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How much does an extreme rainfall event cost? Material damage and relationships between insurance, rainfall, land cover and urban flooding

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ABSTRACT

This research aims to understand how insurance, rainfall, land cover and urban flooding are related and how these variables influenced the material damage in the Lisbon Metropolitan Area (LMA) during the 2000–2011 period. Correlation coefficients show strong relationships between built-up areas and claims (0.94) and payouts (0.88). Despite no significant relationships being found between rainfall and the amount of material damage per event, three likelihood levels of flooding were determined for hourly rainfall. Unlike the studied period, the number of claims and their spatial distribution during the 2008 extreme rainfall event were strongly dependent on rainfall. Flooding related to the old watercourses assumed greater importance during this extreme event, recovering a more natural/ancient hydrological behaviour. In the LMA, the greatest material damage was the result of high-magnitude/low-probability rainfall events. Lower magnitude events can trigger numerous claims in heavily built-up areas, but they are hardly capable of producing large material damage.

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1 Introduction

Flooding is the most frequent natural hazard, affecting the largest number of people worldwide (UNISDR 2002, Douben 2006, Jha *et al.* 2012, Trigo *et al.* 2016). Over recent decades, it is estimated that flooding has been responsible for 20–30% of the economic losses caused by natural hazards (Loster 1999, Douben 2006, Elmer *et al.* 2010). Between 2000 and 2012, average annual flooding costs reached €4.2 billion in the European Union (Jongman *et al.* 2014). The combined effect of intense rainfall with highly impervious areas and an insufficient drainage capacity makes cities increasingly prone and vulnerable to urban flooding (Notaro *et al.* 2014, Bruni *et al.* 2015, Torgersen *et al.* 2015, Sørensen and Mobini 2017).

During recent decades, mainly in developed countries, mortality associated with flooding has declined, while material damage has increased (Jha *et al.* 2012, Hoeppe 2016). However, there is no consensus on trends in material damage. Some authors argue that, after data normalization, there is no clear positive trend, associating the increasing number of events and damage as a result of population growth and wealth (Crompton and McAneney 2008, Barredo 2009, Bouwer 2011, Barthel and Neumayer 2012). Flooding, as for any natural hazard, can only be considered as a catastrophe when there are people or goods affected.

As Mills (2005) notes, business and science meet in the aftermath of disasters. Therefore, insurance companies have become an important player in natural hazard management, behaving as a risk transfer tool (Botzen and van den Bergh 2008, Lamond and Penning-Rowsell 2014, Atreya *et al.* 2015, Surminski *et al.* 2015). The insurance industry is also increasingly concerned with this question, mainly because the gap

between premiums and payouts has been decreasing (Mills 2005, Jongman *et al.* 2014, Paudel *et al.* 2015) due to the increasing costs associated with flooding (Mills 2005, Botzen *et al.* 2010, Aerts and Botzen 2011, Paudel *et al.* 2015).

Insurance databases are a valuable asset in studying the material damage caused by flooding (Spekkers *et al.* 2013a, Hoeppe 2016), but total and insured losses are two different concepts for several reasons: (a) insurance policies are not mandatory in most countries, as happens in Portugal, where flooding is included in multi-risk insurance policies; (b) insurance is relevant, above all, in developed countries (Loster 1999, Hoeppe 2016); (c) in some countries, such as the Netherlands, insurance companies usually do not cover damage due to flooding (Thieken *et al.* 2006, Botzen and van den Bergh 2008, Botzen *et al.* 2010, Surminski *et al.* 2015); (d) insurance companies may demand high premiums due to the history of flooding occurrence, which leads to some owners not having insurance policies for their houses/commercial spaces; (e) the amounts paid are often not enough to cover the damage caused by flooding (Mills 2005), because some losses may not be included in the insurance policies (CNT 2014); and (f) payouts are dependent on the evaluation made by the insurance companies' experts. Additionally, these companies are reluctant to provide their databases, and some of them are not even available due to confidentiality restrictions (André *et al.* 2013, CNT 2014). For this reason, there are still few studies that relate flooding and insurance (Merz *et al.* 2004, Thieken *et al.* 2006, André *et al.* 2013, Zhou *et al.* 2013, Spekkers *et al.* 2013a, 2013b, 2015, Moncoulon *et al.* 2014, Paudel *et al.* 2015, Torgersen *et al.* 2015, Bernet *et al.* 2017, Grahn and Nyberg 2017, Sørensen and Mobini 2017, Cortès *et al.* 2018).

Table 1. Statistical data of the municipalities in the LMA. Built-up areas (2007); buildings, dwellings and inhabitants (2011).

	Municipality	Area		Built-up areas		Buildings			Dwellings			Inhabitants		
		(km ²)	(%)	(km ²)	(%)	(no.)	(no./km ²)	(%)	(no.)	(no./km ²)	(%)	(no.)	(no./km ²)	(%)
Northern LMA	Amadora	23.8	0.8	14.8	62.0	13 696	575.8	3.1	88 036	3701.4	5.9	175 136	7363.4	6.2
	Cascais	97.4	3.2	48.6	49.9	43 624	447.9	9.7	109 171	1120.8	7.3	206 479	2119.9	7.3
	Lisbon	84.9	2.8	61.6	72.5	52 496	618.0	11.7	323 981	3814.1	21.8	547 733	6448.2	19.4
	Loures	169.3	5.6	41.9	24.7	31 095	183.7	6.9	99 344	586.8	6.7	205 054	1211.2	7.3
	Mafra	291.7	9.7	41.9	14.4	28 002	96.0	6.2	42 957	147.3	2.9	76 685	262.9	2.7
	Odivelas	26.4	0.9	15.0	56.8	16 344	620.1	3.6	69 238	2626.9	4.7	144 549	5484.3	5.1
	Oeiras	45.9	1.5	26.2	57.1	18 243	397.6	4.1	86 162	1877.9	5.8	172 120	3751.3	6.1
	Sintra	319.2	10.6	84.3	26.4	56 903	178.3	12.7	182 854	572.8	12.3	377 835	1187.7	13.4
	Vila Franca de Xira	318.1	10.6	32.5	10.2	16 984	53.4	3.8	65 125	204.7	4.4	136 886	1066.4	4.9
Southern LMA	Alcochete	128.4	4.3	7.9	6.2	4 575	35.6	1.0	8 829	68.8	0.6	17 569	250.2	0.6
	Almada	70.2	2.3	32.4	46.2	34 163	486.6	7.6	101 536	1446.2	6.8	174 030	4782.3	6.2
	Barreiro	36.4	1.2	12.8	35.3	11 008	302.5	2.5	41 772	1147.9	2.8	78 764	246.7	2.8
	Moita	55.3	1.8	12.1	22.0	12 398	224.4	2.8	34 673	627.5	2.3	66 029	1194.9	2.3
	Montijo	348.6	11.6	21.1	6.1	12 996	37.3	2.9	26 766	76.8	1.8	51 222	146.9	1.8
	Palmela	465.1	15.5	39.9	8.6	21 631	46.5	4.8	33 196	71.4	2.2	62 831	135.1	2.2
	Seixal	95.5	3.2	38.7	40.5	30 124	315.4	6.7	79 552	833.0	5.3	158 269	1657.3	5.6
	Sesimbra	195.5	6.5	26.0	13.3	20 433	104.5	4.6	31 837	162.9	2.1	49 500	253.2	1.8
	Setúbal	230.3	7.7	37.3	16.2	24 242	105.3	5.4	62 829	272.8	4.2	121 185	526.2	4.3
Totals	Northern LMA	1376.7	45.9	366.8	26.6	277 387	201.5	61.8	1 066 868	775.0	71.7	2 042 477	1483.6	72.4
	Southern LMA	1625.2	54.1	228.4	14.1	171 570	105.6	38.2	420 990	259.0	28.3	779 399	479.6	27.6
	LMA	3001.9	100	595.2	19.8	448 957	149.6	100	1 487 858	495.6	100	2 821 876	940.0	100

As some of those studies have verified, the relationship between the rainfall values and the amount of insurance claims and payouts is usually weak (Zhou *et al.* 2013, Spekkers *et al.* 2013b). The explanation may lie in the characteristics of the study areas and in the types of flooding that affect these areas. The aforementioned studies were developed for urban areas, where there are several factors that contribute to enhancing the frequency and magnitude of flooding (Patton 1988, Smith and Ward 1998, Butler and Davies 2004) and to modifying the spatial distribution of the occurrences (McGrane 2016). However, urban areas are mainly affected by flash floods or pluvial flooding, which occur at smaller spatial and temporal scales than riverine/slow floods (Sørensen and Mobini 2017). This complex context makes it difficult to find strong relationships between rainfall and material damage and, therefore, it is nearly impossible to determine rainfall thresholds for flooding (Norbiato *et al.* 2008).

In Portugal, flooding has been the deadliest among all the natural hazards during the 20th century (Ramos and Reis 2002). While human damage is known, material damage remains practically unknown because the available information is very scarce and, usually, it only exists for specific/major events. Access to the insurance companies' database from the Portuguese Association of Insurers (APS), available between January 2000 and October 2011, made it possible to analyse the material damage caused by flooding triggered by rainfall in the country's most populated region: the Lisbon Metropolitan Area (LMA). During this period, this region was affected by one extreme rainfall event on 18 February 2008 (Fragoso *et al.* 2010), similar in magnitude only to those that occurred in November 1967 (Trigo *et al.* 2016) and November 1983 (Liberato *et al.* 2012). The rainfall values during the 2008 event were the highest recorded in some of the LMA raingauges, with several decades of daily records (Fragoso *et al.* 2010). This event resulted in multiple occurrences caused by

urban flooding and flash floods which caused three fatalities and millions of euros in damage across the LMA.

There are two main goals in this research. The first is to establish relationships between material damage, rainfall, land cover and urban flooding in the LMA during the 2000–2011 period and for the 2008 extreme rainfall event. The second goal is to compare the material damage of the 2008 event to those caused by minor events, and to understand if this low-probability/high-damage event was capable of modifying the usual/anthropogenic hydrological behaviour of the LMA territory when flooding occurs.

2 Study area

The LMA is a Portuguese NUTS 2¹ region located on the Atlantic coast, comprising 18 municipalities including the national capital city (Lisbon). It has an area of 3002 km² and is divided in two NUTS 3 regions separated by the Tagus River (see Fig. 1 and Table 1): (a) the Northern LMA, made up of nine municipalities (Amadora, Cascais, Lisbon, Loures, Mafra, Odivelas, Oeiras, Sintra and Vila Franca de Xira); and (b) the Southern LMA, also made up of nine municipalities (Alcochete, Almada, Barreiro, Moita, Montijo, Palmela, Seixal, Sesimbra and Setúbal). According to the 2011 Census, it is the most populated area of the country, with 2 821 876 inhabitants. Despite corresponding to only 3% of the total surface area of Portugal, the LMA concentrates 27% of the national population, corresponding to a densely populated region (~940 inhab/km²). Built-up areas represent approximately 20% of the LMA area. In the 2011 Census, the LMA registered 448 957 buildings, corresponding to 13% of the national total, and around 25% dwellings. The LMA also accounts for 29% of the national insurance policies.

¹Nomenclature of Territorial Units for Statistics (NUTS) developed by Eurostat and employed for statistical purposes. There are three geographical levels of NUTS: NUTS I corresponds to the national level; NUTS II to regional level; and NUTS III to subregions. See: https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Nomenclature_of_territorial_units_for_statistics_%28NUTS%29.

The Northern and Southern LMA have approximately the same extent, with 46% and 54% of the total LMA area, respectively. However, in the Northern LMA, 27% of the land is built-up and concentrates almost three-quarters of the LMA population, while in the Southern LMA, the built-up area is only 14%. Lisbon municipality constitutes the LMA core, with 73% being built-up areas. In fact, there is a pattern of heavily built-up areas in the municipalities neighbouring Lisbon, mostly Amadora, Odivelas and Oeiras, which subsequently decreases as a function of the distance from Lisbon (Fig. 1 and Table 1).

The study area is a region of moderate relief, where the altitudes range between mean sea level and 528 m a.m.s.l. in the Sintra sub-volcanic massif. There is a high lithological diversity and, consequently, different permeability levels. Small- and medium-size watersheds with low concentrations and lag times drain the LMA, resulting in frequent flash floods and urban flooding. During the 20th century, many of LMA watercourses were culverted or buried, particularly in Lisbon, Cascais, Loures, Oeiras and Setúbal, leading to an increase in urban flooding and a decrease in flash floods (Leal *et al.* 2018). Generically, the Northern LMA can be considered more susceptible to flooding when compared to the Southern LMA, due to its steeper slopes, lower permeability formations, smaller drainage basins and larger impermeable areas (Leal and Ramos 2013).

3 Data and methods

3.1 Insurance data

The material damage caused by flooding in the LMA was estimated using the insurance database provided by the

APS. This database is available for the period between January 2000 and October 2011, and includes about 60% of Portuguese insurance policies. For each APS claim there are data on: (a) communication date (when the APS claim was reported to the insurance company); (b) location (based on the postal code and only accurate with seven digits); (c) capital sum affected; and (d) payouts. The concepts used in this research are defined in Table 2.

The cause of the flooding is not mentioned in this database, which means that APS claims may have been triggered by rainfall, coastal flooding, burst pipes on the street or inside the home, or for other reasons. This research intends to identify only the APS claims that were caused by rainfall. First, newspaper reports were used to detect these claims, because this source of information usually provides very good temporal precision and details to identify the majority of flooding events (Guzzetti and Tonelli 2004, Barrera *et al.* 2006, Brázdil *et al.* 2006, Barnolas and Llasat 2007, Rashid 2011, Petrucci 2013). Furthermore, the same event or occurrence is frequently reported in different newspapers, allowing us to compare information and data. Four national daily newspapers (*Diário de Notícias*, *Expresso*, *Jornal de Notícias* and *Público*) were consulted for the same dates as those in the APS claims. Newspapers mainly report the most important events/occurrences and, for this reason, there were always APS claims during the 2000–2011 period. Altogether, 2935 APS claims were identified and checked by newspapers, corresponding to 64 APS events.

However, there were some APS claims coincident with high daily rainfall values that were not reported in newspapers. Usually, these corresponded to minor flooding events. The daily rainfall data allowed us to complement the

Figure 1. Location of the study area, showing the rain gauge locations and the municipalities of the Lisbon Municipal Area (LMA).

Table 2. Definitions of the concepts used in this research.

Concept	Definition
APS claim	Request to an insurance company made by a policyholder when flooding that affects the property occurs.
Capital sum affected	Amount of capital (€) insured in the insurance policy when an APS claim is reported.
Payouts	Amount of money (€) paid by an insurance company to a policyholder when an APS claim is reported. The maximum value is equal to the capital sum affected.

information provided by the newspapers. Therefore, if a value greater than or equal to 20 mm/d was recorded at least in one of the raingauges located in the LMA (blue and green dots, Fig. 1), and there were two or more APS claims on the same date, an APS event was counted and those APS claims were considered as related to rainfall. When considering two or more claims, it is possible to avoid temporal coincidences, because a single APS claim may have been triggered by a cause other than rainfall. However, the 90th percentile (~20 mm/d) of the 12 raingauges with a 30-year period of daily rainfall data was used to associate the triggering rainfall with the APS claims. When rainfall records (higher than the 90th percentile) are coincident with the APS claims dates, then these were undoubtedly caused by rainfall. Resorting to the raingauge records, 741 APS claims and 70 APS events were identified. In total, 3676 APS claims and 134 APS events caused by rainfall were counted between January 2000 and October 2011 in the LMA. By using newspaper reports and daily rainfall records, it was possible to determine that 1212 APS claims were not caused by rainfall and, as such, these claims were not considered in this research. Incorrect records (misplaced, duplicated and missing data) were also removed.

In the APS database, the claim date and the communication date may not be the same. Five business days is the APS estimate for the lag time between these claim and communication dates. For that reason, an APS claim was considered when it had occurred up to five business days after the last day of an APS event. When two APS events are less than five business days apart, some APS claims may fit in both events. In these cases, we preferred not to associate these APS claims with any event; these constitute less than 5% of the total APS claims.

The 1956 locatable APS claims (postal code with seven digits) represent 53% of the total for the 2000–2011 period. Only these APS claims guarantee a precise location, allowing their spatial representation and the determination of what type of flooding triggered them. As the great majority of the APS claims were caused by urban flooding, there was a need to classify them according to the influence of the drainage network. Based on the hydrological/physical features of the territory, this classification subdivides urban flooding into FREN (flooding related to the ancient natural drainage network) and FUNN (flooding unrelated to the present or ancient natural drainage network). FREN occurs where there are culverted/buried watercourses, also including the old watercourse routes, whereas FUNN happens where there is no influence of the drainage network and the rainwater faces difficulties in flowing. This type of flooding typically occurs in flat, low-lying areas, depressions or overland flow-

blocking situations. The sub-division of urban flooding into these two types of flooding enabled us to determine whether the hydrologic/physical features of the LMA are capable of causing different material damage.

3.2 Rainfall and atmospheric data

Daily rainfall data for the 2000–2011 period were collected from 23 raingauges (Fig. 1) belonging to the National Water Resources Information System (SNIRH) and the Portuguese Institute for Sea and Atmosphere (IPMA). As explained in Section 3.1, these data were used to identify the APS claims that were caused by rainfall.

To demonstrate the exceptional nature of the 2008 event with respect to past decades in the LMA, annual maximum daily rainfall data were collected from the São Julião do Tojal (SJT) raingauge. Hourly rainfall data were also gathered from this raingauge, allowing us to build intensity–duration–frequency (IDF) curves of the extreme events of 1967, 1983 and 2008. The SJT gauge was chosen as the reference raingauge for the LMA due to: (a) the dimension and reliability of the annual maximum daily rainfall series (Fragoso *et al.* 2011, Trigo *et al.* 2016), with 74 years of records between the water years of 1938/39 and 2011/12; (b) the existence of IDF curves defined by Brandão *et al.* (2001); (c) the availability of hourly data for the 2000–2011 period; and (d) its geographical location within the most intense rainfall area during the 2008 event.

To analyse the spatial and temporal rainfall distribution during this event, hourly rainfall data for 42 raingauges were collected; 29 belong to SNIRH and 13 to IPMA. Usually the IPMA hourly records are not available to the public, but, concerning the 2008 event, the maximum rainfall values for 1, 3, 6 and 24 h were published in Moreira *et al.* (2008). The spatial distribution of the triggering rainfall was mapped, resorting to the maximum values for 24 h, because the highest values of rainfall during the 2008 event were recorded for more than 6 h. The ordinary kriging interpolation method was the best option to build the 24-h maximum rainfall map due to it giving the lowest root mean square error (RMSE) when compared to the deterministic methods and compared to simple or universal kriging. The spatial distribution of rainfall estimated by this method was also the closest to the reality.

Considering the different data availability of the raingauges used, three datasets were defined: (a) five raingauges only were used for the 2000–2011 period (Fig. 1; blue dots); (b) 18 stations were used for both the 2000–2011 period and the 2008 event (Fig. 1; green dots); and (c) 24 stations were used only for the 2008 event (Fig. 1; red dots).

The synoptic-scale atmospheric situation responsible for the 2008 extreme event was briefly characterized by using reanalysis data.² The spatial resolution of this dataset is approx. 80 km (Dee *et al.* 2011), which is suitable for analysing the synoptic situation of the rainfall event.

3.3 Land cover data

Built-up areas represent the main land cover type, especially for urban flooding, indicating the exposure of a given area, along

²ERA-Interim reanalysis dataset, available at www.ecmwf.int/.

with buildings and inhabitants. The built-up areas for the LMA were extracted from the Land Cover Map for Portugal dating from 2007, provided by the Portuguese Directorate-General for Territory and generated through the interpretation of digital ortho-rectified aerial photos obtained in 2007. The minimum cartographic unit is 1 hectare. The source of the statistical data used for buildings, dwellings and population is the 2011 Census, produced by Statistics Portugal.

3.4 Spatial relationships between insurance, rainfall and land cover data

One of the goals of this research was to establish spatial relationships between the three elements discussed above (insurance, rainfall and built-up areas) for the 2000–2011 period and for the 2008 event.

The relationship between insurance and rainfall data for the 2000–2011 period was established by APS event, in order to determine if higher rainfall values necessarily promote greater material damage. The spatial and temporal distribution of intense rainfall events is an important factor with regard to flooding events. For this reason, a relationship between the hourly data of the SJT raingauge and the APS claims located within a 10 km radius of the SJT gauge was defined. The 10 km radius was chosen after testing several distances to the raingauge as this is the maximum expected size of a convective cell (Goudenhoofd and Delobbe 2013). Greater distances provided weaker relationships because, when convective rainfall events occur, there are great spatial discrepancies in the rainfall intensities.

Even though the quantity of APS claims per event is dependent on multiple factors other than rainfall, it is worth knowing whether it is possible to determine a rainfall value from which APS claims began to occur (near the SJT raingauge). This was also accomplished using the SJT hourly rainfall values and the APS events that included APS claims located within a 10 km radius of this raingauge. It was checked whether the date of each rainfall record equal to or greater than 5 mm/h coincided with the date of some APS event. If there was a match, this hourly rainfall record was related to at least one APS claim. If not, this rainfall value was certainly not able to trigger an APS claim. To avoid duplication of the results, for each APS event only the highest hourly rainfall value was considered.

The relationships between insurance and built-up areas were set based on linear or logarithmic regressions, and measured by correlation and determination coefficients. The municipality was selected as the geographical unit for these analyses.

Regarding the 2008 event, four insurance variables were tested: APS claims per km², APS claims per built-up km², payouts per km², and payouts per built-up km². To achieve a 24-h maximum rainfall value for this event in each municipality, three methods were tested: (a) the reference raingauge method, which takes the average of the raingauge values inside or near the municipality; (b) the weighted average method based on the weighted average of each 10 m × 10 m cell value, after converting to raster the 24-h maximum rainfall obtained through ordinary kriging

interpolation; and (c) the APS claims location method, using the same raster file and the average of the computed values where the locatable APS claims were reported.

4 Results

4.1 Synoptic context and magnitude of the 2008 extreme rainfall event

On 18 February 2008, the LMA was affected by an active low-pressure system, responsible for intense rainfall and severe thunderstorms over the region. The synoptic context of this extreme event was described in detail by Fragoso *et al.* (2010), who noticed the presence of a cut-off upper low located between the Azores and Western Iberia, from 11 to 19 February. The location and quasi-stationarity of the cut-off cyclone, with its southern flank reaching subtropical latitudes, favoured the advection of relatively warm and very humid air masses at lower levels of the atmosphere. Under such synoptic circulation features, highly unstable thermodynamic conditions were promoted over the Atlantic vicinity of the LMA and mesoscale convective cloud systems started to form and develop on the afternoon of 17 February (Fragoso *et al.* 2010, their Fig. 5), moving slowly northeast, right into the core region of the LMA. These general dynamic features are illustrated in Figure 2(a), which depicts the mid-troposphere circulation, showing a blocking pattern of the westerlies, with a large cut-off (cold core) upper low centred west of the Azores. Simultaneously, the cyclonic circulation at lower levels (Fig. 2(b)) allowed a southwesterly current over the Atlantic Portuguese margin (including the LMA region), advecting warm and moist airflows, increasing the instability of the atmosphere and giving rise to deep convection. On the afternoon of 17 February 2008, this advection of moisture was quite noticeable (Fig. 2(c)). Moreover, at the same time, a high amount of energy available for convection (CAPE,³ Fig. 2(d)), promoted the formation of convective cloud systems over the southeastern Atlantic proximities of the LMA, which was responsible for 2008 extreme event.

The spatial distribution of the 24-h maximum rainfall for the 2008 event is displayed in Figure 3. This rainstorm was spatially confined (Fragoso *et al.* 2010), mainly affecting the Northern LMA and, in particular, the area comprising Loures, Odivelas and the northern limit of Lisbon, where the values exceeded 140 mm. From this rainfall core, where the SJT raingauge is located, the values progressively decreased. A few hours later (between 11:00 and 14:00 h UTC), another core was found in the region of Setúbal, as result of reactivation of the same storm (Fragoso *et al.* 2010); here, the rainfall values ranged between 80 and 100 mm. The spatial distribution of the 24-h maximum rainfall during the 2008 event decisively influenced the spatial distribution of the APS, as described below.

The exceptional effects of this high-intensity/short-duration rainfall event on the LMA are confirmed in Figure 4. Besides this, two more extreme rainfall events affected this region in past decades: November 1967 and November 1983 (Fig. 4(a)). An interesting fact revealed by the IDF curves is that the magnitude of these events differs substantially as function of the considered rainfall duration (Fig. 4(b)). Regarding shorter rainfall durations

³Convective Available Potential Energy.

Figure 2. Large-scale atmospheric circulation and dynamic features of the extreme event of 18 February 2008: (a) 500 mb geopotential heights (dam), (b) sea-level pressure (mb), (c) total column water vapour (mm), (d) convective available potential energy (J kg^{-1}). All panels refer to 12:00 h UTC on 17 February 2008. Source of reanalysis data: www.ecmwf.int.

Figure 3. Spatial representation of the 24-h maximum rainfall during the 2008 event in the LMA.

Figure 4. High-magnitude rainfall in the LMA at the São Julião do Tojal rain gauge: (a) annual maximum daily rainfall for the period 1938/39–2011/12 and (b) IDF curves for several return periods and for the 1967, 1983 and 2008 rainfall events.

(up to 3 h), the 1967 event was the most exceptional. The 1983 event reached the highest rainfall intensity for all durations longer than 3 h, achieving return periods higher than 100 years. Concerning the durations of 4 h and 5 h, the exceptional nature of the 1967 and 1983 events was similar and outstanding, exceeding 100-year return periods. This becomes even more relevant because most of the LMA drainage basins have concentration times of 6 h or less (Leal and Ramos 2013). The 2008 event had different characteristics from the other two events, as its magnitude was considerably higher for longer durations (equal to or greater than 9 h) than for shorter ones. In fact, the rainfall intensities recorded in the SJT rain gauge for periods under 9 h were always of recurrence interval of less than 20 years, exceeding a 50-year return period only for 24 h duration (Fig. 4(b)). The maximum hourly rainfall in this rain gauge reached 26.2 mm; 84.8 mm in 6 h and 149.1 mm in 24 h. However, the highest rainfall intensities during this event were recorded in other LMA rain gauges: 53.1 mm for 1 h, 99.7 mm for 6 h and 153.6 mm for 24 h duration. Although the IDF curves demonstrate a lower magnitude when compared to the other two events, the 2008 event caused three fatalities and large material damage (Leal *et al.* 2018).

4.2 Material damage during the 2000–2011 period and for the 2008 event

Between January 2000 and October 2011, 134 APS events were recorded in the LMA, corresponding to 11 events per year, on average. In total, 3676 APS claims were recorded (0.5% of the total insurance policies) and €9 898 256 607 worth of property was affected by flooding (8% of the total capital insured). Accordingly, insurance companies paid €13 410 434 to policyholders, with an average €3648 being paid per APS claim. Additionally, there were 367 APS claims (10%) on which the insurance companies did not pay anything to the owners. About 25% of the APS claims and 36% of the payouts on the Portuguese mainland were recorded in the LMA during the 2000–2011 period.

The existence in an insurance database of an extreme rainfall event, as occurred on 18 February 2008, is evidence worth exploring and analysing. But, was the material damage of the 2008 event so different from that caused by more frequent events? This event generated 867 APS claims in the LMA, which represent 24% of total APS claims during the 2000–2011 period. The capital sum affected reached €1 043 546 055 (11% of the total), while payouts totalled €5 326 942 (40% of

the total). The peak of the 2008 event was about five times higher than the second highest peak (Fig. 5(a)), which means that this event generated about five times more APS claims and payouts. The importance of the 2008 event was also noticeable through the cumulative curves for APS claims and payouts (Fig. 5(b)). The major slope break in the chart marks the 2008 event, driving away from the evolution patterns before and after that. Furthermore, when this event occurred there was an inversion between APS claims (above before and below after) and payouts (below before and above after). This means that the relevance of payouts was greater in the 2008 event when compared to APS claims, as payouts per APS claim confirm. This value was substantially higher for the 2008 event (€6144) when compared to the total records (€3648). If one excluded this event, the payouts per APS claim would have been only €2878.

The number of APS claims (867) resulting from this event was quite a lot higher than the numbers reached in any of the studied years (Fig. 6(a)). There were 342 more APS claims recorded for the 2008 event than during the year with the second highest number of APS claims (525, in 2010). The amount of APS claims resulting from this event was also higher than the sum of those in the first four years of the database (2000–2003). The payouts of the 2008 event were more than three times larger than those recorded in the second costliest year (€1 546 929, in 2010) and were still higher than the sum for the first eight years of the database (2000–2007) (see Fig. 6(b)). If this event had not happened, 2008 would have been the third year with fewer APS claims and payouts. Note that a period of almost 12 years is not enough to establish reliable temporal trends.

There was a predisposition for an important part of APS claims and payouts to occur in the autumn months, mainly in October and November (see Fig. 6(c) and (d)). This was related to the increasing trend of rainfall concentration during the autumn in the Mediterranean region (Ramos and Reis 2002). Also, high daily rainfall values tend to occur in these months. The lack of proper cleaning/maintenance of the grated inlets, frequently obstructed by leaves or debris before the wet season, can contribute to increasing the number of APS claims made during these months (Cherqui *et al.* 2015, Spekkers *et al.* 2015). However, the 2008 event made February the most important month regarding APS claims and payouts. Again, this would not have happened if this event had not occurred (Fig. 6(c) and (d)).

The spatial representations of the locatable APS claims in the LMA for the 2000–2011 period (1956) and for the 2008 event (492) are presented in Figure 7. Regarding the 2000–2011 period, some situations stood out: (a) a clear asymmetry between the Northern and the Southern LMA; (b) a core in the Lisbon municipality; (c) four alignments corresponding to the four Lisbon municipality suburban growth axes along the Cascais, Sintra and Vila Franca de Xira railways and the route 8/A8 motorway (Odivelas and Loures); and (d) some critical points in specific places such as Setúbal.

The previously mentioned dissimilarity between the two sub-regions of the study area is expressed by the following values. The Northern LMA had more APS claims (84%) and payouts (83%) when compared to the Southern LMA. In part, this is due to the higher percentages of built-up areas (62%) and insurance policies (74%), revealing a higher exposure to flooding. The weight of the Northern LMA on the overall

Figure 5. Temporal evolution of APS claims and payouts in the LMA (2000–2011): (a) number of APS claims and payouts, (b) accumulated APS claims and payouts.

Figure 6. Annual and monthly values of insurance data in the LMA (2000–2011) and the weight of the 2008 event: (a) number of APS claims per year, (b) payouts per year, (c) APS claims per month and (d) payouts per month. Note: the APS database ends in October 2011. This year only has records for 10 months; November and December values are therefore the result of accumulated values of only 11 years of records, unlike the other months (12 years).

results is also shown by the number of APS claims per 1000 insurance policies (5.3‰ against 2.9‰). These facts can be related to aspects described in Section 2 that augment the rainfall effects, enhancing the frequency and magnitude of the flooding events (Leal and Ramos 2013), through increases in the overland flow volume, depth and/or speed (Patton 1988, Smith and Ward 1998, Butler and Davies 2004). The spatial distribution of the APS claims in the LMA was closely related to the location of the most impervious areas and the biggest concentrations of buildings, as well as to the existence of insurance policies.

When compared to the 2000–2011 period, the spatial distribution of APS claims for the 2008 event was not very different (Fig. 7). However, there was an even higher concentration of APS claims in Lisbon and its nearest municipalities, corresponding to the areas with higher rainfall values during this event (Fig. 3).

4.3 Relationship between insurance, rainfall and land cover

In light of what was previously shown, it is important to understand whether there is still a direct relationship between material damage and rainfall. The correlation coefficients (r) obtained between rainfall and insurance data per event were not significant for the LMA. A stronger relationship was found between the maximum daily rainfall value recorded in the 23 raingauges and the number of APS claims per event ($r = 0.55$; $r^2 = 0.30$). Negligible relationships were also obtained when using the rainfall records of the SJT rainauge for 1, 3, 6, 12 and 24 h and the APS claims located within a 10 km radius of this rainauge (Fig. 8). This means that the

number of the APS claims was not dependent on the amount of rainfall, except for the 2008 event. Eventually, this may be due to the different temporal evolution of the rainfall events. To test this, four events that caused material damage were compared. There is no doubt that the 2008 event was different from other events and, therefore, it resulted in more APS claims; however, neither the amount of rainfall in the considered time periods, nor their temporal evolution can justify the quantity of APS claims recorded for the other three events (Fig. 9). For example, the material damage caused by the event of 29 September 2007 (15 APS claims) was greater than that generated by the event of 6 December 2000 (two APS claims), even with much lower rainfall.

If the number of APS claims was not significantly related to the amount of rainfall, the same does not seem to happen with the occurrence of APS claims. Resorting to the records of the SJT rainauge, it was possible to see that the likelihood of occurrence of APS claims (in a 10 km radius) rose as rainfall increased. Three likelihood levels of flooding were determined for hourly rainfall: 55% of the records between 5 and 7 mm/h generated at least one APS claim; this value increases to 85% for between 7.1 and 10.5 mm/h, and to 100% for records above 10.5 mm/h (Fig. 10). This means that, during the 2000–2011 period, there was at least one APS claim (near the SJT rainauge) when rainfall values were higher than 10.5 mm/h.

But there is a strong association between land cover, buildings, dwellings and insurance data for the LMA municipalities (Table 3). The correlation coefficients obtained through linear or nonlinear (logarithmic) regressions were high between almost every variable. Where there were more dwellings, there were more insurance policies (0.99); where there were more

Figure 7. Spatial distribution of the total APS claims (2000–2011) and those resulting from the 2008 event in the LMA.

insurance policies, there were more APS claims (0.94); and where there were more APS claims there were more payouts (0.95). Weaker relationships (0.76–0.88) were established with capital sum affected, because this is a more variable element, since it depends greatly on the insured content. The correlation coefficient between built-up areas and APS claims for the 2008 event was slightly weaker (0.83) when compared to the 2000–2011 period (0.94), which may reveal that urbanization was less important in this case.

It was previously stated that the spatial distribution of the material damage for the 2008 event was slightly different than that for the 2000–2011 period, because there were higher concentrations of APS claims where higher rainfall values were recorded. To evaluate the rainfall effect on the spatial distribution of the APS claims, the 24-h maximum rainfall and the number of APS claims per built-up km² were selected as indicators, as they have presented the highest correlation coefficients among all the variables tested. The weighting of APS claims by built-up km² allows us to minimize the area effect that affects larger and/or less urbanized LMA municipalities.

Three methods were tested to achieve the 24-h maximum rainfall value for each municipality: the reference raingauge, the weighted average and the APS claims' location. The correlation values (r) obtained between them and the number of APS claims per built-up km² in each municipality were 0.839, 0.843 and 0.757, respectively. Despite the slightly higher correlation coefficient presented by the weighted average method, it was chosen due to its reliability, because this method uses the values of all cells (10 m × 10 m) of each municipality. As for the reference raingauge method, it is a more subjective way to obtain a rainfall value, because it is based on the researcher's judgement as to which should be the reference raingauges for each administrative/geographical unit.

The scatter chart of municipalities between the 24-h maximum rainfall and the number of APS claims per built-up km² is presented in Figure 11. Lisbon had the highest value of APS claims (3.9), but Odivelas had the highest value of rainfall (129.9 mm). Lisbon and three of its neighbouring municipalities (Odivelas, Oeiras and Loures) had above 2.5 APS claims per built-up km², while Cascais, Setúbal, Amadora and Sintra had values ranging between 1 and 2.5. This distribution means that, for the 2008 event, the number of APS claims generally decreased as a function of the distance from Lisbon/rainfall core, confirming the aforementioned concentration pattern. Another relevant fact is that Setúbal was the only municipality in the Southern LMA with APS claims above 1 (2.1), denoting similar behaviour to most of the Northern LMA municipalities. Being above or below the trend line is also a relevant point. The municipalities below the trend line did not need such high rainfall values to have many APS claims in the 2008 event, and the inverse happened with municipalities above the line. Unlike the majority, the outliers were less dependent on the rainfall, as happened with Amadora (positive outlier) or Cascais (negative outlier). Amadora had a rainfall value higher than Loures or Oeiras, yet its APS claims were lower owing to its position in the upstream area of four drainage basins. Being a downstream municipality, Cascais was the opposite case, having the ninth highest rainfall value and it is the fifth municipality with more APS claims.

4.4 Relationship between material damage and type of flooding

The 2008 event registered the highest rainfall values and material damage of the 134 events identified in the LMA for the 2000–2011 period. This combination of low-probability rainfall and high damage can be explained by the fluvial/

Figure 8. Rainfall vs APS claims for each APS event at 1, 3, 6, 12 and 24 hours on the SJT raingauge. Note: only the APS events with APS claims located within a 10 km radius of the SJT raingauge are represented.

pluvial processes that occur when a high-intensity rainfall event occurs in heavily built-up areas. In these situations, part of the rainwater is not captured by the urban drainage systems (Aronica and Lanza 2005, Jha *et al.* 2012, Yu and Coulthard 2015). The higher the rainfall intensity, the greater is the amount of rainwater that is not gathered by the grated

inlets. As a consequence, the overland flow heads to the valley bottoms and the streets built over the culverted/buried watercourses behave as streams, causing flooding related to the ancient natural drainage network (FREN). The overland flow reaches high speeds in steeper streets and accumulates in flat areas, rapidly increasing the water level. FREN tends to

Figure 9. Temporal evolution of four rainfall events that caused a different number of APS claims in a 10 km radius of the SJT rain gauge.

Figure 10. Likelihood levels of flooding for the SJT rain gauge.

Figure 11. Scatter chart between the APS claims per built-up km² and the maximum rainfall in 24 h for the 2008 event.

acquire greater importance in areas with high degrees of imperviousness and when large amounts of rainfall occur in short periods of time (i.e. a few hours).

The FREN has a higher destructive capacity when compared to flooding unrelated to the present or ancient natural drainage network (FUNN), which is the most common type of flooding in urban areas. Both occur frequently in the LMA, as do flash floods. These are capable of causing severe damage, but the exposure of the LMA and its vulnerability to flash floods is much lower nowadays than it was some decades ago, due to the culverting of the watercourses and the improvements in buildings/dwellings.

The APS claims (Fig. 12(a)), payouts (Fig. 12(b)) and payouts per APS claim (Fig. 12(c)) generated by FREN, FUNN and flash floods demonstrate the differences between the 2008 event and the other events (2000–2011) in the LMA. The number of APS claims caused by FREN during the 2008 event is higher when compared to the other events (44% vs 33%), unlike what happens with FUNN (50% vs 62%). This confirms the greater importance of FREN during an extreme rainfall event. Despite the loss of relevance, FUNN was still able to trigger the highest number of APS claims. The differences expressed by APS claims were even more evident in payouts (Fig. 12(b)), where 58% of the 2008 event payouts were due to FREN, while it was only 42% for the other events. Concerning FUNN, this type of flooding resulted in 37% of the payouts for the 2008 event and 50% for the other events. These numbers confirm the higher destructive capacity of FREN when compared to FUNN, especially when an extreme rainfall event occurs. By weighting the payouts for the number of APS claims, the magnitude of the material damage caused by the 2008 event is noticeable (Fig. 12(c)). The amounts paid increased from €2817 to €8287 in FREN and from €1784 to €4660 in FUNN. As stated previously, flash floods are less important than urban flooding in the context of insurance in the LMA: such flooding accounted for 6% of the APS claims for the 2008 event and 5% for the other events. Payouts for flash floods represented 4% for the 2008 event and 8% for the other events. Nevertheless, through the payouts for APS claims the capacity of flash floods to generate material damage is perceptible.

As FREN and FUNN can be considered as urban flooding, the material damage was also accountable for the most built-up municipality of the LMA, Lisbon, for which 33% of the locatable APS claims and 36% of the payouts were recorded. As almost all the watercourses are culverted or buried, there were no APS claims due to flash floods in this municipality for the 2000–2011 period. This analysis enables us to prove that FREN were even more relevant in highly impervious areas (73% of the total surface of Lisbon is built-up). For

Table 3. Correlation matrix between land use/cover, building features and insurance data for the LMA municipalities. LIN: linear regression; LOG: logarithmic regression.

	Built-up areas (%)	Buildings/km ²	Dwellings/km ²	Insurance policies/km ²	APS claims/km ²	Capital sum affected/km ²	Payouts/km ²
Built-up areas (%)		0.97 (LIN)	0.92 (LIN)	0.95 (LOG)	0.94 (LOG)	0.85 (LOG)	0.88 (LOG)
Buildings/km ²	0.97 (LIN)		0.92 (LIN)	0.93 (LOG)	0.91 (LOG)	0.76 (LOG)	0.83 (LOG)
Dwellings/km ²	0.92 (LIN)	0.92 (LIN)		0.99 (LIN)	0.95 (LIN)	0.78 (LOG)	0.83 (LIN)
Insurance policies/km ²	0.95 (LOG)	0.93 (LOG)	0.99 (LIN)		0.94 (LIN)	0.79 (LOG)	0.83 (LIN)
APS claims/km ²	0.94 (LOG)	0.91 (LOG)	0.95 (LIN)	0.94 (LIN)		0.83 (LOG)	0.95 (LIN)
Capital sum affected/km ²	0.85 (LOG)	0.76 (LOG)	0.78 (LOG)	0.79 (LOG)	0.83 (LOG)		0.88 (LIN)
Payouts/km ²	0.88 (LOG)	0.83 (LOG)	0.83 (LIN)	0.83 (LIN)	0.95 (LIN)	0.88 (LIN)

Figure 12. Material damage by type of flooding in the LMA and in the Lisbon municipality: (a) and (d) APS claims, (b) and (e) payouts, and (c) and (f) payouts per APS claim. (a), (b) and (c) correspond to the LMA, and (d), (e) and (f) to the Lisbon municipality.

the 2008 event, FREN produced the highest number of APS claims (58%), unlike the LMA as a whole (Fig. 12(d)). Concerning payouts, FREN produced 71% for the 2008 event, while it was just 48% for the other events (Fig. 12(e)). In Lisbon, the weight of FUNN was reduced when compared to the LMA, except for the payouts for other events. The values of payouts per APS claim were similar to those presented for the LMA, but the differences between the 2008 event and the other events were smaller (Fig. 12(f)).

5 Discussion

As for all natural hazard databases, the APS database has a few limitations. First, it was not possible to realize the total dimension of the material damage caused by flooding in the LMA, because the APS database includes only 60% of Portuguese insurance policies. However, the spatial distribution of the APS claims is obviously conditioned by the spatial distribution of built-up areas and the population, meaning that APS claims are only made where there are insured buildings/dwellings. The financial capacity, the level of education and/or the degree of perception of a person/family with regard to natural hazards may also explain whether or not an insurance policy is acquired (Lave and Lave 1991, Thieken *et al.* 2007, Hung 2009, Botzen and van den Bergh 2012, Lo 2013, Diakakis *et al.* 2018). It should also be noted that the amounts paid are partially related to the capital sum insured/affected, which means that high payouts can be

explained by highly insured capital in the insurance policies. In the APS database, the lack of information about the cause of the flooding and the average lag time of five business days between the communication date and the flooding date can be considered the major sources of uncertainty. Regarding rainfall events, for those that last for several hours or even some days, it is not always possible to determine what really triggered the flooding event, because it may have been caused by a peak of more intense rainfall included in a longer period of rain or by the accumulated values. The fact that the claim date and communication date may not be coincident makes that task even more difficult. By cross-checking some data sources (newspapers, rainfall and APS claims) the uncertainty decreased substantially. This provided a validation of the results and enabled the exclusion of several APS claims that were surely not caused by rainfall (almost 25% of the original APS database).

The relationship between material damage and rainfall per event for the 2000–2011 period in the LMA was not significant, but it was similar to the results obtained by Spekkers *et al.* (2013b) and Zhou *et al.* (2013). It is not reasonable to expect a more direct relationship because it depends on: (a) the quality and availability of rainfall and insurance data (Merz *et al.* 2004, Spekkers *et al.* 2013a); (b) the spatial and temporal distribution of the triggering rainfall (Bruni *et al.* 2015); (c) the geomorphological, lithological and hydrological features; (d) the extent of built-up areas; (e) the amount of exposed (and insured) dwellings; (f) the capacity of storm-

water drainage systems to cope with heavy rainfall events (Aronica and Lanza 2005, Yu and Coulthard 2015); (g) the urban morphology (McGrane 2016); and (h) the tidal and/or storm surge effects in low-lying coastal areas (Archetti *et al.* 2011, Condon and Sheng 2012, Chen and Liu 2014). The spatial distribution of APS claims was largely dependent on the spatial distribution of built-up areas, buildings and insurance policies, as demonstrated by the strong correlation coefficients obtained. In contrast, payouts were due not only to the characteristics of the triggering rainfall, flooding and affected buildings, but also to the capital sum affected/insured and the evaluation of the insurance companies' experts.

Additional data on the water level reached in each APS claim, the consequent structural damage, the type and construction material of the affected buildings and/or the content losses after a flooding event (Thieken *et al.* 2008, Elmer *et al.* 2010, Zhou *et al.* 2013, Spekkers *et al.* 2013a) would help to improve the results. The lack of this kind of data imposes several constraints in determining the true degree of loss, which ranges between no loss and total loss, or in the quantitative estimation of damage caused by flooding in each affected building/dwelling (Merz *et al.* 2004, 2009, Freni *et al.* 2010, Hurford *et al.* 2012, Spekkers *et al.* 2013a). However, the stage–damage curves were not applied in this research because they are usually related to direct damage in large drainage basins (Spekkers *et al.* 2013a), there being many uncertainties in application of these curves for urban flooding (Freni *et al.* 2010, Notaro *et al.* 2014).

Despite previous remarks, rainfall is still the most important factor with regard to flooding. Through the hourly rainfall records of the SJT raingauge and the APS claims for the 2000–2011 period, three likelihood levels of flooding were defined. However, these levels would be more reliable if both data series (rainfall and insurance) were longer. It must also be recognized that high hourly rainfall may not be enough, by itself, to trigger a flooding event, because the duration of a triggering rainfall event is frequently longer than one hour. For these reasons, those hourly values should not be understood as rainfall thresholds, but the likelihood levels of flooding can be treated as references for rainfall forecasting and flooding warning systems.

Data availability on raingauges played an important role in the accurate spatial representation. The high-density network of raingauges allowed an accurate spatial representation of the triggering rainfall of the 2008 event through the ordinary kriging interpolation method. Of the three methods tested to obtain a rainfall value for each of the LMA municipalities, the weighted average produced the best results. It was, simultaneously, the most reliable and robust method, since the final value was based on all computed values inside a given area.

The material damage associated with the 2008 event was greater than that caused by other situations reported, forcing the insurance companies to pay higher amounts than the standard values. It may be assumed that only high-magnitude rainfall events can cause very high material damage. Rainfall events of low and medium magnitudes can produce several APS claims, mainly in densely built-up areas, but they are hardly capable of generating high material damage. The frequency and magnitude of urban flooding have grown, and impervious surfaces play an important role in this context

(Smith and Ward 1998, Freni *et al.* 2010, Jha *et al.* 2012, Bruni *et al.* 2015). The decreases in infiltration rates, the constraints imposed by the urban grid or the lack of maintenance of grated inlets make FUNN frequent even when low-intensity/long-duration rainfall events occur. However, when high-intensity/short-duration rainfall events occur, the impervious surfaces increase the volume and speed of the overland flow, allowing rainwater to reach the (built-up) valley bottoms very quickly and causing FREN. In these situations, the topographic relief and the floodplains of ancient watercourses are still crucial factors in the current overland flow behaviour of urban areas (Oliveira and Ramos 2002, Diakakis *et al.* 2016, Sørensen and Mobini 2017).

High-intensity/short-duration rainfall events can more easily result in FREN. As a consequence, FREN tend to cause more damage when compared to FUNN, due to their higher destructive potential. The results and findings obtained for the LMA are very similar to those of Sørensen and Mobini (2017). However, as Torgersen *et al.* (2015) have noted, intense rainfall events that last for several hours are capable of triggering more damage than shorter torrential events, as the consequences of the 2008 event showed. When it comes to riverine/slow floods, it is the low-intensity/long-duration rainfall events that cause more damage (Merz *et al.* 2009).

6 Conclusions

Flooding insurance databases enable us to understand, for a given area and time period, the spatial and temporal distribution of this natural hazard. Their main advantage is that they support the quantification of material damage.

For the 2000–2011 period there was no direct relationship between the amount of rainfall and the amount of material damage per event in the LMA. The number and weight of natural and human-induced conditioning factors in an urbanized area explain the weak relationships obtained. However, as hourly rainfall increased, the greater was the likelihood of APS claims occurring. This means that the quantity of APS claims was not dependent on the amount of rainfall, unlike their occurrence. Three likelihood levels of flooding (with material damage) were determined for the SJT raingauge. The proposed likelihood levels of flooding may be used as references for rainfall forecasting and flood warning systems, but should not be assumed as rainfall thresholds.

In this study, it was found that APS claims and payouts are strongly dependent on the built-up areas. This dependence confirms that the likelihood of APS claims is higher where there are more buildings, and therefore higher exposure. This apparently logical evidence, along with the fact that many of the watercourses are culverted or buried, indicates the current importance of urban flooding in the LMA. The extent and density of the built-up areas, together with the hydro-geomorphological features, explains the considerably higher number of APS claims in the Northern LMA in the 2000–2011 period. This also explains their concentration in Lisbon and in its neighbouring municipalities.

The weight of the 2008 event in the APS database was noteworthy and different from the other 133 APS events

recorded in the 2000–2011 period. This event had substantially higher costs than all APS events that occurred over several years. It is significant that a rainstorm that lasted less than one day resulted in 24% of the APS claims and 40% of the payouts in the 4322 days of this insurance database. For the 2008 event, the relationship between material damage and built-up areas is lower than for the other events, and a stronger relationship was found between insurance and rainfall data. Thus, it can be assumed that the importance of rainfall in the 2008 event was greater when compared to the other events.

The natural drainage network and relief are still relevant factors in the hydrological behaviour of urban areas in the LMA, especially when high-intensity/short-duration rainfall events occur. As a consequence, the territory assumes a more natural behaviour and less dependence on urban morphology, as happened for the 2008 event. As such, flooding occurs in the same places that it occurred in before the culverting of the watercourses. High-intensity/short-duration rainfall events are capable of causing more FREN and greater damage, representing a greater danger with regard to urban flooding in the LMA. In contrast, low-intensity/long-duration rainfall events mainly cause FUNN, which is the most common type of flooding in the study area. It does not require a high-intensity rainfall event to cause material damage, which is even more noticeable in densely urbanized areas, as in the Lisbon municipality, where flooding may occur almost anywhere.

The material damage caused by urban flooding may require some actions by the organs of sovereignty, civil protection, civil society and populations. The areas of higher flooding susceptibility must be known and mapped, the grated inlets should be frequently cleaned and, in more serious cases, the storm-water drainage systems should be improved. Ground floors and basements located in the floodplains of the ancient watercourses should also adopt prevention and mitigation measures for flooding events. Assessing the material damage caused by flooding, and especially that triggered by an extreme rainfall event, provides valuable information for insurance companies, decision making and spatial planning. The results from this research show a reality unknown in the LMA until now.

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References

- Aerts, J.C.J.H. and Botzen, W.J.W., 2011. Climate change impacts on pricing long-term flood insurance: a comprehensive study for the Netherlands. *Global Environmental Change*, 21 (3), 1045–1060. Elsevier Ltd. doi:10.1016/j.gloenvcha.2011.04.005
- André, C., et al., 2013. Contribution of insurance data to cost assessment of coastal flood damage to residential buildings: insights gained from Johanna (2008) and Xynthia (2010) storm events. *Natural Hazards and Earth System Sciences*, 13 (8), 2003–2012. doi:10.5194/nhess-13-2003-2013
- Archetti, R., et al., 2011. Development of flood probability charts for urban drainage network in coastal areas through a simplified joint assessment approach. *Hydrology and Earth System Sciences*, 15 (10), 3115–3122. doi:10.5194/hess-15-3115-2011
- Aronica, G.T. and Lanza, L.G., 2005. Drainage efficiency in urban areas: a case study. *Hydrological Processes*, 19 (5), 1105–1119. doi:10.1002/hyp.5648
- Atreya, A., Ferreira, S., and Michel-Kerjan, E., 2015. What drives households to buy flood insurance? New evidence from Georgia. *Ecological Economics*, 117, 153–161. doi:10.1016/j.ecolecon.2015.06.024
- Barnolas, M. and Llasat, M.C., 2007. A flood geodatabase and its climatological applications: the case of Catalonia for the last century. *Natural Hazards and Earth System Sciences*, 7 (2), 271–281. doi:10.5194/nhess-7-271-2007
- Barredo, J.I., 2009. Normalised flood losses in Europe: 1970–2006. *Natural Hazards and Earth System Sciences*, 9, 97–104. doi:10.5194/nhess-9-97-2009
- Barrera, A., Llasat, M.C., and Barriendos, M., 2006. Estimation of extreme flash flood evolution in Barcelona County from 1351 to 2005. *Natural Hazards and Earth System Sciences*, 6 (4), 505–518. doi:10.5194/nhess-6-505-2006
- Barthel, F. and Neumayer, E., 2012. A trend analysis of normalized insured damage from natural disasters. *Climatic Change*, 113 (2), 215–237. doi:10.1007/s10584-011-0331-2
- Bernet, D.B., Prasuhn, V., and Weingartner, R., 2017. Surface water floods in Switzerland: what insurance claim records tell us about the damage in space and time. *Natural Hazards and Earth System Sciences*, 17 (9), 1659–1682. doi:10.5194/nhess-17-1659-2017
- Botzen, W.J.W. and van den Bergh, J.C., 2008. Insurance against climate change and flooding in the Netherlands: present, future, and comparison with other countries. *Risk Analysis*, 28 (2), 413–426. doi:10.1111/j.1539-6924.2008.01035.x
- Botzen, W.J.W. and van den Bergh, J.C., 2012. Risk attitudes to low-probability climate change risks: WTP for flood insurance. *Journal of Economic Behaviour and Organization*, 82 (1), 151–166. doi:10.1016/j.jebo.2012.01.005
- Botzen, W.J.W., van den Bergh, J.C., and Bouwer, L.M., 2010. Climate change and increased risk for the insurance sector: a global perspective and an assessment for the Netherlands. *Natural Hazards*, 52 (3), 577–598. doi:10.1007/s11069-009-9404-1
- Bouwer, L.M., 2011. Have disaster losses increased due to anthropogenic climate change? *Bulletin of the American Meteorological Society*, 92 (1), 39–46. doi:10.1175/2010BAMS3092.1
- Brandão, C., Rodrigues, R., and Costa, J.P., 2001. *Análise de fenómenos extremos: precipitações intensas em Portugal Continental*. Lisboa: Direcção dos Serviços de Recursos Hídricos.

- Brázdil, R., Kundzewicz, Z.W., and Benito, G., 2006. Historical hydrology for studying flood risk in Europe. *Hydrological Sciences Journal*, 51 (October), 739–764. doi:10.1623/hysj.51.5.739
- Bruni, G., et al., 2015. On the sensitivity of urban hydrodynamic modelling to rainfall spatial and temporal resolution. *Hydrology and Earth System Sciences*, 19 (2), 691–709. doi:10.5194/hess-19-691-2015
- Butler, D. and Davies, J.W., 2004. *Urban drainage*. 2nd ed. London; Spon Press. doi:10.1017/CBO9781107415324.004
- Chen, W.B. and Liu, W.C., 2014. Modeling flood inundation induced by river flow and storm surges over a river basin. *Water (Switzerland)*, 6 (10), 3182–3199. doi:10.3390/w6103182
- Cherqui, F., et al., 2015. Assessing urban potential flooding risk and identifying effective risk-reduction measures. *Science of the Total Environment*, 514, 418–425. doi:10.1016/j.scitotenv.2015.02.027
- CNT, 2014. The Prevalence and Cost of Urban Flooding: A Case Study of Cook County, IL. Available from: http://www.cnt.org/sites/default/files/publications/CNT_PrevalenceAndCostOfUrbanFlooding2014.pdf [Accessed 18 Oct 2017].
- Condon, A.J. and Sheng, Y.P., 2012. Evaluation of coastal inundation hazard for present and future climates. *Natural Hazards*, 62 (2), 345–373. doi:10.1007/s11069-011-9996-0
- Cortés, M., et al., 2018. The relationship between precipitation and insurance data for flood damages in a region of the Mediterranean (Northeast Spain). *Natural Hazards and Earth System Sciences, Discuss*, 18, 857–868. doi:10.5194/nhess-2017-278
- Crompton, R.P. and McAneney, K.J., 2008. Normalised Australian insured losses from meteorological hazards: 1967–2006. *Environmental Science and Policy*, 11 (5), 371–378. doi:10.1016/j.envsci.2008.01.005
- Dee, D.P., et al., 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137 (656), 553–597. doi:10.1002/qj.828
- Diakakis, M., et al., 2016. Factors controlling the spatial distribution of flash flooding in the complex environment of a metropolitan urban area. The case of Athens 2013 flash flood event. *International Journal of Disaster Risk Reduction*, 18, 171–180. doi:10.1016/j.ijdrr.2016.06.010
- Diakakis, M., Priskos, G., and Skordoulis, M., 2018. Public perception of flood risk in flash flood prone areas of Eastern Mediterranean: the case of Attica Region in Greece. *International Journal of Disaster Risk Reduction*, 28 (March), 404–413. doi:10.1016/j.ijdrr.2018.03.018
- Douben, K.J., 2006. Characteristics of river floods and flooding: a global overview, 1985–2003. *Irrigation and Drainage*, 55 (SUPPL. 1), 25–27. doi:10.1002/ird.239
- Elmer, F., et al., 2010. A Delphi method expert survey to derive standards for flood damage data collection. *Risk Analysis*, 30 (1), 107–124. doi:10.1111/j.1539-6924.2009.01325.x
- Fragoso, M., et al., 2011. Assessment of frequency-magnitude of extreme rainfall events and flooding—Portugal. N1.2 Report WP1. Secoa—Solutions for Environmental contrasts in Coastal Areas, Project: 244251 FP7-ENV.2009.2.1.5.
- Fragoso, M., et al., 2010. The exceptional rainfall event in Lisbon on 18 February 2008. *Weather*, 65 (2), 31–35. doi:10.1002/wea.513
- Freni, G., Loggia, G.L., and Notaro, V., 2010. Uncertainty in urban flood damage assessment due to urban drainage modelling and depth-damage curve estimation. *Water Science Technology*, 61 (12), 2979–2993. doi:10.2166/wst.2010.177
- Goudenhoofd, E. and Delobbe, L., 2013. Statistical characteristics of convective storms in Belgium derived from volumetric weather radar observations. *Journal of Applied Meteorology and Climatology*, 52 (4), 918–934. doi:10.1175/JAMC-D-12-079.1
- Grahn, T. and Nyberg, L., 2017. Assessment of pluvial flood exposure and vulnerability of residential areas. *International Journal of Disaster Risk Reduction*, 21 (January), 367–375. Elsevier Ltd. doi:10.1016/j.ijdrr.2017.01.016
- Guzzetti, F. and Tonelli, G., 2004. Information system on hydrological and geomorphological catastrophes in Italy (SICI): a tool for managing landslide and flood hazards. *Natural Hazards and Earth System Sciences*, 4 (2), 213–232. doi:10.5194/nhess-4-213-2004
- Hoeppe, P., 2016. Trends in weather related disasters - Consequences for insurers and society. *Weather and Climate and Extremes*, 11, 70–79. Elsevier. doi:10.1016/j.wace.2015.10.002
- Hung, H.C., 2009. The attitude towards flood insurance purchase when respondents' preferences are uncertain: a fuzzy approach. *Journal of Risk Research*, 12 (2), 239–258. doi:10.1080/13669870802497702
- Hurford, A.P., et al., 2012. The effectiveness of extreme rainfall alerts in predicting surface water flooding in England and Wales. *International Journal of Climatology*, 32 (11), 1768–1774. doi:10.1002/joc.2391
- Jha, A.K., Bloch, R., and Lamond, J., 2012. *Cities and flooding: a Guide to integrated urban flood risk management for the 21st century*. World Bank. doi:10.1596/978-0-8213-8866-2
- Jongman, B., et al., 2014. Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change*, 4 (4), 1–5. doi:10.1038/NCLIMATE2124
- Lamond, J. and Penning-Rowsell, E., 2014. The robustness of flood insurance regimes given changing risk resulting from climate change. *Climate Risk Management*, 2, 1–10. Elsevier B.V. doi:10.1016/j.crm.2014.03.001
- Lave, T.R. and Lave, L.B., 1991. Public Perception of the Risks of Floods: implications for Communication. *Risk Analysis*, 11 (2), 255–267. doi:10.1111/j.1539-6924.1991.tb00602.x
- Leal, M. and Ramos, C., 2013. Susceptibilidade às cheias na Área Metropolitana De Lisboa Norte: factores de predisposição e impactos das mudanças de uso do solo. *Finisterra*, 95, 17–40. doi:10.18055/Finis3129
- Leal, M., Ramos, C., and Pereira, S., 2018. Different types of flooding lead to different human and material damages: the case of the Lisbon Metropolitan Area. *Natural Hazards*, 91 (2), 735–758. Springer Netherlands. doi:10.1007/s11069-017-3153-3
- Liberato, M.L.R., et al., 2012. Moisture sources and large-scale dynamics associated with a flash flood event. *Geophysical Monographs Series*, 200 (November), 111–126. doi:10.1029/2012GM001244
- Lo, A.Y., 2013. The likelihood of having flood insurance increases with social expectations. *Area*, 45 (1), 70–76. doi:10.1111/area.12002
- Loster, T., 1999. Flood Trends and Global Change. *Global Change Catastrophe Management*, 1–7. Available from: <http://fp.arizona.edu/kkh/hwrs/pdfs/trends/T-loster-Flood-Trends-summary-Reinsurance-Co.pdf>
- McGrane, S.J., 2016. Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. *Hydrological Sciences Journal*, 61 (13), 2295–2311. doi:10.1080/02626667.2015.1128084
- Merz, B., Elmer, F., and Thieken, A.H., 2009. Significance of 'high probability/low damage' versus 'low probability/high damage' flood events". *Natural Hazards and Earth System Sciences*, 9, 1033–1046. doi:10.5194/nhess-10-3-2010
- Merz, B., et al., 2004. Estimation uncertainty of direct monetary flood damage to buildings. *Natural Hazards and Earth System Sciences*, 4, 153–163. doi:10.5194/nhess-4-153-2004
- Mills, E., 2005. Insurance in a Climate of Change. *Science*, 309 (5737), 1040–1044. doi:10.1126/science.1112121
- Moncoulon, D., et al., 2014. Analysis of the French insurance market exposure to floods: a stochastic model combining river overflow and surface runoff. *Natural Hazards and Earth System Sciences*, 14 (9), 2469–2485. doi:10.5194/nhess-14-2469-2014
- Moreira, N., et al., 2008. *Cheias de 18 de Fevereiro de 2008*. Relatório DMC/CIME-01/2008. Lisbon, Portugal: Instituto de Meteorologia.
- Norbiato, D., et al., 2008. Flash flood warning based on rainfall thresholds and soil moisture conditions: an assessment for gauged and ungauged basins. *Journal of Hydrology*, 362 (3–4), 274–290. doi:10.1016/j.jhydrol.2008.08.023
- Notaro, V., et al., 2014. The effect of damage functions on urban flood damage appraisal. *Procedia Engineering*, 70, 1251–1260. doi:10.1016/j.proeng.2014.02.138
- Oliveira, P.E. and Ramos, C., 2002. Inundações na cidade de Lisboa durante o século XX e seus factores agravantes. *Finisterra*, 37 (74), 33–54. doi:10.18055/Finis1589
- Patton, P., 1988. Drainage basin morphometry and floods. In: V. Baker, R.C. Kocher, and P. Patton, eds. *Flood geomorphology*. New York: Wiley, 51–65.

- Paudel, Y., Botzen, W.J.W., and Aerts, J.C.J.H., 2015. Influence of climate change and socio-economic development on catastrophe insurance: a case study of flood risk scenarios in the Netherlands. *Regional Environmental Change*, 15 (8), 1717–1729. doi:10.1007/s10113-014-0736-3
- Petrucci, O., 2013. Brief communication the assessment of damage caused by historical landslide events. *Natural Hazards and Earth System Sciences*, 13 (3), 755–761. doi:10.5194/nhess-13-755-2013
- Ramos, C. and Reis, E., 2002. Floods in southern Portugal : their physical and human causes. *Mitigation and Adaptation Strategies for Global Change*, 7 (3), 267–284. doi:10.1023/A:1024475529524
- Rashid, H., 2011. Interpreting flood disasters and flood hazard perceptions from newspaper discourse: tale of two floods in the Red River valley, Manitoba, Canada. *Applied Geography*, 31 (1), 35–45. doi:10.1016/j.apgeog.2010.03.010
- Smith, K. and Ward, R., 1998. *Floods: physical processes and human impacts*. Chichester: Wiley.
- Sörensen, J. and Mobini, S., 2017. Pluvial, urban flood mechanisms and characteristics – assessment based on insurance claims. *Journal of Hydrology*, 555, 51–67. doi:10.1016/j.jhydrol.2017.09.039
- Spekkers, M.H., Clemens, F.H.L.R., and Veldhuis, J.A.E.T., 2015. On the occurrence of rainstorm damage based on home insurance and weather data. *Natural Hazards and Earth System Sciences*, 15 (2), 261–272. doi:10.5194/nhess-15-261-2015
- Spekkers, M.H., et al., 2013a. A statistical analysis of insurance damage claims related to rainfall extremes. *Hydrology and Earth System Sciences*, 17 (3), 913–922. doi:10.5194/hess-17-913-2013
- Spekkers, M.H., et al., 5-7 September 2013b. Correlations between rainfall data and insurance damage data related to sewer flooding for the case of Aarhus, Denmark. In *International Conference on Flood Resilience, Exp. Asia Eur*, Exet, UK.
- Surminski, S., et al., 2015. Reflections on the current debate on how to link flood insurance and disaster risk reduction in the European Union. *Natural Hazards*, 79 (3), 1451–1479. doi:10.1007/s11069-015-1832-5
- Thieken, A.H., et al., 2008. Methods for the evaluation of direct and indirect flood losses. In *Fourth International Symposium on Flood Defence*, Toronto, Canada, 1–10.
- Thieken, A.H., et al., 2007. Coping with floods: preparedness, response and recovery of flood-affected residents in Germany in 2002. *Hydrological Sciences Journal*, 52 (5), 1016–1037. doi:10.1623/hysj.52.5.1016
- Thieken, A.H., et al., 2006. Insurability and mitigation of flood losses in private households in Germany. *Risk Analysis*, 26 (2), 383–395. doi:10.1111/j.1539-6924.2006.00741.x
- Torgersen, G., et al., 2015. Correlation between extreme rainfall and insurance claims due to urban flooding – case study fredrikstad, Norway. *Journal of Urban Environmental Engineering*, 9 (2), 127–138. doi:10.4090/juee.2015.v9n2.127138
- Trigo, R.M., et al., 2016. The deadliest storm of the 20th century striking Portugal: flood impacts and atmospheric circulation. *Journal of Hydrology*, 541 (November), 597–610. doi:10.1016/j.jhydrol.2015.10.036
- UNISDR, 2002. *Guidelines for reducing flood losses*. United Nations. Available from: https://www.unisdr.org/files/558_7639.pdf
- Yu, D. and Coulthard, T.J., 2015. Evaluating the importance of catchment hydrological parameters for urban surface water flood modelling using a simple hydro-inundation model. *Journal of Hydrology*, 524, 385–400. doi:10.1016/j.jhydrol.2015.02.040
- Zhou, Q., et al., 2013. Verification of flood damage modelling using insurance data. *Water Science Technology*, 68 (2), 425–432. doi:10.2166/wst.2013.268