfall events in many regions due to rising temperatures that are expected to alter the hydrological cycle (European Environmental Agency (EEA), 2016).

Urban environments are extremely vulnerable to floods from different sources, mainly pluvial and fluvial (Chen et al., 2010). However, pluvial flooding is a global challenge for all cities, not only those located in riverine floodplain areas. An urban drainage system deals with stormwater, and two subsystems form it; major (overland flow paths), and minor (pipes) (Butler et al., 2018). Heavy rainfall may lead to pluvial floods in many cities once the minor drainage system exceeds its capacity. Although fluvial floods tend to be more calamitous, they do not occur that often as pluvial ones (Ootegem et al., 2015). The higher frequency of pluvial floods results on relevant aggregated damage over the years. Also, growing urbanisation leads to a higher volume of runoff, due to decreasing of infiltration, thereby exacerbating flooding consequences. The already vulnerable situation of urban areas and their drainage systems is forecasted to worse due to climate change. Changes in precipitation patterns will lead to more frequent sewer surcharging (Arnbjerg-Nielsen et al., 2013; Zhou et al., 2012).

Therefore, more frequent pluvial urban floods are expected and, both residents and assets will be exposed to them. For this reason, a comprehensive risk assessment is paramount from a social and economic point of view. Although the complexity of flood risk assessments in urban areas is added. Factors that may potentially influence the severity of flooding can be topography, building and household and urban drainage characteristics, and spatial distribution of rainfall (Spekkers et al., 2013). Land-use planning that does not pay attention to potential flooding and climate change effects may contribute to increase risks.

As urban areas cannot be made completely free from flooding (pluvial), a certain acceptable level of risk (Dickson et al., 2012) in major drainage systems has to be established. Among the diversity of flood risks in urban areas, direct damage to property has been extensively studied. A variety of flood damage assessment methodologies approaches can be found globally. Nevertheless, they share the aim of prioritising adaptation measures according to their effectiveness in terms of economic direct damages reduction.

Pluvial flooding acts on a different scale than fluvial flooding, where mechanisms and characteristics are functionally different. A variety of flood loss estimation models exist worldwide (Galasso et al., 2020)~~Accordingly,~~and a particular distinction can be made between those ~~damage assessment models~~ based on aggregated land use data (e.g. CORINE) and those focused on individual objects (Jongman et al., 2012; Merz et al., 2010). Both types are generally applied through GIS techniques. The first is usually employed when assessing damages at meso- and macro-scales (fluvial floods), and the second is more appropriate at a micro-scale level (pluvial urban floods) (Merz et al., 2010). Object-based models require a high complexity rather than simplicity linked to the ones based on aggregated land use. These characteristics lead to different advantages for each type of model. Land use-based models provide with a rapid calculation, and object-based models offer a detailed building distribution within the study area.

Notwithstanding, object-based models use a large number of object types and corresponding flood damage characteristics (IBI Group, 2015). An additional classification for damage models may be done according to their data source, distinguishing between empirical and synthetic. While the first can be accurate when applied to similar studies, the second group provides an unreliable application to another region.

Different factors contribute to cause damages to property, such as the time of the year the flood occurs, flood duration, water velocity, suspended debris, or warning time (Kelman, 2007;

Kreibich et al., 2009; Merz et al., 2004). Based on the number of factors considered, another classification can be established, by defining bivariate models as those considering only floodwater depth as the primary driver of damage, and multivariate as those encompassing a variety of factors (Ootegem et al., 2015). The first relies on the so-called depth-damage curves that represent the vulnerability of elements at risk. These are functions that relate a floodwater depth to its corresponding damage in relative or absolute terms (Velasco et al., 2016). Although there is an intrinsic uncertainty to depth–damage approaches (Jongman et al., 2012) these tend to be widely used in many damage models. Jongman et al. (2012) compared seven flood damage models developed for different European regions and the United States. An intrinsic characteristic of flood damage models is their limitation in terms of transferability in space and time (Thieken et al., 2008). Damage models based on depth-damage curves require the flood extent as input which is obtained through hydrodynamic coupled 1D/2D models in urban environments. The damage assessment process is conducted through the overlaying of flood inundation, buildings, and their corresponding depth-damage curves.

Recently, Jamali et al. (2018) proposed an integrated hydrodynamic and pluvial flood damage assessment model. The first was developed as a rapid inundation model coupled to a 1D drainage network model to reduce computational efforts and thus computing time. The flood damage assessment module uses monetised (€/m^2) depth-damage curves for Australia. Only two types of property use are considered, residential and commercial. An example of a multivariate flood damage model is the one proposed by Ootegem et al. (2015). It includes non-hazard indicators (i.e. properties flooded without related damage) based on a survey conducted in Flanders (the northern region of Belgium). Some other indicators used were building characteristics, victims' behavioural predictors (e.g. risk awareness) and properties income. Damage functions were constructed not only based on water depth (i.e. depth-damage functions) but also for various categories of specific hazard indicators. It is explicitly said that no consideration is made regarding the place where the water enters the building. Although it is a comprehensive model, it is not supported by a GIS platform, and thus damage distribution is not predicted. This type of models generally does not account for the enhancements of the drainage network over the considered time period of damaging events analysed. Likely, a variety of interventions have been conducted over this period which may bias the model outcomes. However, the advantage of these models is that they do not require a previous hydrodynamic simulation. There exist also approaches focused on specific types of buildings, such as the study of Milanesi et al. (2018) that considers building' structure stability against floods occurred in mountain areas. Namely, the model encompasses only masonry building and considers masonry walls' impact by flow under different building configurations. Although the purpose of the study is to identify potential structural damages, no monetisation is considered.

Merz et al. (2010) expounded the scarcity of damage data and the overall crudeness of damage assessment models. This statement is still current, and due to this lack of damage data and damage assessment models are transferred in time and space without sufficient justification. The concern takes on particular relevance when it comes to dealing with the complexity of assessing economic damage to property caused by pluvial floods in urban environments.

On the other hand, the EU Floods Directive (The European Parliament and the Council of the European Union, 2007) requires the Member States to develop, adopt, and implement flood risk management plans. In Spanish plans, measures aiming at reducing the building's vulnerability (Manrique et al., 2017) have been proposed, but the plans take into consideration mainly riverine and coastal floods. Sewer flooding though should not be undervalued since worldwide urban environments, to a greater or lesser degree, are exposed to this threat. Pluvial flooding is also expected to become more frequent due to the effects of climate change (Arnbjerg-Nielsen et al., 2013), increasing risk, damage, and disruptions to citizens. Therefore, pluvial flood risk assessments for urban areas should be considered as one of the main challenges for the implementation of the EU Floods Directive by EU member states (Kellens et al., 2013). A comprehensive framework, like the proposed by Zhou et al. (2012), may be adequate for future Flood Risks Directive updates.

This paper presents the development of a comprehensive pluvial flood damage model to predict economic losses to property in dense urban environments. The model has been termed SFLOOD that stands for Stormwater FLOOding Damage. For simplicity, although a variety of variables contribute to causing damages when a pluvial flood occurs (Ootegem et al., 2015), the proposed approach herein only considers floodwater depth as the primary damage driver. The lack of tools to estimate pluvial flood damages in Spanish urban areas led to the need in defining this model and their related tools presented herein. In despite of its tailored approach for Spanish urban environments, this model may be adapted to similar city landscapes and property layout out of Spain. It is especially adequate for large cities with complex drainage networks, for which these tools are of major importance (Ashley et al., 2005). According to previous descriptions, our development can be classified as a micro scale-, depth-damage- and GIS-based model.

The model and tools presented herein will contribute to a common pluvial flood risk mitigation framework in Spain, thereby complementing a previous work on nationwide depth-damage curves (Martínez-Gomariz et al., 2020). The model will allow predicting overall damage at the municipal level but also providing a reliable damage distribution, thereby identifying risk hotspots in cities. It will be a tool to assist institutions dealing with urban drainage management, to prioritise adaptation scenarios (i.e. a set of measures) according to their effectiveness in terms of risk (i.e. direct tangible damages) reduction. Therefore, it will be a decision-making tool in terms of local investments (e.g. regional Master Drainage Plans). Standardisation of the use of this tool at a national level would allow comparing the Expected Annual Damage (EAD) of different regions. The EAD is an aggregated value of the damage model outcomes (Zhou et al., 2012), and tend to be used as a risk indicator in monetary terms.

In terms of policy implications, these new tools to predict pluvial flood damages in urban areas may lead to consider pluvial flood risk assessments in future updates of the EU Floods Directive (2007/60/EC). Tools developed in the present work align well with the framework proposed by Zhou et al. (2012) and can contribute largely to the implementation of Floods Directive in Spanish urban areas. In alignment with this, providing these tools will contribute to new approaches of risk-oriented (Merz et al., 2004) Master Drainage Plans at a municipal level.

Finally, this development is expected to contribute to the Spanish insurance market. After a pluvial flood event, the Spanish Insurance Compensation Consortium (CCS, for its acronym in Spanish) receives an uncertain number of claims. Accordingly, these claims amount to an unknown payout quantity, which does not allow CCS to anticipate the disbursement of existing funds. The compensation payout process is complex and slow enough to allow a quick damage assessment in just a few hours (e.g. 24 to 48 hours).

Following sections of this paper include: 2) methods and materials; 3) results and discussion; and 4) conclusions. Section 2 (methods and materials) presents the description of the case study, the urban drainage model and a comprehensive explanation of the approach taken for the pluvial flood damage model. Section 3 (results, limitations of the method and discussion) encompasses the flood risk assessment carried out for Barcelona. This assessment is only based on the economic damage to property estimations, carried out through runs of the damage assessment model presented herein. As the damage model is the main aim of this paper, its accuracy is analysed too. Discussion about uncertainties and further research necessities is provided. Finally, section 4 (conclusions) gathers some take-home messages, and the main benefits of the presented research are recalled.

2. Methods and materials

2.1. The case study description: Barcelona

Barcelona (Figure 1) has a population of 1,620,943 inhabitants and a municipal area of 101.4 km^2. The city is located in Catalonia, Spain, on the Northeast coast of the Iberian Peninsula and is facing the Mediterranean Sea. It is highly urbanised, and most of the urban area is located on a rather flat area few tens of meters above mean sea level and surrounded by the mountain range of Collserola, the Llobregat River to the south-west and the Besós River to the northeast. The average population density of the city is 15,985 inhab./km^2 with higher values on the city centre and lower ones on the surrounding hills.

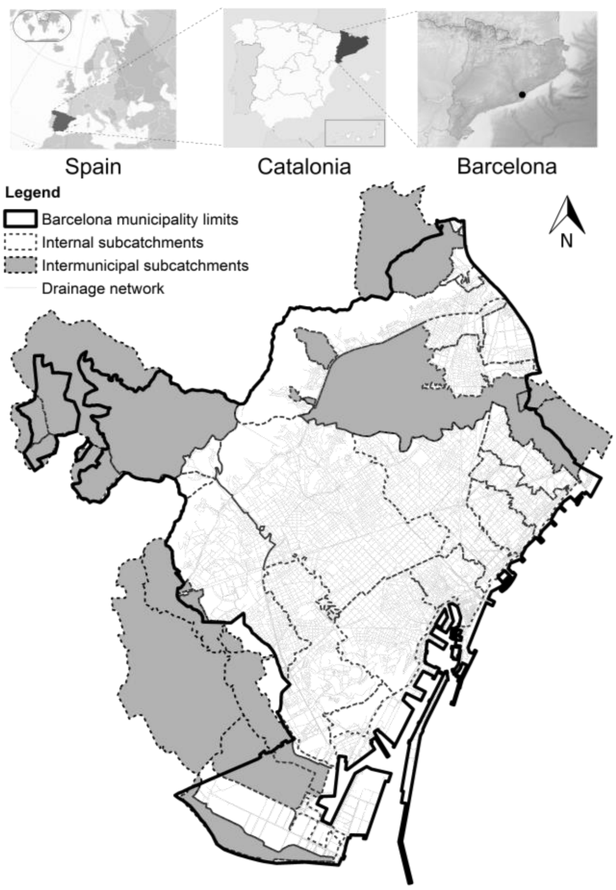


Figure 1. Barcelona limits, subcathments, and drainage network

Barcelona has a Mediterranean climate with mild winters and warm summers, experiencing heavy rainfalls of high intensities and flash floods events. The yearly average rainfall is approximately 600 mm, the maximum 5-minutes rainfall intensity corresponding to a return period of 10 years is 204.7 mm/h (Russo et al., 2015), and it is not rare that 50% of the annual precipitation occurs during two or three rainfall events. This rainfall patterns, together with the old and mostly combined drainage system, the high degree of imperviousness and the terrain slopes, cause urban pluvial floods and combined sewer overflows. The degree of imperviousness is estimated to be approximately 70% of the whole municipal area with higher percentages in the urban areas and lower ones on the surrounding hills.

The morphology of Barcelona presents areas close to Collserola mountain with high gradients (with an average of 4% and maximum values of 15–20%) and other flat areas near to the Mediterranean Sea with mild slopes (close to 0–1%), and there are also local low-lying areas susceptible to floods. During heavy storm events, Barcelona suffers critical flooding with significant impacts in terms of economic damage and possible service interruptions (transport, energy, etc.).

2.2. Urban drainage model of Barcelona

The pluvial (or urban) flood model of Barcelona is used to simulate spatially distributed maximum flood depth on the urban areas that are used as an input for the flood damage model. The pluvial flood model is a 1D/2D (sewer/overland flow) model that can continuously simulate the spatial and temporal distribution of both sewer and surface flood processes and their mutual interaction. This model was calibrated and validated using historical observation data during different rain events. Data such as water level measurements in the sewer network, rainfall intensities from local rain gauges and photos and videos of urban floods during different past rain events were used for calibration and validation.

The 1D/2D hydrodynamic model was developed with InfoWorks ICM®. The model includes 2041 km of pipes, 85 834 maintenance holes, 980 weirs, 44 sluice gates, 75 pumps and 285 storage nodes representing diverse kinds of chambers and 10 detention tanks with a total volume of more than 400 000 m^3. The 2D overland flow model covers the whole administrative land of the city and all the upstream catchments discharging into the Barcelona sewer network. The 2D domain includes 1,361,324 cells. The 1D/2D model is made of different sub-models continuously interacting with each other:

- A rainfall-runoff model that simulates rainfall-runoff processes for each of the approximately 85,000 sub-catchments. Sub-catchments were created using Thiessen polygons applied to each drainage network node except for the upstream undeveloped areas where sub-catchments were delineated with GIS hydrological tools applied to the DTM model. Each sub-catchment has a GIS estimation of both pervious and impervious areas. Continuous hydrological losses were associated only to pervious areas and were simulated using the Horton infiltration model. Initial losses up to few mm were specified for both pervious and impervious areas. Initial losses usually have a minor impact on urban flooding. The routing model was based on a non-linear reservoir with a kinematic-wave equation. For each sub-catchment, the flow rate resulting from the rainfall-runoff model is diverted into the corresponding 1D model node representing a sewer manhole.
- A 1D hydraulic model of the drainage network that solves the 1D Saint-Venant equations to simulate the spatial and temporal distribution of flow velocities and depth in the network.
- A 2D overland flow model made of an unstructured grid to simulate overland flow over floodable urban areas. This 2D grid was generated from a digital terrain model (DTM) of 2.25 m^2 resolution obtained from LIDAR data of 15 cm precision. The 2D cells have variable areas that can vary from a minimum of 25 m^2 in the streets of Barcelona up to a maximum of 100 m^2 in the less urbanised and hilly upstream areas.

The 1D/2D coupled model was conceived as a semi-distributed model, commonly applied in urban stormwater modelling, that is based on subcatchment units where rainfall is applied, while runoff is estimated and routed according to specific hydrological losses and rainfall-runoff transformation methods. 2D overland flow module is activated only in case of flooding produced by surcharged sewer pipes, causing overflow on the urban surfaces (Russo et al., 2020).

2.3. Pluvial flood damage model approach

2.3.1. The role of an insurance surveyor in flood claims in Spain

Risks posed by natural hazards are among the so-call extraordinary risks covered by the Spanish Insurance Compensation Consortium (CCS, for its acronym in Spanish). This is a government institution attached to the current Ministry of Economy Affairs and Digital Transformation, which is subject to the private insurance rules. In Spain, the receipts of private insurance policies include a surcharge to the endowment of a CCS common fund. Generally, the CCS will be responsible for flood damages compensations, unless this specific risk is covered by the private insurer. In any case, a policyholder will be only entitled to compensation once an insurance surveyor (or more) appraises the damaged property. Focusing on pluvial floods in urban areas, when these occur, the CCS sends one or more insurance surveyors to provide them with a first evaluation of damages. This first damage evaluation, according to the CCS, tends to be accurate and is extremely useful for the insurer to forecast the total payouts to be finally compensated. This fact denotes significant knowledge of these experts. The expert opinion was already taken into consideration in the British Multi-Coloured Manual (Penning-Rowsell et al., 2010), which was developed mostly through a synthetic analysis and using of expert judgment (Jongman et al., 2012).

Therefore, flood insurance surveyors well know the characteristics and behaviour of pluvial urban floods. Besides, it is not clear to what extend property owners may remember the amount of the damage or the floodwater depth inside the property (Ootegem et al., 2015). However, fortunately, a flood insurance surveyor has records of this valuable information. We have put this knowledge into practice by depicting a conceptual model of water intrusion into properties and developing tools to predict pluvial flood damages.

2.3.2.A conceptual model of the floodwater transfer from outside to inside a property

Depth-damage curves are the most established approach~~an essential element~~ to estimate flood damages. When it comes to a detailed study in urban areas, the water level to consider must be the one inside the property. Typically, floodwater depths surrounding the parcel or building are applied to estimate the damage for a specific property. This assumption could be acceptable for a riverine flood, which residence time could be considered enough to let water level inside the building reach the outside level. However, the low residence time of pluvial floods cannot allow taking such an assumption. Water contact damage is the damage caused by material getting wet, not by any physical force applied by the water (Kelman, 2007). This study focuses on property use rather than building or material type because when it comes to urban pluvial floods damage to contents is especially relevant.

As stated by Merz et al. (2010), flood damage assessment can be performed on three different scales: macro, meso and micro. The main differences between spatial scales relate to the spatial accuracy of potential damage analysis. When the assessment focussed on an urban area, it should be considered as a micro-scale; thus, aspects such as the relations between water depths outside and inside must be considered. Therefore, a conceptual model based on discussions with an insurance surveyor expert in flood damages is proposed here to understand the transfer of water from outside to inside the building. Buildings are naturally leaky, and it is difficult to be entirely certain of keeping all water out of all possible entry points (Kelman, 2007). There are two main ways for floodwater to access into the property: a) overland flow into the building, and b) surcharge of the drainage system. Sinks and toilets are many times connected by gravitational flow to the sewers. It makes basements and lower ground floors vulnerable to surcharged flow that may reverse up the combined building drains and be forced backward through the household appliances into the properties during heavy rainfall (Sörensen and Mobini, 2017). A depth differential between the inside and outside of the property occurs when floodwater rises outside property without rising at the same rate on the inside of the property (Kelman, 2007). These situations may lead to structural failures, mainly in the case of riverine flooding and sealed properties. However, no structural stability problems are expected when it comes to stormwater flooding in urban areas. The basis of this statement refers to the available historical flood damage records in Barcelona. Experimental and numerical studies have been conducted to estimate flow intrusion towards buildings within highly urbanised areas (Mignot et al., 2020) or isolated buildings (Gems et al., 2016). Nevertheless, these studies consider closing systems open by themselves after being submerged and thus become damaged or entirely removed. These situations are more likely to occur during riverine flooding. According to our experience and records in Barcelona, closing systems do not tend to be damaged or removed during stormwater flood events. For this reason, in the present approach, we consider all closing systems are closed during a flood event, which although does not guarantee entirely sealed properties.

The existing front steps to enter the properties act as flood protection and reduces the water depth on the pavement ($\bar{y}$, Figure 2) to a lower depth (y_o, Figure 2). It has to be noted though that commercial uses do not present these front steps or it is very low-lying to facilitate customers to enter, thereby providing none or little flood protection (Figure 3). Fieldwork has been conducted in the city of Barcelona (Spain) in order to obtain an average height value for these steps according to a variety of property uses. This work consisted of the visit and measurement of step heights from around 50 properties of different uses located in the neighbourhoods that historically have been more affected by floods: El Raval, Poblenou and Poble Sec.

Therefore, depending on the water depth acting on the entrance from the property (y_o, Figure 2), a greater or lesser water ingress into the property will occur. As the flood residence time is expected to be low for pluvial floods (Chen et al., 2010), the depth inside will be likely lower than the outside one. According to this approach, the conceptual model of water ingress into properties depicted in Figure 2 is proposed here. This scheme considers different layouts of buildings: 1) only ground floor, 2) ground floor and one basement, and 3) ground floor and two basements. Moreover, these layouts consider the presence of car parks, which means that six possible layouts are considered in this model, which would cover the vast majority of layouts that can be found in Spanish urban areas. When a property does not present any basement, the water depth could reach the outside water level. However, the existence of one or more basements would cause the water to flow down to lower stories (i.e. basements) thus not allowing the water to exceed a certain maximum level (Max depth, Figure 2), lower than the outside one. Basements act as small water storage tanks and water depths could even become higher than those present on the streets. There may be several connections to let the water leak from one floor to the other, but stairwells are supposed to be the main ones. Therefore, the maximum damage on a floor with an underneath level will be related to the *maximum depth*. It may also be accepted a *residual depth* because a certain amount of water will remain on the ground floor without flowing down to the basements. In case of the existence of a car park, a water leak will occur from one floor to other but also from the street, due to the entrance gate to the car park, which is in contact with the water depth outside the building. If this approach is accepted, depth-damage curves should be applied to the depths inside the property (y_{GF}, y_{B1}, y_{B2}, Figure 2). Closing systems such as doors and windows are the spots through which water could enter the property. During a flood event, these closing systems are expected to be closed, but even then, water may percolate since their sealing capacity is not fully guaranteed (Figure 4).

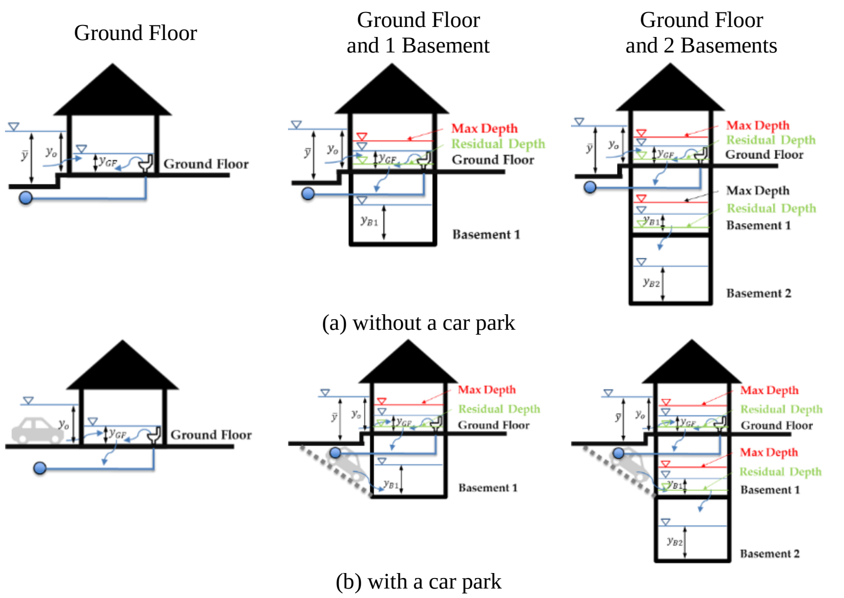


Figure 2. Conceptual model of the water transfer from outside to inside the property during pluvial floods in urban areas.

The main idea in this approach is that a "Permeability Coefficient" (P_C) will determine the difference between the water depth outside and inside ($P_C = y_{GF}/y_o$). The higher is the water depth outside, the higher is the Permeability Coefficient (P_C). In other words, when the water depth outside is high enough, the water depth inside the building is expected to be the same that the outside one ($P_C = 1$). The Permeability Coefficient is a function of the water depth outside but also depends on the type of property. Tailored relations between water depth outside and inside the buildings have been developed for 14 property uses considered. Diverse types of closing systems and number of toilets (another source of water ingress) have been considered for each property use.

Figure 3. Entrance to trades in Barcelona with a nearly inexistent front step height.

Figure 4. Signals of floodwater level inside and outside the property.

On the other hand, this conceptual model fits with properties with a reduced floor area, because large floor areas are usually not entirely covered by water. According to this, it might be distinguished between total floor area and flooded floor area. The most conventional trades usually have floor areas not exceeding 250 square meters. Therefore, for small floor areas (Figure 5a) total floor areas correspond to the flooded area, unlike large floor areas (Figure 5b), which use to be partially flooded.

Although flood recurrence can be relevant (Elmer et al., 2010) in terms of self-protection measures, the changes in small business' ownership, the most affected by pluvial floods in highly dense urban environments like Barcelona, is extremely frequent in recent times. For this reason, the fact of non-considering property's self-protection is not assumed as a model's shortcoming.

(**a**) (**b**)

Figure 5. Entrance to properties with a) small floor areas, and b) large floor areas.

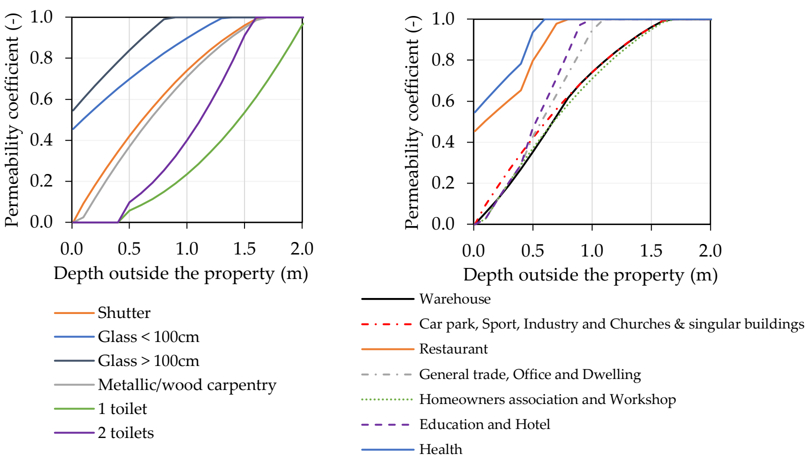
2.3.3.Functions of permeability coefficients

Although water depth inside a property damaged due to flooding is part of the recorded data from a damage survey, the water level on the street is not usually registered. However, an experienced flood surveyor can estimate this water level. Therefore, the permeability coefficient for different water depths has been estimated based on the experience of one of the authors of this piece of work. Initially, these values have been related to specific water entry points, such as closing systems and number of toilets (drains and traps). For instance, a property with glass closing systems, without aluminium carpentry, would allow the water entry in an easier manner than a property with closing systems with any carpentry.

Moreover, it is expected that these coefficients will vary with the existing water depth on the street since the higher is the water depth on the streets a higher flood residence time is assumed. Therefore, functions that depend on water depth on the streets and the type of closing system and the number of toilets have been derived first (Figure 6a). A certain number and type of closing systems, as well as the number of toilets (Table 1), have been related to each type of property considered. By aggregating per type of property, the effects of single water entry elements total functions of permeability coefficients per type of property have been developed (Figure 6b). There exist a discussion about the dilemma of to seal or not seal an individual property (Kelman, 2007). However, the fact is that most residents tend to seal their properties to prevent floodwater infiltration. The concept of indoor water depth was also considered by Chen et al (2019), who assumed that floodwater flows into the buildings through doors with known location and it follows the fluid mechanics of discharge over a rectangular weir.

Table 1. Closing systems and toilets related to each type of property.

Type of property	Combination of closing systems and number of toilets
Warehouse	Shutter and glass > 100cm
Car park	Shutter
Restaurant	Glass < 100cm and two toilets
General trade	Metallic/wood carpentry and one toilet
Homeowners associations	Metallic/wood carpentry
Sport	Shutter
Education	Metallic/wood carpentry and two toilets
Hotel	Metallic/wood carpentry and two toilets
Industry	Shutter
Office	Metallic/wood carpentry and one toilet
Health	Glass > 100cm and two toilets
Workshops	Metallic/wood carpentry
Dwelling	Metallic/wood carpentry y one toilet
Churches and singular buildings	Shutter



(a) **(b)**

Figure 6. Permeability coefficient functions according to a) a specific water entry element and b) different property types.

2.3.4. Functions of floor area potentially flooded

These functions allow estimating the flooded floor area of each type of property depending on the water depth outside the property (Figure 7). By way of illustration, a 1000-square-meter property is not expected to be entirely flooded until the water level on the street reaches one-meter depth according to the functions proposed. Water depths lower than one meter are assumed to increase lineally up to reach a one-meter depth when the floor area would be entirely flooded.

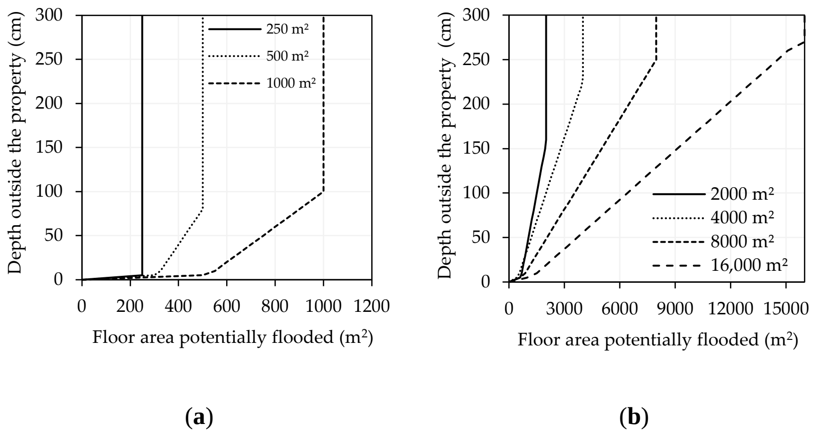


Figure 7. Floor area potentially flooded functions versus depth outside the property according to the total floor area: a) up to 1000 m^2, and b) up to 16,000 m^2.

2.3.5. Flood depth-damage curves for Barcelona

Semi-empirical flood depth-damage curves for 14 different property uses have been derived for the city of Barcelona (Figure 8). This development has been based on a sample of actual flood damage records. These were taken by an insurance surveyor, who is included among the authors of this work, during his flood damage appraisal processes. The depth-damage curves construction relied on statistical data analysis; however, in case of lack of data the curves were adjusted according to expert opinion. For instance, in case we did not have data between 50cm and 1m water depths, the insurance surveyor proposed the expected damage according to his own experience. Details of this development can be found in Martínez-Gomariz et al. (2020), a study which, moreover, provides with a methodology to obtain nationwide depth-damage curves. Therefore, both the present and the previous studies will contribute to a common pluvial flood risk mitigation framework in Spain.

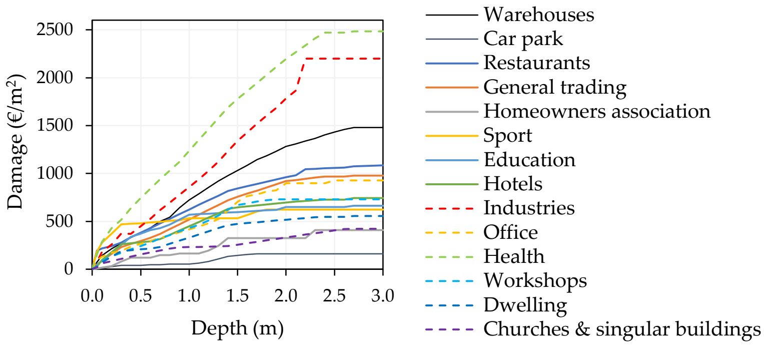


Figure 8. Semi-empirical depth-damage curves for Barcelona.

2.3.6. GIS toolbox

The main output of the SFLOOD model is a map of the municipality and the expected flood damage distribution among the parcels (i.e. a risk map). Also, the overall flood damage is provided as an aggregation of damages from individual properties. To obtain this, a GIS-based tool (i.e. SFLOOD model), which allows automating the flood damage assessment process, has been built up. The steps to be conducted are listed following and inputs and outputs of the tool are depicted in Figure 9.

1) Initially, both the city parcels and the cadastral information database must be downloaded. These files are freely downloadable from the Spanish Cadastre website (www.sedecatastro.gob.es). This database contains the use of each property, among other information. Thus, both files should be provided to the tool as a first step. The tool will select from the database only the information required to conduct the process, and the property uses will be transformed into the 14 categories proposed here.

2) Secondly, a shapefile with the floodwater depths of the flood event to analyse must be provided to the tool. This file must be obtained from different software. In this case, Infoworks ICM® has been employed to obtain the flooding dataset.

3) Water depths, resulting from the 2D hydrodynamic model, within a property influence area specified by the user, are averaged to obtain a single water depth on the pavement ($\bar{y}$, Figure 2). This water depth will be reduced initially according to the front step related to the type of property exposed (y_o, Figure 2) and following it will be multiplied by the corresponding Permeability Coefficient, thereby obtaining the expected water depth inside the building (y_{GF}, y_{B1}, y_{B2}, Figure 2).

4) Small flooding areas resulting from the hydrodynamic model were observed to mislead the damage model to unrealistic damaged properties. For this reason, a parameter to eliminate these small flooded areas is included in the tool. Therefore, a minimum threshold of flooding area to cause damages must be indicated by the user. This parameter can also be considered in the calibration process.

5) Two parameters must be indicated within the tool, maximum water depth and residual depth inside the property (Figure 2). The water depth inside each story of a property (y_{GF}, y_{B1}, Figure 2) with a possible underneath level will be related to the maximum depth unless the water depth obtained in the previous step is lower than the maximum. In this case, the previous water depth will be kept. Maximum and minimum water depths are calibration parameters of the model.

6) A database of depth-damage curves for Spanish municipalities is contained in the tool (Martínez-Gomariz et al., 2020). Therefore, the municipality aim of the study must be indicated to the tool, and its corresponding depth-damage curve will be automatically used in the damage assessment process. Depth-damage curves are applied by relating the water depth inside the building (y_{GF}, y_{B1}, y_{B2}, Figure 2) and the type of affected property. This step provides the economic losses per square meter of property (€/m^2).

7) Functions of floor area potentially flooded are applied in this step. The floor area is reduced when required before being multiplied by the economic losses per unit area determined previously. The total economic losses per story of each property are calculated in this step.

8) Once all input data is provided to the tool, the tool can be run. The conceptual model depicted in Figure 2 is carried out through a python code included in the GIS-tool.

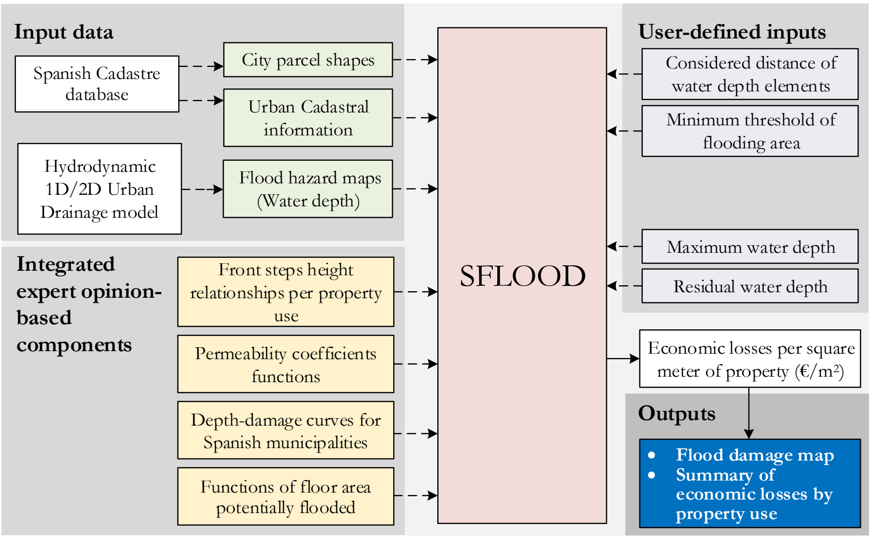


Figure 9. GIS toolbox: inputs-outputs.

Pluvial flood damages were already assessed in Barcelona in the framework of the EU funded CORFU project (2010–2014). To do this a GIS-based toolbox was developed (Hammond et al., 2014) and its process to assess flood damages can be summarised in three steps: 1) Assign a water depth to each building; 2) Interpolate this value in the stage-damage curve to obtain the relative cost, and 3) Multiply the relative cost by the area, obtaining the total damage value per each block. Unlike the CORFU tool in the present development it is considered the water depth inside the property to assess damages. This can be considered the key difference between both models, which can be understood as a more realistic approach.

2.3.7.Model testing and accuracy

2018 was a very damaging year with more than 4.5 M€ of insurance compensations due to damages to property caused by pluvial floods in Barcelona (Figure 10). A single flood event originated most of these damages on the 6th of September which compensations amounted to 3.5 M€. On the 17th of August of the same year, another intense rainfall hit Barcelona, causing extensive flooding which led to the CCS to compensate nearly 0.5 M€ due to damages to properties. In 2011, on 30th of July, a heavy rainfall event also hit Barcelona leading to more of 2 M€ of CCS payouts. These three flood events have been selected to test the damage model presented herein. Rainfall main characteristics and damages produced by these three flooding events are presented in Table 2.

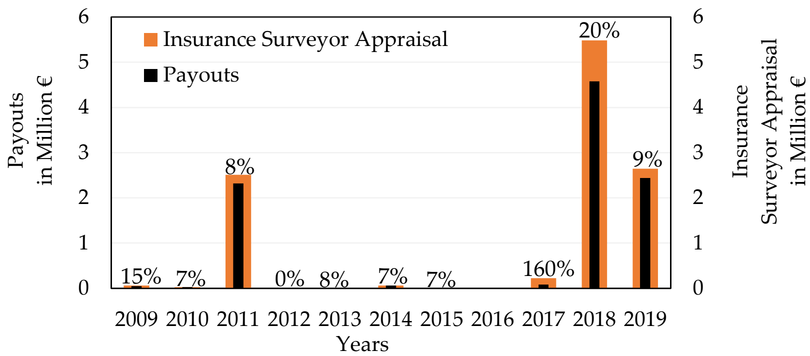


Figure 10. Yearly payouts and appraisals due to pluvial flood damages to properties in Barcelona within the period 2009-2019.

Table 2. **Rainfall characteristics and economic damages related to the selected flood events**

	Rainfall					Damage	
Date	Maximum accumulated rainfall (mm)	Start time	End time	Duration	Weekday	Appraisal	Payout
30/07/2011	58.6	14:45h	16:00h	1h 15’	Saturday	2,263,750.22 €	2,089,426.79 €
17/08/2018	64.8	11:50h	14:30h	2h 40’	Friday	487,999.38 €	444,966.78 €
06/09/2018	89.1	00:25h	02:40h	2h 15’	Thursday	4,323,259.13 €	3,498,118.48 €

It must be noted the difference between the insurance surveyor appraisal and the final CCS Payouts. This difference is due to the deductible (7% for most of the cases) and the underinsurance in some cases. Therefore, the appraisal figures have been considered as the reference values, instead of CCS payouts, because they are assumed to be closer to the actual flood damage. The testing process has been conducted based on the comparison of computed damage and the economic appraisal carried out by the insurance surveyor after the policyholders' claims. It has been used the term "testing" because of the particular inaccuracy of the term "validation" in this case since the actual damages are unknown and the comparison of model's outcomes is made with the insurance surveyor appraisal.

As stated by Zischg et al. (2018), insurance claims constitute a potential validation dataset because of their consistent and relatively homogeneous records over time; however, the data availability constrained by privacy protection is a critical point. To solve this concern, the CCS provides unconditionally with aggregated economic compensations at a larger scale than that of individual properties. For the present study, the CCS provided a single value for both payouts and appraisals at a census district-scale as can be observed in Figure 11, where CCS payouts are distributed per census district for the three selected flooding events. Also, in the same figure, it is shown the spatial distribution of the accumulated rainfall that caused each flooding event.

The accuracy of the model relies not only on the aggregated computed economic damages but also on the damage distribution within the studied area. For this reason, a census district-scale comparison approach was conducted. To test the accuracy of the model, economic damage was compared between computations and insurance data. However, it must be noted that the damage model outcomes are strictly dependent on the accuracy of the hydrodynamic model since the latter's outputs are damage model input. For instance, if the drainage model does not reproduce the flood extent correctly, the flood damage model will not provide any damage to properties that, according to the drainage model, are not in contact with floodwater.

The accuracy of the model was analysed taking into account the four calibration parameters (see user-defined inputs in Figure 9): a) minimum threshold of flooding area to cause damages, b) distance of water depth elements (property influence area), c) maximum depth, and d) residual depth. The 2011 flooding event was used to analyse the model outcomes by varying these four parameters. The parameters combinations (63) are presented in Table 3.

Table 3. Combinations of user-defined parameters considered

# Combination	Distance of water depth elements (m)	Maximum depth (cm)	Residual depth (cm)
1	1	20	5
2	1	20	10
3	1	10	5
4	3	20	5
5	3	20	10
6	3	10	5
7	5	20	5
8	5	20	10
9	5	10	5
10	7	20	5
11	7	20	10
12	7	10	5
13	10	20	5
14	10	20	10
15	10	10	5
16	15	20	5
17	15	20	10
18	15	10	5
19	20	20	5
20	20	20	10
21	20	10	5

Three minimum thresholds of flooding area to cause damages were proposed 500, 1000 and 1500 m^2. For each threshold, 21 combinations of the other parameters have been proposed (Table 3). Distance of water depth elements (property influence area) has been tested from 1 to 20 meters, although the lower is this distance, the more realistic is the physical process. Two values for maximum (10 and 20 cm) and residual (5 and 10 cm) depths have been proposed too. The ranges of parameters' values were established based on the insurance surveyor opinion.

The Normalised Root Mean Square Error (NRMSE) [1] was used to assess how accurate was the output of the model when compared with the insurance surveyor appraisal per census district. Therefore, the differences are accounted within the entire study area at a census district level. The minimum NRMSE obtained for a model run indicates that the selected parameters provide the most accurate estimation. The NRMSE variance will indicate the model accuracy. We are using the term “error” inaccurately since the comparison was made between computed damage and insurance surveyor appraisal, which is different from the actual damage to a greater or lesser extent.

$$NRMSE = \frac{\sqrt{\frac{\sum_1^n (C_{Di} - D_{Ai})^2}{n}}}{D_{Ai,max} - D_{Ai,min}} \qquad [1]$$

where n is the number of census districts (n=1068), C_{Di} and D_{Ai} are the computed damage and the damage appraisal in the census district i, and $D_{Ai,max}$.and $D_{Ai,min}$ are the maximum and minimum damage appraisal respectively within the 1068 census districts. $D_{Ai,min}$ is always 0 because not all census districts are damaged when a flood event occurs.

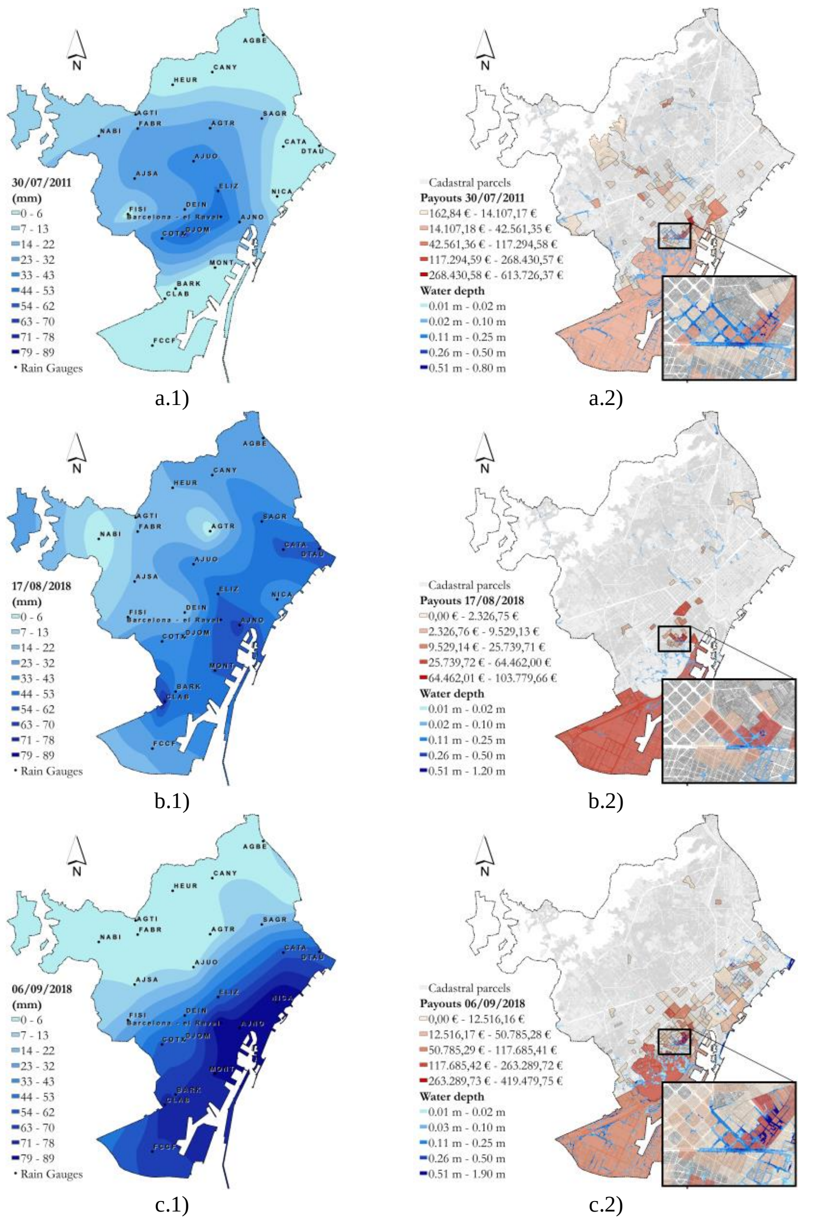


Figure 11. Geospatial distribution of accumulated rainfall volume and CCS payouts in Barcelona for different events: a) 30/07/2011, b) 17/08/2018, and c) 06/09/2018.

3. Results and discussion

3.1. Model accuracy for the selected flood events

The flood damage model (SFLOOD) was run 189 times to obtain computed damage for 63 parameters' combinations and three flood events (30/07/2011, 17/08/2018, and 06/09/2018).

Figure 12 presents plots with the overlapping of the damage appraisal and the computed damages resulting from 63 model runs, per census district. The continuous line indicates the aggregated damage appraisal per census district and the dashed line represents the computed damages that presented the lowest NMRSE for each flood event. The shadowed data series represent the other model's outputs for the rest of the parameters' combinations. The observation of these plots provides a qualitative overview of the model accuracy. All model outputs provided a similar damage distribution pattern across the census districts, which is basically flood extent dependent. However, the model response was not evenly accurate across all census districts. Focusing on the 2011 event (Figure 12a), it can be observed how some damaged census districts (points (2) and (4)) according to the insurance surveyor appraisal are not represented accurately. While point (2) marks a non-damaged census district, point (4) shows how the model overestimates damages. On the contrary, point (1) and (3) show an excellent correspondence with the insurance surveyor appraisal. As said before, the accuracy of the damage model also depends on the output of the hydrodynamic model, mainly the flood extent. In this regard, the damage model cannot predict any damage to census districts that are not flooded (point (2)), according to the hydrodynamic model.

This fact is generally observed in the results obtained from the second flood event (Figure 12b) where the most damaged census district was predicted as non-damaged (points (1), (2) and (3)). The results for this second flood event are weak in terms of damage distribution; however, as could be observed in Figure 11b.2 the flood extent does not fit accurately with the parcels damaged. This means that the hydrodynamic model seems not to reproduce the actual flood event accurately, thus, we cannot state a wrong behaviour of the damage model.

Finally, the computed damage distribution fit much better with the insurance surveyor appraisal for the third flood event (Figure 12c). The census district with major damages (point (1)) is well represented, although the model does not identify damages in others (point (3)) with relevant actual damage. Some other census districts' damages are correctly identified (points (2) and (4)), providing though considerably more damage. This may not mean an inaccuracy since actual damage is expected to be greater than or equal to the insurance surveyor appraisal.

In Figure 13 it is shown the variance of the NRMSE for each simulation. The simulations conducted for the 2011 event provided an NRMSE mean of 3.75% with a maximum of 3.91% and a minimum of 3.55%. It means an error variance of 10%. In the case of the second event (17/08/2018), the NRMSE mean was 16.71%, and the maximum and minimum were 18.51% and 14.85% respectively. It means an error variance of 25%. Regarding the third event (06/09/2018), the NRMSE mean was 38.99%, and the maximum and minimum were 41.13% and 36.18% respectively. It means an error variance of 14%. Therefore, the error variability is considered low for the proposed parameters' combinations, especially for the first flood even which hydrodynamic simulation fits better with the parcels damaged (Figure 11a.2). Therefore, due to the low error variability proven, the selection of the user-defined parameters, as long as they fall in the ranges proposed by the expert opinion, is not considered as critical. On the contrary, an inaccurate flood extent obtained through the hydrodynamic model considerably mislead damage model outputs.

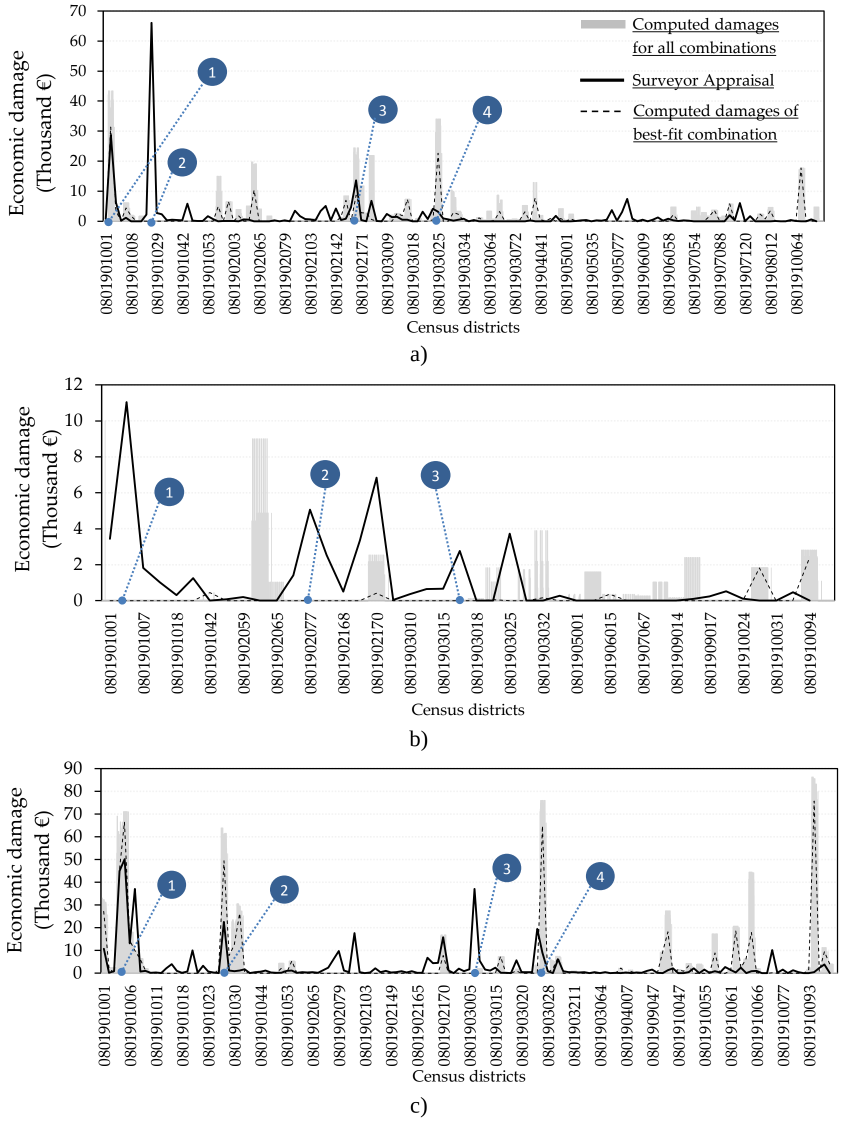


Figure 12. Comparison of damage distribution per census district between surveyor appraisal and damage model output for the three selected events: a) 30/07/2011 (# combination 19 and a threshold of 500 m^2), b) 17/08/2018 (# combination 17 and a threshold of 500 m^2), and c)

06/09/2018 (# combination 17 and a threshold of 500 m^2). Circled numbers indicate locations to be discussed within the text.

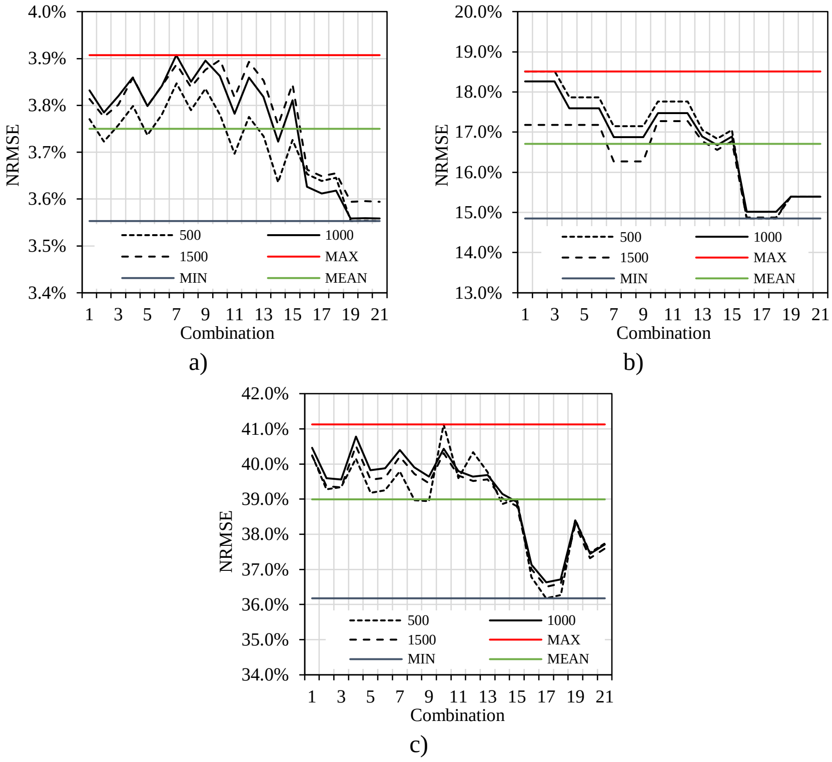


Figure 13. Normalised Root Mean Square Error (RMSE) for each parameters' combination and each flood event: a) 30/07/2011, b) 17/08/2018, and c) 06/09/2018.

3.2. Pluvial flood damage estimates

The aggregated estimate damage at the municipal level for the three selected flood events is presented in Table 4.

Table 4. Flood damage estimations for the three selected events

Date	Maximum accumulated rainfall (mm)	Appraisal	Payout	Combination Id	Computed damage (€)	Difference against appraisal	Difference against payouts
30/07/2011	58.6	2,263,750.22 €	2,089,426.79 €	50019	1,973,940.42	14.68%	5.85%
17/08/2018	64.8	487,999.38 €	444,966.78 €	50017	56,755.00	754.84%	684.01%
06/09/2018	89.1	4,323,259.13 €	3,498,118.48 €	20017	5,503,679.16	21.45%	36.44%

As Merz et al. (2007) stated, the spatial description of the risk plays an important role when trying to communicate the results of risk analyses and to sensitise people at risk. In accordance with this, Figure 14 presents the computed damage at a census district scale for the three selected flood events.

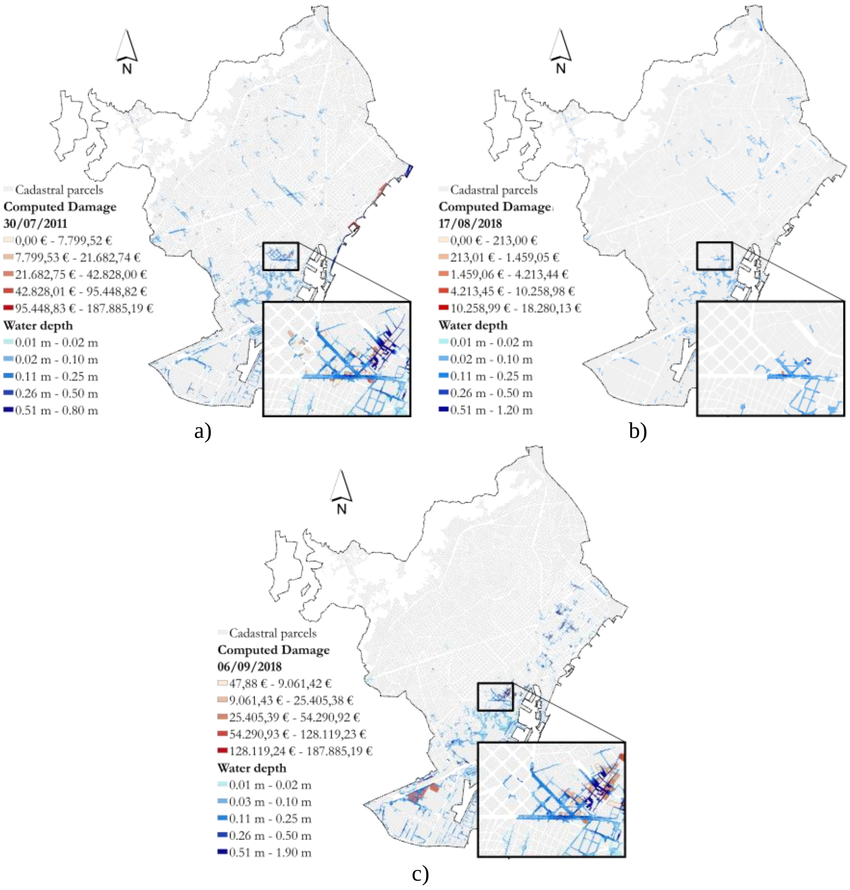


Figure 14. Computed damage maps for the three selected events: a) 30/07/2011 (combination id: 50019), b) 17/08/2018 (combination id: 50017), and c) 06/09/2018 (combination id: 50017)

3.3. Limitations of the method

We do not certainly know how far the insurance appraisal could be from the actual flood damage; thus, there is significant uncertainty in the results (Velasco et al., 2016). For this reason, it cannot be stated that a lower difference between computations and appraisals indicates a more accurate result. Some aspects to consider between these differences are described following:

1. Flood recurrence. If a property was flooded two or more times in a brief period, the second and subsequent damage appraisals only consider new damage, different from the one caused by the precedent event. It would be in this way if the property owner or tenant did not have time enough to replace the flooded assets.

2. Date and time of the flood event. The flood event may occur at any day and daytime hours. When it occurs at night or non-working days, the property owner or tenant cannot act to avoid or restrict the water ingress. Self-protection measures may reduce damages significantly, but they are usually applied only during working days and work hours. The model does not consider self-protection measures.

~~2.~~3. The consideration of only floodwater depth as the primary damage driver. As discussed in the introduction section, different factors contribute to cause damages to property, such as the time of the year the flood occurs, flood duration, water velocity, suspended debris, or warning time (Kelman, 2007; Merz et al., 2004). Therefore, part of the total flood damage may be due to those other factors, which are not considered in our model.

~~3.~~4. Areas frequently flooded. Property in these specific parts of a city is widely insured, unlike those zones where flooding is not frequent. This means that flood damage appraisal is expected to be closer to the actual damage in those areas that are frequently flooded.

5. Hydrodynamic model assumptions and simplifications. Before, the relevance of an accurate flood extent was highlighted as an essential aspect for the flood damage model to provide more accurate estimates. However, there are other aspects related to the drainage model that may influence on the damage model outcomes. The first is the establishment of maximum water depths over the simulation time across the entire model domain. The hydrodynamic variables (e.g. water depths) in each grid cell vary over time,

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but maximum values were used as input data for the damage model. Since the 2D overland flow module is activated only in case of flooding produced by surcharged sewer pipes, it cannot generate flooding before entering a manhole or a gully. It means that the computed overland flow may be slightly different from reality, thereby misleading somehow the damages computation.

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4.6. On the other hand, when a real flood event occurs, the public institution responsible for managing the drainage network carries out several operations of opening and closing of retention tanks. These operations are not considered in the hydrodynamic model, which also may cause some differences between actual and computed floods.

5.7. Sinks and toilets connections to the sewers. Although no overland flow may be observed in certain areas, damage to property could occur due to backflow if the property's sinks and toilets are connected to the combined sewer. This is especially relevant for basements and lower ground floods that can be flooded due to reverse flow from surcharged combined sewers.

3.4. Discussion

This section provides a discussion regarding various aspects of the flood damage estimation carried out in this study: 1) The damage model, 2) the insurance data, 3) the hydrodynamic 1D/2D model and, 4) statistical or multivariate damage models.

The damage model: it was developed based on the knowledge of an insurance surveyor and can be classified as a micro scale-, depth-damage- and GIS-based model. Usually, the vulnerability of properties is related to their corresponding depth-damage curves. Nevertheless, the proposed conceptual model considers property's vulnerability as the combination of both their permeability and the damage rate for the water level rising (i.e. depth-damage curves). This point arises from the fact that we apply depth-damage curves to the floodwater level inside the property. We acknowledge the scientific weakness of the permeability and floor area potentially flooded functions. Thus, an experimental campaign to validate the tools provided herein will be necessary

(Mignot et al., 2020), thereby reducing uncertainty to the model. Some limitations of this model are the non-consideration of self-protective measures and damage to property related to reverse flow from surcharged combined sewers. According to Jongman et al. (2012), uncertainty in depth-damage curves is higher than uncertainty in maximum damage values. However, the development of site-specific depth-damage curves was demonstrated by Albano et al. (2018) to reduce the epistemic uncertainty considerably. Even being a detailed model with which less uncertain is expected, a certain degree of it cannot be avoided. The decision-making process based on uncertain predictions can have a huge economic impact. In this regard Bhola et al. (2020) proposed a methodology for obtaining a multi-model combination as an effective alternative to the traditional best-model approach for producing detailed hazard maps. Their novel approach can be included into the process of decision making to complement the use of the SFLOOD tool. Finally, aspects such as the dependence of computational cell size of the hydrodynamic model on the distance of water depth elements parameter (i.e. property influence area) require further analysis.

The insurance data: it was used to calibrate and validate the damage model through a direct comparison between insurance surveyor appraisals and compute damage for selected actual flood events, at a census district scale. The fact of basing the model validation on the comparison of appraisals and computed damage may lead to inaccurate estimates. For instance, an area containing a high percentage of insured buildings will likely result in a larger total number of claims than an area with less buildings insured (Gradeci et al., 2019). According to this, the model must guarantee a computed damage greater than or equal to the insurance surveyor appraisal. It is worthy of mention that resilient reinstatement (Kelman, 2007) is not mandatory for receiving CCS compensations. This means that residents are not obliged to implement resilience measures to reduce damage for the next flood. Otherwise, the model will present another limitation, but Spanish cities would be more flood resilient. For areas not frequently flooded, insurance coverage tends to be less extensive. For this reason, insurance surveyor appraisals may vary significantly among census districts.

The hydrodynamic 1D/2D model: unlike statistical (i.e. multivariate) damage models, the GIS-based development presented herein requires from the flood extent and floodwater depths obtained through a hydrodynamic model. It means that the damage model inherits the uncertainty related to the hydrodynamic model. For instance, the unrealistic fact that the 2D overland flow module is activated only in case of flooding produced by surcharged sewer pipes can be considered as a limitation of the hydrodynamic model, and thus another uncertainty to account for. Ideally, uncertainty should be reduced jointly between both models. In the present study, the drainage model was borrowed from the municipal water cycle company responsible for the drainage network management, which means that the joint uncertainty reduction was not possible. Also, ideally, the validation process of both models should be conducted under the same criterion. In this case, the validation of the hydrodynamic model based on the actual parcels damaged according to the insurance data (Zischg et al., 2018), would have allowed obtaining a more accurate flood extent and thus the exposed element. Zischg et al. (2018) stated that the selection of the flood model validation technique should be based on the type of flood analysis conducted. When it comes to flood exposure and risk analyses, accurate results at locations of interest for risk assessment are required.

The needed simplifications, limitations and assumptions of the hydrodynamic model also affect the damage model results. Previously was already mentioned the consideration of maximum water depths over simulation time in each grid cell and the non-consideration of opening and closing operations of retention tanks, but some other aspects may affect the damage estimates. Mignot et al. (2020) highlighted the importance of considering largest obstacles, such as parked cars, in operational numerical models that calculate urban floods for an accurate estimation of the intrusion discharge. Forero-Ortiz et al. (2020) analysed flood risks posing potential Barcelona metro disruptions due to a substantial amount of water flowing down to the underground metro system. None of these aspects was considered in the hydrodynamic model used herein, which implies an added uncertainty to the damage assessment process.

Statistical or multivariate damage models: these are a different approach from the one presented herein since these do not require a hydrodynamic model. Instead, these models establish relations among several explaining variables and flood damage. Although these models seem to be more advantageous than those GIS-based, they can mislead estimates if, for instance, interventions (improvements) to the drainage network are made. Gradeci et al. (2019) conducted a comprehensive review of studies that proposed relationships between different explaining variables and flood damages in urban areas. The authors gathered all explaining variables found in the literature and groped them into four categories: meteorological, geographic, demographic, and building. Part of the variance will always remain unexplained if no account is taken of variables from any of the identified categories. The spatial and temporal perspectives of the rainfall are paramount to the flood-related damages (Gradeci et al., 2019). However, although rainfall is agreed to be the most relevant factor to explain damages, its single consideration is not enough to explain observed variance. The selection of the explaining variables also depends on the working scale. The explaining variables are interminable: binary variable depending on whether the event occurred during the day shift or night shift, urban exposure, the permeability of surfaces, property value, household income, age and education of breadwinner or fraction of homeowner, urban drainage system properties (drainage capacity, age of infrastructure, percentage of surface water), level of urbanisation, socioeconomic indices (household income and property value), district-related parameters (percentages of low-rise and high-rise buildings, percentage impervious surface), weather conditions prevailing during preceding days, green spaces, self-protective behaviour, precautions, external response and early warning, building condition, age of residents, willingness to pay for insurance, presence during occurrence of the event. This denotes the great uncertainty behind flood damage estimates.

4. Conclusions

A comprehensive pluvial flood damage model (SFLOOD) to predict economic losses to property in dense urban environments has been developed and presented herein. It is a micro scale-, depth-damage- and GIS-based model where water depth is the only hydrodynamic variable considered as a damage driver. Although a variety of uncertainties related to the flood damage estimates have been revealed here, the model is able to predict the order of magnitude of the actual damages according to the results obtained. Assumptions and limitations of the hydrodynamic 1D/2D model may influence largely to the damage predictions. A correct flood extent is one of the major aspects to ensure more accurate damage estimates.

The model's primary design purpose was to predict pluvial flood damages in Spanish urban environments; however, it could be used for predicting damages caused by fluvial flooding and adapted to be applied in urban areas out of Spain. Nevertheless, it is of interest to tackle the lack of tools to estimate flood damages in Spain and to contribute to a common pluvial flood risk mitigation framework nationwide. This tool will benefit institutions dealing with urban drainage management, to prioritise adaptation scenarios according to their effectiveness in terms of risk reduction. Besides, it is expected to lead to policy implications by contributing to future updates of the EU Floods Directive in Spain. The Spanish insurance market can be benefited from this tool too; in particular, the CCS, which could anticipate the disbursement of existing funds.

Acknowledgments

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Credit Author Statement

Eduardo Martínez-Gomariz: Conceptualization, Methodology, Validation, Investigation, Data Curation, Writing - Original Draft, Visualization **Edwar Forero-Ortiz:** Validation, Investigation, Writing - Original Draft, Visualization **Beniamino Russo:** Methodology, Writing - Review & Editing, Supervision, Project administration **Luca Locatelli:** Methodology, Writing - Review & Editing, Supervision **Maria Guerrero-Hidalga:** Methodology, Data Curation, Writing - Review & Editing **Dani Yubero:** Methodology, Software **Salvador Castan:** Conceptualization, Data Curation, Resources

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dear Editor,

On behalf of all the authors I am pleased to submit the reviewed manuscript entitled “A novel expert opinion-based approach to compute estimations of flood damage to property in dense urban environments. Barcelona case study”. We hope that all comments and suggestions from the reviewers have been properly addressed.

Kind regards,

Dr. Eduardo Martínez-Gomariz

Revision Notes

REVIEWER #1

The authors have improved their manuscript according with my suggestions.

However, I still feel that the **limitations section** must be extended. At the moment it is solely focus on the insurance appraisal. This section should include also the limitations of the SFLOOD approach. At the moment **the method developed considers only the water depth**. what are the issues related with this. It is not enough to reference it in the introduction. The reads needs to understand if this is a limitation in the authors approach as well, hence it belongs to this section. Also another important limitation is that **the authors are assuming that rainfall cannot land on the 2D overland flow and generate flooding before entering a manhole or a gully**. Is this realistic? No. hence this should be discussed and added to this section. This section should give a quick impression of the main limitations of SFLOOD, and where is room for improvement.

AUTHORS REPLY:

These two aspects have been added to the limitation section as proposed. Many thanks for your comments.

REVIEWER #3

After the first round of review, the paper sounds robust and almost ready for publication. I have just minor comments.

1. Fig. 1: add some words to the three-top picture (e.g. region name, city name)

AUTHORS REPLY:

We have added the proposed words to each image: Spain, Catalonia, Barcelona.

2. L268: DD curves are not essential elements, I would say they are the most established approach.

AUTHORS REPLY:

We have reworded the sentence according to your suggestion.

3. I would add these papers to literature: https://eur01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fnhess.copernicus.org%2Farticles%2F9%2F1679%2F2009%2Fnhess-9-1679-2009.pdf&data=04%7C01%7Ceduardo.martinez%40cetaqua.com%7C1dbba5bde47349401f5d08d8e1d79613%7Cf4a12867922d4b9dbb859ee7898512a0%7C0%7C0%7C637507663826125001%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C3000&sdata=SBMXyDahvFGBJKq74V5oVT%2Fe74IOiK7CeLQ74%2B6OW%2Fs%3D&reserved=0; https://eur01.safelinks.protection.outlook.com/?url=https%3A%2F%2Fwww.sciencedirect.com%2Fscience%2Farticle%2Fabs%2Fpii%2FS2212420920314874&data=04%7C01%7Ceduardo.martinez%40cetaqua.com%7C1dbba5bde47349401f5d08d8e1d79613%7Cf4a12867922d4b9dbb859ee7898512a0%7C0%7C0%7C637507663826134992%7CUnknown%7CTWFpbGZsb3d8eyJWIjoiMC4wLjAwMDAiLCJQIjoiV2luMzIiLCJBTiI6Ik1haWwiLCJXVCI6Mn0%3D%7C3000&sdata=hTyteoBfUZTM2z8YKeAbGAZUr0i2p0YSGHKdMTdml2I%3D&reserved=0

AUTHORS REPLY:

Both papers have been referenced in line 60 and line 76. Many thanks for your suggestion.

4. Fig. 8: is this figure new or taken from other sources? if so, cite them in the caption. Actually, given the length of the paper, I don't think this figure is adding much to the paper (since it is just an example).

AUTHORS REPLY:

This figure includes depth-damage curves that have been derived for this case study. It is not an example but the real curves for Barcelona. However, the complete description of their development can be found in Martínez-Gomariz, E., Forero-Ortiz, E., Guerrero-Hidalga, M., Castán, S., Gómez, M., 2020. Flood Depth–Damage Curves for Spanish Urban Areas. Sustainability 12, 2666. https://doi.org/10.3390/su12072666. This paper has already been referenced in the manuscript.

5. Fig. 11 and 14: caption text is too small

AUTHORS REPLY:

We have redone all images in Figure 11 and 14 to increase the Font size in the Maps' legend.