Analysis of pluvial flood damage costs in residential buildings – A case study in Malmö

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ABSTRACT

Pluvial flood damage to residential buildings causes a significant part of direct tangible flood losses. In this study, we investigate the non-hazard variables and sewer system types in relation to damage costs in the city of Malmö, Sweden. A comprehensive data set of around 1000 records of direct damage to residential buildings from a cloudburst event on 31 August 2014 in Malmö, Sweden has been analysed at property scale with no lumping together of data. The results show that properties connected to combined sewer systems are much more exposed to pluvial flood damage than properties connected to separated sewer systems, with the ratio of the number of claims being close to three. The analysis of building-specific variables shows no clear statistical relationships to the damage costs. To further the understanding of damage costs caused by urban pluvial flooding, it is necessary to extend the group of explanatory variables to include information about the socio-economic background of households, the actual value of assets in basements and the precautionary measures taken by house owners.

1. Introduction

Urban flooding is increasingly coming into focus as the costs incurred by flood damage escalate globally [1–8]. Although the main focus historically has been on the overflowing of rivers and other watercourses (fluvial flooding), in recent years concerns have also grown with regard to flooding due to insufficient drainage capacity (pluvial flooding) [9, 10]. Attention to pluvial flooding is of particular importance in urban areas. Urbanisation increases the concentration of people and assets whilst also extending impermeable surfaces that reduce local infiltration and the evaporation of precipitation [11]. This occurs in cities where more than half the global population resides and where the entire global population growth is expected in the future [12]. While many of the most vulnerable people live in developing countries [13], flooding also threatens to undermine sustainable development in Europe [14], especially since climate change is expected to exacerbate flood risks [15, 16].

Europe has experienced many extreme cloudburst events that caused pluvial flooding in recent years. For instance, the 2008 cloudburst in Dortmund (Germany) resulted in flood damage amounting to 17.2 million Euro [17]; the 2011 cloudburst in Copenhagen (Denmark) resulted in more than 800 million Euro in insurance payouts [6,18–20], and the 2014 cloudburst in Malmö (Sweden) resulted in more than 600 million SEK of damage. Such sensational events call into question the conventional notion that fluvial flooding is more devastating than pluvial flooding. Although fluvial flooding can cause more significant destruction, the cumulative direct damage of the more frequent pluvial flooding is at least equivalent to and at times greater than the damage from fluvial or coastal flooding [21]. For instance, between 5000 and 7000 buildings a year are flooded by sewage in England and Wales [1]. Besides material damage, pluvial flooding inundates buildings and streets [17,22] and can disrupt transportation and expose people to pollutants and pathogens [23–25]. Pluvial flood damage has been referred to as an ‘invisible hazard’ [26] and an understudied area in the available literature [24,27], and consensus is now growing about the need for improved understanding of the mechanisms behind pluvial flood damage [6,28,29].

In recent years, efforts to research flood damage have increased significantly in several parts of the world (e.g. Refs. [30–33]. These
studies are usually carried out to quantify flood damage after a flood event (ex-post), or they focus on potential future flood damage scenarios (ex-ante) [34] to support the work of policymakers, urban planners, insurance companies and reinsurers [35,36]. Actual flood damage data is fundamental for ex-post approaches and crucial for building reliable ex-ante impact models [34,37]. Common sources for historical flood damage data are insurance data, surveys, and call centers such as emergency centers that are contacted by people affected by flooding [19,37–42]. Flood damage can be categorized as direct or indirect and tangible or intangible [43]. Direct damage refers to physical damage to people or assets caused by floodwater. In contrast, indirect damage refers to other disruptions caused by floodwater, such as a disturbance in traffic or trade, a loss of working hours [44], or health impacts or mental stress [45]. The distinction between tangible and intangible flood damage relates to whether the damage can be assessed monetarily [46]. Historically there has been less focus on the intangible aspect of flood damage mainly due to the complexity involved in capturing these effects [47]. Direct tangible loss has gained the most attention in the literature [48]. Recent studies have mainly focused on direct tangible loss for residential buildings, (e.g. Refs. [49,52]). This type of loss is also the focus in the study.

Many valuable studies have focused on the hazard aspect of urban pluvial flood damage apply different 1D-2D hydraulic models and damage modelling [10,27,53–55] that include factors like rainfall (intensity, duration), floodwater level, contamination, flood warning, and buildings (construction, age, material) [36,38,46,56–58]. Hazard assessment is an essential part of the flood risk assessment, and rainfall is often suggested as a crucial factor in both ex-ante and ex-post approaches [10,19,38,39,59,60]. For instance, both Blumenthal and Nyberg [38] and Sörensen and Mobini [19] found that rainfall was an essential driver of flood damage in the 2014 cloud burst in Malmö (Sweden) and that the relationship between flood damage and rainfall intensity is nonlinear [19,38]. Studies in Denmark further substantiate this, showing a shift in the relationship for rainfall intensities near the ten-year return period [10,61].

While hydrological and hydraulic factors have attracted substantial attention, a need for more research into other potentially important drivers of urban pluvial flood damage has been suggested [20]. For instance, it has been pointed out that the importance of socio-economic factors and building characteristics cannot be neglected [38–40]. This aligns with the conventional notion of risk as a function of hazard, exposure and vulnerability [62,63], where the value at stake plays a fundamental role. This has also been pointed out in previous studies of flood damage [64], where direct damage has been significantly associated with building characteristics and content [65,66].

Spekkers et al. [39] showed that real-estate value, ground floor area, and building age are associated with flood damage frequency, and while they could explain 25% of the variance of claim frequency, they could not establish a model for damage claim size. They highlighted the fact that their data was at the district level, and they therefore recommend investigating the relationship between flood damage and exposed value that their data was at the district level, and they therefore recommend investigating the relationship between flood damage and exposed value. They showed that their model could estimate relative losses to building and content damage as a function of water depth, water velocity, return period, floor space area, and a household’s net disposable income per capita in the region. The coefficient of determination (R²) was between 0 and 0.3 for fluvial cases and 0–0.14 for pluvial cases. Their results are in line with several other studies in which much of the statistical variance in the damage costs is left unexplained, which has also been highlighted in the review of this specific field by Gradeci et al. [68]. The review work by Gradeci et al. offered some possible reasons for the low degree of explanation for the regression analysis; one possible explanation could be related to aggregated data. These recent research works are significant contributions towards better understanding of the mechanisms behind pluvial flood damage. However, they were mainly carried out at aggregated levels, with a few exceptions like the study by Bernet et al. which investigated at single property level for the whole of Switzerland for multiple events and the study by Paprotny et al. which studied and compared residential loss for three different countries, Germany, Italy and the Netherlands [67,69,70]. In an effort to advance the understanding of the drivers of urban pluvial flood damage, we take heed of these recent findings and investigate potential patterns of flood damage in relation to building-specific variables (building age, ground floor area and building value) at the building level (micro-level), and we also include sewer type (combined or separated), which – to our knowledge – has not previously been studied as an explanatory variable at this level.

The study aims to contribute to an increased understanding of the mechanisms behind urban pluvial flood damage by investigating potential patterns in the distribution of such damage in relation to building-specific variables. This paper focuses on the cloud burst on 31 August 2014 in Malmö (Sweden), for which different hydrological and hydraulic factors have been well researched [19,71,72]. The study is rare as it allows analysis of the flood damage of individual residential properties concerning a number of their specific attributes, including their exact location. The findings are theoretically interesting and initially surprising, and complement the valuable studies referred to above.

2. Case study description

This study focuses on the city of Malmö, which has a history of pluvial flooding problems, especially sewer flooding. The cloud burst event in August 2014 was selected as a specific flooding case, and is presented further in Section 2.1. Malmö is Sweden’s third largest city by population, following Stockholm and Gothenburg. According to Statistics Sweden (SCB), Malmö municipality has a population of 344,166 (SCB, 2020) and is Sweden’s third largest city by population. Malmö is also an interesting case due to its socio-economic diversity and the segregation within the city [73]. Malmö is located on the southwestern coast of Sweden (see Fig. 1). The topography is flat, and the maximum elevation is around 41 m [74]. In recent decades, intense rainfall during the summer months has led to many damage claims; this has been highlighted in previous studies [19,38,75]. Another key feature of flooding in Malmö is the difference between separated and combined sewer systems (see Fig. 1). Malmö is thus a significant and valuable case for understanding the consequences of pluvial flood damage and the distribution of damage costs. Fig. 1 shows the location of the sewer systems and rain gauges in Malmö.

2.1. Flood event 31 August 2014

This study focuses specifically on the cloud burst that hit Malmö at around 3 a.m. on 31 August 2014 and lasted for 6 h. Several rain gauges captured the cloud burst; one rain gauge belonged to the Swedish Meteorological and Hydrological Institute (SMHI), and nine rain gauges belonged to the municipal water and wastewater utility. The SMHI station measures rainfall volume over a period of 15 min, while the municipal water and wastewater utility’s rain gauge stations use tipping buckets with 0.2 mm resolution. The SMHI rain station measured a total rain volume of 85.5 mm; a summary of the municipal water and wastewater utility rain gauges is presented in Table 1. The location of rain gauges is also shown in Fig. 1 except for the portable rain gauge on the roof of Söderkulla school. The peak of rainfall was at Söderkulla school, where it registered 122 mm of rainfall in 6 h. This gives a return period of this event around twice as large as what was previously considered a 100 years’ rainfall event. The cloud burst is the most intense cloud burst on record in Sweden. The stations’ location and a detailed map of rainfall distribution have been presented by both Hernebring et al. [72] and Sörensen et al. [19,19,72].
The heavy rainfall caused extensive flood damage, making the event exceptional in Sweden regarding the number of claims and damage expenses. The cloudburst lasted around 6 h, but it took four days for all of the water to leave Malmö, and the pressure on the wastewater treatment facility and pump stations remained high for an extended period. The damage was not limited to basements or cars (more than 3000 cars were affected); around 20 households were displaced for a year following the flood incident [76]. The city’s main hospital and several schools were also critically affected [75]. The flood event affected all of the city and was not limited to only some areas. There has also been indications of overland flooding in some areas of the city, e.g. Söderkulla and Heleneholm, which has been highlighted in a previous study [19]. People have been rescued from their cars and homes.

![Map of Malmö with the location of type of sewer, rain gauges, and catchment.](image)

**Fig. 1.** Map of Malmö with the location of type of sewer, rain gauges, and catchment.

| Rain gauge ID | Rain gauge name                  | Measured volume (mm) |
|---------------|----------------------------------|----------------------|
| MA01          | Turbinen                         | 104                  |
| MA02          | Limhamn                          | 73                   |
| MA03          | Augustenborg                     | 104                  |
| MA04          | Djupadalskolan                   | 101                  |
| MA05          | Bullofa                          | 68                   |
| MA06          | Hammars Park                     | 63                   |
| MA07          | Bellevue                         | 100                  |
| MA08          | Höja                             | 51                   |
| SMHI          | SMHI                             | 85                   |
| N/A           | Portable Söderkulla school       | 122                  |

Table 1

Summary of the rain measurements [72], the location of rain gauges can be found in Fig. 1.
According to reports from rescue centres, floodwater has reached the same level as home windows in some locations [77]. In some places, flood marks on walls were found to be more than 1 m high. These locations have been documented by municipal water and wastewater utility personnel, as well as newspapers. The majority of stormwater basins were overloaded, resulting in massive lakes on the surface that were photographed. The unusual severity of the 2014 cloudburst event is clear from comparing the annual numbers of flood damage claims; see Fig. 2.

3. Data

The literature review conducted by Gradeci et al. [68] summarised response variables that express damage influencing factors in the following four main categories: meteorological, geographic, demographic, and building/property variables. In this study, our focus is on the building/property, including the sewer type that is connected to the building. In summary, our variables are the sewer system type, age of the building, building footprint, and the building’s assessed value. The databases used in this study are summarised in Table 2 and described in greater detail below.

3.1. Damage claim data

We obtained the flood damage cost data from insurance companies’ claims to the municipal water and wastewater utility in Malmö. Damage costs are the compensation that the insurance company paid to their policyholders (i.e., property owners) after the flood event. However, the exact deductible parts and the insurance negotiations between policyholders and insurance companies for the submitted damage cost were unknown. Therefore, the cost we have is not the total damage cost for each property following the flood event. However, according to other studies investigating the flood damage costs from insurance companies in Sweden, the deductible is generally either 10% or 10 000 SEK [65]. We received the damage claim as one total cost that comprised structural damage to the building, content damage and cleaning costs.

Rather than asking different insurance companies in order to obtain flood damage data for this study, we received damage data from the municipal water and wastewater utility. In Europe, property owners’ damage claims are commonly submitted to insurance companies at the first stage [40]. Sweden’s regulations and praxis regarding pluvial flood damage are different than in other European countries. The municipalities usually own the sewer systems in Sweden. There is a specific regulation regarding basement flooding that makes the municipal water and wastewater utility liable after the flood damage. Therefore, insurance companies claim the damage cost that they paid to the property owners from the municipal water and wastewater utility. This dataset is therefore very comprehensive. It includes all of the parameters, which are often problematic to obtain, such as the exact location of the flood damage and the building’s connection to the sewer system. Previous scientific research work has reported a lack of available data due to privacy issues and commercial confidentiality. Many studies have emphasised the quality and availability of data as very important when investigating and assessing flood damage [27,38,48,65,71,78,79]. Because our damage cost data are not aggregated and our analysis is based on the exact locations of flood damage, this study is a valuable endeavour in the field of urban flood damage assessment.

3.2. Urban drainage system in Malmö

Malmö’s urban drainage system can be categorised into two systems: combined and separated sewer systems. The combined sewer system consists of only one pipeline, which receives both stormwater and wastewater. The separated sewer system consists of two separated pipelines: one for stormwater and one for wastewater. Around 30% of the sewer systems in Malmö are combined sewer systems [19].

Before the 1960s, there were only combined sewer systems. After the 1960s, separated sewer systems became standard. The combined sewer system is sensitive to extreme rainfall events, and it is not designed to handle very intensive rainfalls. According to Swedish practice, the combined sewer system should be able to handle rainfall with a ten-year return period, which corresponds to a block rain volume of around 39 mm in 6 h. A previous study showed how vulnerable houses connected to the combined system are compared to houses connected to the

Table 2
Overview of included data.

| Data | Temporal resolution | Spatial resolution | Data provider |
|------|---------------------|--------------------|--------------|
| Database of property damage claims from insurance companies to the municipality | Daily | Household-level | Municipal water and wastewater utility |
| Urban drainage system | Per object | Municipal water and wastewater utility |
| Database of assessed real-estate values | Annually | Per object | Swedish Tax Agency |
| Building classification | Per object | The Swedish Mapping, Cadastral and Land Registration Authority (SMLRA, Lantmäteriet) |
| Building construction year | Per object | Online map service (www.hitta.se) |

Fig. 2. The number of pluvial flood damage claims per year in Malmö, 1994–2019.
separated system [19,80]. The detailed flood damage data is important, e.g. flood depth which was not available in our study.

3.3. Property information

Property specific data on living area, commercial area, land area, building assessed value, and land assessed value were obtained from the Swedish Tax Agency for 2014. The assessed value is the value on which taxation is based, and it is usually less than the market value. The damage claim data from the municipal water and wastewater utility did not contain a detailed classification regarding the property type. We thus retrieved the property classification data from SMLRA, an authority responsible for the property division in Sweden that provided information on geography and property. We matched the two data sets to assign a building classification such as residential building, industry or school. In this study, we have chosen to investigate the houses, as the focus is residential buildings. We did not analyse damage to the blocks of flats since we could not identify which part of a building was damaged. Information on the building construction year was retrieved from an online map service that supplied information for 87% of the original cases (~ [81]).

4. Research method

The spatial classification of flood damage assessment is usually done at three different scales: micro-scale (e.g. single element at risk, such as a building), mesoscale (e.g. residential areas), and macro-scale (e.g. municipalities). Our study is conducted on both the building and the neighbourhood level, i.e. the intermediate level between micro- and mesoscale.

The research method mainly consisted of four stages. In the first stage, pre-processing of data was conducted by harmonizing different data sources and performing quality control of the data. In the second stage, analysis of the spatial features of the damage was carried out. In the third stage, descriptive analysis on the distribution of the damage cost and the explanatory variables were conducted. In the fourth and final stage, regression analysis was performed to evaluate potential determinants of the variation in damage costs. These stages are described in more detail in the coming sections.

4.1. Pre-processing

The damage cost data, the building’s assessed value and the building type classification all had a common identifier in the building area and block number identifiers in all databases. This was used to create a geographically common database with all property units in Malmö municipality. The data from SMLRA included the building’s living area. However, it is unlikely that the flooding caused damage to more than the basement and ground floor in a multistorey building. Based on the SMLRA data, which also contains spatial data on all buildings, we calculated each building’s footprint in order to be able to estimate the ground floor area. From the Swedish Mapping, Cadastral and Land Registration Authority, SMLRA data set, we found cases with multiple buildings belonging to a single property ID. This indicated that the property ID included several houses. Such cases were not included in the analysis.

We controlled the quality of data set to identify obvious errors. We found that there were cases of more than one damage claim being assigned to a single property; in such cases, the costs were added together. The reason for multiple claims for a single property could be that the insurance company claims the damage at different stages, or that the policyholder is insured by different insurance companies for different types of damage. For instance, there could be one claim for damage to the building and one claim for loss of material. There were also cases with zero damage cost or blank cost; this could mean that the insurance company later retracted those claims or did not provide the final amount. Those data items were deleted from the list. There were also some cases of multiple property IDs with only one damage cost. Since we could not identify the property to which to assign the damage, we omitted those cases from the final data list.

4.2. Spatial analysis on damage cost

To evaluate spatial features of the data a spatial autocorrelation analysis with Moran’s I was carried out. Moran’s I describes how a spatial variable correlates with itself spatially [82], where a +1 result indicates a strong positive spatial auto-correlation and a result of zero indicates no spatial auto-correlation. A high spatial correlation may call for further geostatistical analyses.

4.3. Descriptive statistical analysis

The data set was sorted into two main categories to evaluate the effect of the type of sewer system: damage cost data for properties connected to the combined sewer system and damage cost data for properties connected to the separated sewer system. We summarised the basic statistics on distribution of our variables, i.e., damage costs, assessed building value, age of the building, and living area for each sewer category.

4.4. Regression analysis

Relationships between the damage cost data and explanatory variables were evaluated with stepwise linear regression analyses using the computational software Matlab [83]. While several other studies have used relative damage as the response variable, e.g., damage per m² or damage per building value, the total damage cost was retained as the response variable. However, in order to evaluate the role of both building area and value as explanatory variables and to reduce collinearity in the regression models, these were combined with the building footprint to estimate the value exposed to flooding of each building on the ground floor:

\[ \text{Building value on ground floor} = \text{Building value} \times \text{Footprint/Building living area} \]

This combination of building-specific variables was used together with the type of sewer system and building age as explanatory variables. Building age is relevant to include as older buildings might be more sensitive to flood damage, and has been included in several other studies (e.g. Refs. [84–86]). The analyses were conducted on both the full sample and on clusters based on the location of houses. Analyses of location clusters were included to evaluate whether there were distinguishable location effects in the relationships between the explanatory variables and the damage cost. The K-means clustering method was used on the coordinates of the houses to identify clusters, with a requirement set for a minimum of 20 houses in each cluster, to achieve an acceptable degree of freedom for the regression analyses. The natural logarithm was used in order to normalise the distribution of the damage cost for the regression analyses. The stepwise regression analysis was then conducted on each of the clusters and the full sample, with interaction terms included. The inclusion criteria for explanatory variables in the regression models were set to the F-statistic’s significance level compared to a preceding model step being less than 0.05. The focus was to identify statistically significant correlations between the explanatory variable and the damage cost, and to identify the explanatory capacity of the full multivariate models. Outliers were removed based on Z-scores larger than 3 for both the damage cost and explanatory variables in the full sample [87], as well as leverage and Cook’s distance values for each regression model according to Ref. [88]:

\[ \text{Leverage}_{\text{outlier}} = \text{Leverage} > \frac{2 \times \text{number of explanatory variables}}{\text{number of observations}} \]
5. Result

In order to gain an overview of the spatial distribution of damage, all locations associated with damage claims were plotted on a city map. For reasons of data secrecy and personal integrity however, these locations cannot be presented at the individual building scale. An aggregated map showing the mean damage cost for 150 by 150 m grid cells is presented in Fig. 3.

The Moran’s I test resulted in 0.29 for the damage cost (Fig. 3), which indicates a lack of spatial autocorrelation. This result shows that the geographical location does not determine the extent of the damage claims. And as all buildings are connected to sewer systems, it is more likely that exposure to pluvial flooding is more dependent on the location of the sewer system than on the geographical location of the building itself.

The distribution of the included variables is shown in Table 3.

The descriptive statistical analysis reveals that more properties connected to the combined sewer system claim their damage cost than properties connected to the separated sewer system (see Table 3). This finding in relation to the distribution of type of sewer in Malmö – which is 30% combined and 70% separated – shows that properties connected to the combined sewer system are 86% exposed in comparison to 14% in separated system [19].

There is a substantial difference between the minimum and maximum damage costs (1 and 4000 kSEK), which shows the wide range of the cost of damage in the city. The minimum damage is very close in both sewer categories, and there is no difference based on the type of the sewer. However, there is a significant difference between the maximum damage cost based on the type of sewer system (combined: 1000 kSEK; separated: 4000 kSEK). The assessed value of houses connected to the combined and separated systems respectively did not differ much in their median and mode. The only difference we could observe was the high maximum value for a house connected to the combined sewer system (7000 kSEK) compared to the maximum value for a house connected to the separated system (23 000 kSEK). We did not observe any specific deviation of living area between the two sewer categories except the maximum area belonging to houses connected to combined sewer systems.

However, there was a difference in the median year of construction for the houses, which was 1936 for houses with a combined sewer system and 1963 for houses connected to the separated sewer system.

As can be seen in Fig. 4, the damage cost data is positively skewed. This was accounted for in the regression analysis by using the natural logarithm of the insurance damage costs. Most of the damage cost claims were small; 10 kSEK was the mode for combined sewer and 15 kSEK for separated systems. Age has a weak negative correlation, and the estimated building value on the ground floor has a weak positive correlation. These results also show a significant overlap in the cost of damage between combined and separated systems, and a large spread in damage cost within narrow variable ranges for age and building value

Table 3
Summary of descriptive statistical analysis of damaged residential buildings (only ‘houses’ as defined in the text), for the cloudburst event in Malmö, 31 August 2014, categorised based on their connection to the sewer system (combined and separated). Values are presented as min-max (median).

| Variable name                      | Combined sewer | Separated sewer | Total         |
|------------------------------------|----------------|-----------------|---------------|
| Count (#)                          | 714            | 264             | 978           |
| Response variable                  |                |                 |               |
| Damage cost (kSEK)                 | 1–1000 (67)    | 1–4000 (97)     | 1–4000 (75)   |
| Explanatory variables              |                |                 |               |
| Assessed building value (kSEK)     | 143–23 000     | 312–7000        | 143–23 000    |
| (kSEK)                             | (1000)         | (1000)          | (1000)        |
| Living area (m²)                   | 58–1916 (134)  | 42–604 (146)    | 42–1916 (137) |
| Construction year                  | 1905–1999      | 1884–2004       | 1884–2004     |
|                                    | (1936)         | (1963)          | (1937)        |

SEK = Swedish crown (kSEK = 1000 SEK). 1 kSEK = €100.

Fig. 3. Spatial distribution of damage costs for houses for the cloudburst event in Malmö on 31 August 2014, aggregated in 150 × 150 m cells.
on the ground floor.

The cluster analysis resulted in nine clusters, as shown in Fig. 6 is more compact.

The results from the multiple regression for each cluster and the full sample are show in Table 4, Note that due to the outlier exclusion based on leverage and Cook’s distances, the number of observations was reduced below the cluster requirement of 20 in one cluster. Overall, the multiple regression analyses for both the full sample and the clusters can explain a very small portion of the variation in damage costs. Sewer type and building value on the ground floor were selected in several of the regression models, while age was always excluded. The effects produced by the selected variables show some consistency, with combined sewer systems generally having lower damage costs of 16 000–40 000 SEK, except for in Cluster 8, where the damage cost is 44 000 SEK higher. According to the regression models, building value on the ground floor generates higher damage costs of 50–240 SEK per 1000 SEK value. Beyond identifying these differences between the clusters and the full sample, no further conclusions could be drawn from the statistical analyses of the included data sets.

6. Discussion

The empirical results have both confirmed expectations and offered an initial surprise. The analysis reveals significantly more damage claims from properties connected to combined sewer systems than from properties connected to separated sewer systems. This confirms the higher exposure to urban pluvial floods associated with the former that has been identified in previous studies [19,80]. However, the results suggest that this higher exposure to pluvial flood is not associated with more severe damage. On the contrary, the distribution of damage costs for the two sewer types show only minor differences (Fig. 5), with slightly lower damage costs on average for the properties with combined sewer systems than for the properties connected to separated sewer systems. The reason, at least in part, for this perhaps surprising result is a large number of small damage costs with combined systems that introduce a positive skew in the distribution (Fig. 4). These results mean that the type of sewer system is relatively inconsequential for determining the extent of damage when a property is flooded. We will return to the discussion of the potential reasons for this further below.

The most surprising result concerns the role of building-specific variables in driving pluvial flood damage, which is anticipated to be significant in both general risk theory and previous empirical studies [39,70]. Instead, the high-resolution analysis at the building-level reveals that only a negligible proportion of damage costs could be statistically explained by the property-specific variables studied for the 2014 flood event in Malmö ($R^2 = 0.04$, see Table 4). This was in line with the

![Fig. 4. The distribution of damage cost for houses connected to combined sewer and separated sewer. Cloudburst event, 31 August 2014, Malmö.](image)

![Fig. 5. Bivariate plots between each explanatory variable and the natural logarithm of the damage cost. A total of 832 cases were included.](image)
result of Spekkers et al. which showed that the relationship between their explanatory variables (e.g. ground floor area, property value) with average claim size has been weak or nonexistent [39]. Results were similar when analysing different location-based clusters of properties. While the regression models for some of these clusters provided slightly higher but still weak coefficients of determination ($R^2$), the considerable inconsistencies in the effects of the different variables between the clusters strongly suggest that the included property-specific variables cannot explain any significant part of the variation in damage costs in this case. This means that sewer type, building age and exposed property value matter little in determining pluvial flood damage; this is initially surprising considering established theory. It appears at first to be inconsistent with the central role afforded to exposed value in conventional notions of risk. Our results are in line with those of previous researchers, although we had detail data at the property level. This issue is therefore not resolved as expected by analysing flood damage at a higher resolution.

The initial surprise concerning the very similar damage costs between sewer types, regardless of the much higher exposure to the pluvial flood of properties connected to combined sewer systems and the negligible explanatory power of property-specific variables may diminish when considering the socio-economic context of the study. Most of the residential properties in our case study in Malmö contain substantially more valuable material than the value of the flood damage. It is also fair to assume that the damage to the buildings and goods and materials are similar regardless of the total exposed property value. For instance, replastering a wall with the same dimensions costs the same regardless of the total value of the flooded floor. This means that, although properties connected to combined sewer systems are more at risk of pluvial floods than properties connected to separated systems due to their much higher exposure, the damage is similar when flooding occurs. This can be explained by the fact that the exposed value does not restrict the damage costs in Sweden. However, it is easy to imagine contexts where the cost of flood damage is restricted by a property’s total value.

Research on pluvial flood damage costs is a relatively new area compared to research on fluvial flood damage. The lack of higher explanatory capacity in this analysis shows that it is necessary to advance this research field. Based on these results, several directions for improved research can now be proposed; these are presented below. This study included the type of sewer system, as previous studies have highlighted the difference in flood exposure between them [19,40,80]. While only a slight difference could be identified in damage cost distribution between combined and separated sewer systems, there is a clear difference in the frequency of damage cost cases.

Our analysis did not investigate owners’ behaviour before and after the flood event, which previous studies have highlighted as affecting damage costs [17,46,68–70]. Precautionary measures could be a critical hidden factor that explains the small differences in damage costs for the different categories [90,91], which calls for further research on this topic. Historically, buildings connected to combined sewer systems are more subject to flooding, so awareness and precautionary measures could play an important role. However, in this case, the cloudburst event started at middle of the night on a Sunday, and there were no warnings from the Swedish authorities about the cloudburst. While precautionary measures were not investigated, it can thus be assumed that because the cloudburst started on a Sunday morning in the very early hours and there was no official warning given, their effect on damage is expected to be small.

Although using damage costs at the property level provided additional detail compared to previous studies, precision may still be improved by distinguishing between damage to buildings and damage to content. This would require detailed data from insurance companies, which is generally very hard to obtain due to confidentiality issues [71].

Moreover, as only single-family houses were included, and not blocks of flats, a large proportion of the population has been excluded. While the building values of the included houses show a large spread (Fig. 6), a more diverse selection of housing types is required to identify the role of socio-economic features.

The data on damage costs came from official registers on insurance claims received by the municipal water and wastewater utility. As there is no national systematic flood damage database in Sweden, as there is in e.g. Germany, establishing a flood damage database is crucial to

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**Table 4**

Multiple regression results. Variables effects are recalculated as mean damage cost effects (SEK), while the response variable in the models was the natural logarithm of the insurance damage costs.

| Data      | Observations | $R^2$ | Sewer (Combined) | Age of Building | Building value on the ground floor (kSEK) |
|-----------|--------------|-------|-----------------|-----------------|-----------------------------------------|
| Cluster #1| 115          | 0.07  | $-40\,272^{***}$| –               | –                                       |
| Cluster #2| 143          | 0.11  | –               | –               | –                                       |
| Cluster #3| 103          | 0.05  | –               | –               | 241^{***}                              |
| Cluster #4| 36           | 0.16  | $-32\,997^{**}$ | –               | 64^{*}                                  |
| Cluster #5| 64           | 0.00  | –               | –               | –                                       |
| Cluster #6| 15           | 0.00  | –               | –               | –                                       |
| Cluster #7| 59           | 0.00  | –               | –               | –                                       |
| Cluster #8| 71           | 0.21  | $44\,222^{**}$ | –               | 217^{***}                              |
| Cluster #9| 148          | 0.04  | $-29\,997^{**}$ | –               | –                                       |
| Full sample| 784         | 0.04  | $-16\,063^{***}$| –               | 46^{***}                                |

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\( ^{**}\text{Significant at 0.05 level; }^{***}\text{ Significant at 0.01 level.} \)
improve the understanding of damage costs. As a complement to a flood damage database from the municipal water and wastewater utility, conducting surveys connected to flood events could facilitate filling this knowledge gap. As the addresses of damaged properties are available, this could be implemented in future research. The surveying method with questionnaires is an established method used in other studies [6,25, 57,67,89], and it could be applied in these cases. This could also be useful for addressing the socio-economic features behind the damage costs – there were not included in this study, and they have identified as important non-hazardous factors, e.g. household income and education, the number of people in the household, and the value of content in the basement, as well as the precautionary measures taken by property owners [25,57].

7. Conclusion

In this study, we investigated the damage costs caused by an extreme rain event in the city of Malmö, Sweden on 31 August 2014. The purpose was to increase our understanding of pluvial flood damage and its relationship to characteristics of the built environment. A special feature of our data material is the spatial resolution of the information about properties, which allowed us to include costs at property level and the exact geographical location of all properties that submitted claims for damage compensation.

The uncertainty regarding the data used in this study is in the actual damage costs. They are based on information received from the municipal water and wastewater utility, which in turn contains the damage claims from the insurance companies. Since the data is of commercial value, the companies are anonymous, and we have thus not been able to double-check the values. Access to direct damage data from insurance companies would therefore improve future studies. It is also likely that some minor claims made by the property owners corresponded to values below the deductible and therefore were not passed on to the municipal water and wastewater utility. However, it is unlikely that these issues interfere with the results in any substantial way.

The results show that properties connected to combined sewer systems are much more exposed to pluvial flood damage than properties connected to separated sewer systems, with the ratio of number of claims being close to three. This difference in exposure is even more pronounced when considering that the number of properties connected to combined sewer systems in Malmö make up only about 30% of the total. While there was a clear difference in exposure based on the number of claims, the actual costs did not differ significantly between the two categories. The analysis of building-specific variables did not show any clear statistical relationships between those variables and the damage costs. Despite the added spatial detail of this analysis, multivariate regression with building-specific variables showed that only a very small part of the variation in damage costs could be explained.

In order to further our understanding of the damage costs caused by urban pluvial flooding, it is necessary to extend the group of independent variables to include information about the flood hazard data e.g. flood depth, socio-economic background of households, the actual value of assets in basements and the precautionary measures taken by house owners.

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Declaration of competing interest

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.

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