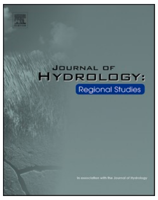
Journal of Hydrology: Regional Studies 65 (2026) 103512

Contents lists available at ScienceDirect

Journal of Hydrology: Regional Studies

journal homepage: www.elsevier.com/locate/ejrh



Drivers of basement flooding: Rainfall intensity and infrastructure impacts in Trelleborg, Sweden

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ARTICLE INFO

Keywords:
Urban basement flooding
Rainfall intensity
Flood recurrence
Sewer system configuration
Reported flood data

ABSTRACT

Study region: Trelleborg is a mid-sized coastal municipality in southern Sweden that has experienced repeated pluvial flooding in recent decades. The city comprises areas served by both combined and separate sewer systems and is increasingly exposed to intense short-duration rainfall events. This study uses 17 years (2006–2023) of property-level flood reports, in situ rainfall observations from multiple local gauges, and detailed information on sewer system configuration and property type.

Study focus: The study investigates how rainfall characteristics and urban infrastructure are associated with flood frequency and recurrence at the property level. Flood reports were linked to rainfall event characteristics and analysed using non-parametric statistical tests and tree-based models, including Poisson regression and classification trees. Rainfall intensities across multiple durations were evaluated to identify relevant temporal scales, while infrastructure and property characteristics were assessed as influencing factors.

New hydrological insights: Short-duration rainfall intensity, particularly at the 60-minute scale, is more strongly associated with flood frequency and recurrence than total rainfall volume. Higher 60-minute intensities are linked to increased numbers of reported cases and a greater likelihood of repeated flooding at affected properties. Flooding was observed across a wide range of rainfall conditions, including events below nominal design thresholds, indicating that moderate rainfall can still result in substantial impacts. The results further show that flood recurrence is influenced by interactions between rainfall intensity and property characteristics. These findings provide empirical evidence on rainfall–infrastructure interactions in Trelleborg and support improved urban drainage assessment and adaptation planning.

1. Introduction

Floods are among the most frequent natural hazards, causing major impacts on economies and societies, with urban areas being particularly vulnerable due to dense populations and concentrated infrastructure (Cea and Costabile, 2022; Rosenzweig et al., 2018).

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https://doi.org/10.1016/j.ejrh.2026.103512
Received 8 January 2026; Received in revised form 23 April 2026; Accepted 30 April 2026

Urban pluvial flooding is a type of urban flooding receiving increasing concern, caused by short, intense rainfall that exceeds the capacity of urban drainage systems. In the coming decades, extreme rainfall events are expected to become more frequent and severe due to climate change (Fowler et al., 2021; Intergovernmental Panel on Climate Change IPCC, 2023), while ongoing urbanisation and population growth further amplify flood risk (Intergovernmental Panel on Climate Change IPCC, 2023). Among many regions, Sweden is increasingly exposed to pluvial flooding, with approximately 45 rainfall-induced flood events reported annually (Nyberg et al., 2019). Records from the Swedish Meteorological and Hydrological Institute show that short-duration rainfall extremes are prominent, particularly in southern Sweden, indicating a more challenging future (Olsson et al., 2021, 2019). Therefore, it is important to understand the driving factors of urban pluvial flooding in Sweden and to develop effective adaptation measures to reduce vulnerability in these situations. Sweden's drainage systems have evolved over centuries, with historical laws and governance structures continuing to shape today's infrastructure (Jacks, 2019; Jakobsson, 2013). Many older districts still rely on combined sewer systems, which heighten the risk of cross-contamination and overload treatment plants during heavy rainfall Swedish Environmental Protection Agency (Naturvårdsverket), 2020. At the same time, urbanisation and climate change are placing increasing demands on aging infrastructure, while fragmented governance, unclear liability for flood damages, and limited municipal resources undermine sustainable stormwater management (Swedish Government, 2024). In response, Sweden's national climate adaptation strategy calls for stronger municipal mandates and legal reforms, supported by tools from the Swedish Meteorological and Hydrological Institute (SMHI), such as the Klimatanpassningsportalen, and planning guidelines from the Swedish National Board of Housing, Building and Planning (Boverket) (Boverket, 2023; SMHI, 2025).

Previous studies have applied a range of approaches to assess urban flood risk, but most rely on hydraulic models that are rarely validated against observed flood impacts. For example, Roth et al. (2024) applied hydrodynamic modelling of compound flooding (rainfall, river flow, and sea level) in Trelleborg, Sweden, demonstrating that rainfall intensity contributes substantially to flood hazard patterns in the urban area. Spekkers et al. (2014) used decision-tree analysis on insurance claims in the Netherlands and found that maximum rainfall intensity was the strongest driver of flood damage, followed by property characteristics. Similarly, Jiang et al. (2022) emphasized the importance of detailed field-survey data for basement flooding assessments, including drainage-related and property-specific characteristics.

Basement flooding remains less explicitly represented in many urban flood assessments, even though these processes are critical for understanding observed property damage. Hydrodynamic flood models typically focus on surface flow processes, while studies of urban flooding highlight the importance of subsurface pathways and internal building connections for explaining basement flooding (Jiang et al., 2022; Palla et al., 2018). Reviews of urban flood impacts further show that damage depends strongly on building-specific characteristics and mechanisms (Hammond et al., 2015), including drainage features, basement configuration, and protection measures such as foundation drainage systems and backwater valves (Irwin et al., 2018; Kaur et al., 2022).

The role of drainage infrastructure in urban flooding is also well established. Sewer systems are typically designed for specific return periods, and exceedance of system capacity can lead to surcharge conditions, during which water may backflow through the network and enter connected buildings (Cea and Costabile, 2022; Sandink and Robinson, 2022). Both modelling and empirical studies demonstrate that drainage system performance, including pipe capacity and inlet efficiency, strongly influences flooding likelihood and extent (Leitão et al., 2017; Schmitt et al., 2004). The interaction between rainfall characteristics and drainage networks is therefore critical, as high-intensity rainfall events can exceed system capacity and contribute to urban flooding (Cristiano et al., 2019).

These mechanisms are particularly relevant for basement flooding, where sewer backup and property-level protection measures directly influence whether floodwater enters buildings. Together, these findings highlight the need for studies that explicitly link rainfall characteristics with sewer-system performance and observed basement flooding impacts.

Previous work by Mobini (2021) analysed damage costs from a single pluvial flooding event in Malmö, southern Sweden, and demonstrated that properties connected to combined sewer systems were substantially more exposed to flood damage than those connected to separated systems. That study highlighted sewer-system configuration as a key infrastructural driver of urban flood impacts but was limited to a single event and did not examine rainfall-intensity thresholds or recurrent basement flooding in a coastal urban context.

Building on this earlier work, the present study extends the analysis to 17 years of flood reports in Trelleborg, a coastal city in southern Sweden. Using an empirical, threshold-based framework, we investigate how rainfall intensity and duration, sewer system type, and property type are associated with flood frequency and recurrence among affected properties. This approach enables validation of previously identified drivers across a longer timescale and provides a more comprehensive understanding of the mechanisms governing urban flood impacts.

In this city, basement flooding is a common manifestation of pluvial flooding, typically occurring when stormwater enters buildings as sewer systems become overloaded. By combining long-term observational flood reports with statistical and decision-tree analyses, we aim to address the following question:

What rainfall intensities and infrastructure characteristics are most strongly associated with basement flood frequency and recurrence?

Here, rainfall thresholds are defined as intensities that consistently coincided with basement flooding, reflecting observed system performance rather than nominal design criterion.

2. Materials and data

2.1. Case study: Trelleborg

Trelleborg is a coastal municipality in southern Sweden, with approximately 47,000 residents and spanning an area of 340 km^2. The present study focuses on the urban area of the city of Trelleborg (Fig. 1). The city lies at a low elevation with predominantly flat terrain. These features, combined with its proximity to the Baltic Sea, make Trelleborg particularly susceptible to basement flooding during high-intensity rainfall events (Laster Grip et al., 2021).

The long-standing archive of documented flood reports, accessibility of rainfall and drainage data, and strategic relevance within Sweden's climate adaptation framework make Trelleborg a highly suitable case study. Ongoing urban expansion, such as the Kuststad 2025 coastal development initiative, further underscores the importance of assessing drainage system performance under intensifying climatic stress (Trelleborg municipality, 2025).

Over several decades, the city has gradually transitioned from combined to separated sewer systems through drainage upgrades and flood mitigation initiatives. Despite more than 1600 separations of sewer systems since the 1990s, recurring basement flooding continues during extreme rainfall, often due to sewer system surcharge. This persistence highlights the need to better understand how the drainage system performs under stress and how rainfall characteristics interact with local infrastructure to trigger flood events.

2.2. Data sources

This study integrates multiple datasets to analyse basement flooding patterns in Trelleborg city (Table 1). These datasets were combined to analyse the relationships between rainfall characteristics, infrastructure attributes, and observed basement flooding events. The primary sources include:

2.2.1. Flood reports

Records of 591 flood reports between 2006 and 2023, provided by the Water and Wastewater Department (WWD). Each flood report includes property designation and the date of flooding. These reports form the basis for identifying affected properties and analysing patterns of reported basement flooding. Flooded properties are identified based on basement flooding incidents submitted to the WWD by property owners or insurance companies. In addition, some reports include information on the property's connection to the drainage system and the reported point of water entry into the property. For example, a typical flood report includes a property designation and the date of flooding and may additionally contain information on sewer connection type and the reported point of water entry. The dataset refers to basement flooding events. In most cases, water was reported to enter basements through internal drainage points such as floor drains or toilet connections, indicating sewer surcharge rather than surface runoff. As a result, unreported incidents may not be included, and the dataset likely underestimates the total number of flooding events. Property-level protection measures, such as backflow valves, may influence the likelihood and severity of basement flooding. However, information on their presence or performance was not available in the dataset and could therefore not be considered in the analysis.

2.2.2. Building attributes

Property type, obtained through an online mapping service linked to property designation. Buildings are categorized into houses, townhouses, apartment and businesses (including industrial and public facilities). Houses dominate the dataset, but all categories are represented, enabling analysis of property-level vulnerability. Table 2 summarizes the distribution of flood reports by type between 2006 and 2023. Houses accounted for 49.1% of all flood reports, followed by apartments (26.6%) and townhouses (20.3%). Business

Fig. 1. Location of Trelleborg in southern Sweden and overview of the study area. The left panel shows the location of Trelleborg within Sweden, while the right panel presents a zoomed-in view of the study area corresponding to the urban extent of the city. The black boundary indicates the study area, and the three rain gauges (W, C, and E) represent the western, central, and eastern parts of the city, respectively.

Table 1
Summary of data sources used for the analysis.

Data	Description	Data provider
Flood Reports	Reports of flooded properties	Water and Wastewater Department (WWD)
Building attributes	Property type	Online map service (www.hitta.se)
Urban drainage system	Information on the type of sewer systems (combined or separated)	Municipal infrastructure records
Rainfall Data	Intensity and duration of rainfall events over the study period.	Municipal weather stations in the city of Trelleborg

Table 2
Distribution of flood reports by building type in the city of Trelleborg during 2006–2023.

Property Type	Count	Percentage
House	271	49.1%
Apartment	147	26.6%
Townhouse	112	20.3%
Business	15	2.7%
Unknown	7	1.3%

properties and unknown types together represented less than 5%.

2.2.3. Urban drainage system

Records from the municipal drainage system office indicating whether properties are connected to combined or separate sewer systems. Citywide, approximately 2% of all properties are served by combined sewers, concentrated in older districts. Among the flood reports in our dataset, however, 36% were located in combined-sewer areas (Table 3). This distinction is critical for evaluating system performance under different rainfall intensities.

In Sweden, urban drainage systems are generally expected to meet a functional requirement corresponding to approximately a 10-year return period, under which flooding inside buildings should not occur (Svenskt Vatten, 2016). In practice, urban drainage systems do not have a uniform design criterion. Older combined sewer systems are often originally designed for lower return periods (approximately 2–5 years), while their performance may be modified over time through upgrades and operational measures. As a result, observed system performance may differ from nominal design criterion.

2.2.4. Rainfall data

Local rainfall measurements with high temporal resolution were collected from tipping-bucket gauges operated by WWD at three fixed locations across Trelleborg (West, Central, and East), as shown in Fig. 1, for the period 2012–2023. These gauges provide spatial coverage across the study area and were used to characterise rainfall conditions associated with reported flood events. For the period 2006–2012, high temporal resolution rainfall data were stored in offline logger systems and were not directly accessible in digital format. Access to these data required specific requests and manual extraction from archived records; therefore, data were retrieved only for selected dates corresponding to major flood events identified from the flood report dataset.

To assess whether the gauges recorded significantly different rainfall during flood events, maximum rainfall intensities (15-, 30-, and 60-minute) and total event volumes were compared across the three stations for events where complete data were available. No statistically significant differences were found between gauges (Kruskal–Wallis test, all p-values were above 0.28), indicating that rainfall measurements were broadly consistent across the study area. Based on this consistency, the maximum recorded rainfall intensity among the gauges was used to represent each event. Besides duration-based intensity, event intensity was also calculated as the total rainfall amount divided by the event duration, providing a measure of average rainfall intensity over the event. This approach ensures that localized high-intensity rainfall is not underestimated and avoids potential data loss due to occasional gauge malfunctions or missing records.

3. Methodology

The methodological framework comprised three components Fig. 2: (1) data acquisition and preprocessing, including the integration and cleaning of multiple data sources and the preparation of potential drivers to ensure analytical consistency and reduce noise in the dataset; (2) univariate analysis of these drivers to assess their individual influence on basement flooding reports, and (3)

Table 3
Distribution of flood reports by sewer system type in the city of Trelleborg during 2006–2023.

Sewer Type	Count	Percentage
Separate sewer system	354	64%
Combined sewer system	198	36%

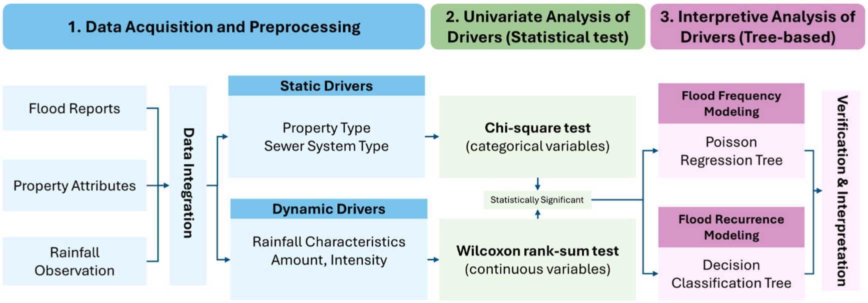

Fig. 2. Flowchart of the methodology.

interpretive analysis, in which all drivers were considered simultaneously to identify combined effects and reveal configurations associated with critical increases in basement flooding frequency.

3.1. *Data acquisition and preprocessing*

Flood reports were retrieved from the WWD archives, yielding 591 cases after removing duplicate reports based on matching the property designation (fastighetsbeteckning) and flooding date. Flood reports were compiled by the lead author through internal access to WWD's archival system. All data processing was conducted in accordance with the department's confidentiality agreements governing personal property records. Each flood report was manually verified and categorized to ensure integrity and consistency across data sources. To focus exclusively on rainfall-induced flooding, each event was cross-referenced with rainfall data from WWD's municipal rain gauges. Events with fewer than three flooded properties were excluded to minimize noise from localized household issues such as pipe defects or pump failures. Three or more affected properties were considered more indicative of rainfall-driven system overload.

Two types of potential drivers were considered in this study: static drivers, represented by property attributes, and dynamic drivers, represented by rainfall-event characteristics. Based on our previous analyses, property type and sewer system configuration were identified as significant determinants of basement flooding (Mobini et al., 2021). Therefore, among the various property attributes available, two were selected for this study: building type and sewer system connection type (combined or separated). These attributes were linked to individual flood reports using the property designation associated with each reported flooded property (Mobini et al., 2021). Rainfall data described in Section 2.2 were used for the analysis. For rainfall analysis, events were identified on days with reported flooding, resulting in a total of 14 events during the analysis period (2006–2023). Rainfall intensity (mm/h) was then calculated over 15-, 30-, and 60-minute accumulation periods, as well as for the overall event intensity, defined as the total rainfall amount divided by event duration. These time intervals were chosen to reflect typical urban drainage response times and to align with established design practice (CIWEM, 2016; Cristiano et al., 2019).

The above data sources (flood reports, property attributes, and rainfall observations) were mapped into a final dataset structured at the flooded property level, with each observation containing the flooded property, its static property characteristics (i.e., property type, sewer system type), and the rainfall amount and event characteristics associated with that property on the date of flooding. The dataset was structured at the property level to examine variation among affected properties. As the dataset includes only properties that experienced at least one flooding event, the analysis does not address the probability of flooding across all properties. Instead, two outcome representations were used depending on the analytical method: (i) flood recurrence, defined as a binary variable distinguishing properties flooded once from those experiencing recurrent flooding (two or more flood events at the same property during the study period); and (ii) flood frequency, defined as the number of flood events recorded per affected property. The choice between these representations depends on the statistical method applied and is described in the corresponding sections below.

3.2. *Univariate analysis of potential drivers*

To evaluate the individual influence of each potential driver, univariate analyses were conducted for both static and dynamic drivers, Fig. 2. The choice of statistical method depended on the type of variable under consideration, that is, whether the variable was categorical or continuous.

For static categorical drivers (e.g., property type and sewer system configuration), chi-square tests were used to assess whether flood frequency (number of flooding events per property, grouped into categories) differed significantly across groups. The strength of these associations was quantified using Cramér's V (Cramér, 1999). The results include the likelihood ratio χ^2 statistic, which measures the deviation between observed and expected frequencies under the assumption of independence, the degrees of freedom (df), which reflect the number of independent comparisons in the contingency table, and the associated p-value, which represents the probability of observing a result at least as extreme as the observed value under the null hypothesis. Statistical significance was evaluated at $\alpha = 0.05$. Where expected cell counts were low (less than 5), p-values were estimated using a Monte Carlo simulation approach with $B = 10{,}000$ replicates to ensure robust inference.

For dynamic drivers (i.e., rainfall event characteristics), flood recurrence was analysed in binary form, distinguishing properties flooded once from those flooded on multiple occasions. Differences in rainfall characteristics between these two groups were evaluated using the Wilcoxon rank-sum test (Wilcoxon, 1945). The results present Wilcoxon values as the test statistic, based on the relative ranking of observations in the two groups. Together with the p-value, it indicates whether the observed difference between groups is likely due to chance. Statistical significance was evaluated at $\alpha = 0.05$.

3.3. Interpretive analysis of potential drivers

To further investigate flood frequency among affected properties and to identify potential critical thresholds among the considered drivers, tree-based methods were employed, Fig. 2. Whereas the univariate analyses in the previous step evaluated the influence of each potential driver individually, the tree-based analysis in this section incorporated all selected drivers. This approach enabled the assessment of their combined effects on flood impacts and provided an exploratory basis for identifying interactions and non-linear threshold responses among rainfall characteristics and property-level attributes.

Two complementary tree-based methods were adopted to provide mutual validation of the results. First, a Poisson regression tree was used to analyse flood frequency, defined as the number of flood events recorded per property. Second, a classification tree was used to analyse flood recurrence, defined as whether a property experienced flooding once or on two or more occasions. Both approaches are based on the Classification and Regression Trees (CART) framework (Breiman et al., 1984), a recursive partitioning method that divides the dataset into increasingly homogeneous subgroups according to the predictor variables.

In this framework, the algorithm repeatedly selects the predictor and split point that best separate the response variable according to an optimization criterion. For the classification tree, splits are chosen to improve class purity, that is, to better distinguish between one-time and recurrently flooded properties. For the Poisson regression tree, splits are selected to improve the fit to the count response, thereby identifying subgroups with different expected numbers of flood events. The resulting tree structure provides an interpretable representation of how combinations of predictors are associated with flood outcomes (Breiman et al., 1984; Spekkers et al., 2014) and allows the identification of threshold effects and interactions that may not be evident in univariate analyses.

To reduce overfitting, the initial trees were pruned using standard model selection principles within the statistical learning framework(Hastie et al., 2009) . Model performance was evaluated using ten-fold cross-validation. In addition, model robustness was evaluated using a train/test split approach, where the dataset was randomly divided into training and test subsets. The models were trained on the training set and evaluated on independent test data. For the classification tree, performance was assessed using a confusion matrix and overall accuracy, while for the Poisson regression tree, performance was evaluated using mean squared error (MSE). These measures provide an indication of the model's ability to generalize beyond the training data. The final models were used in an exploratory manner to identify influential thresholds and interactions among rainfall intensity, sewer system type, and property type in explaining variation in flood recurrence and flood frequency.

In practice, each tree was first grown to its full size and subsequently pruned based on cross-validated prediction error to determine the optimal model complexity. The final trees presented in the Results section correspond to the pruned models that achieved a balance between predictive performance and interpretability. Additional splits in the fully grown trees that did not significantly improve model performance were removed during pruning, ensuring that the final models reflect robust and generalizable patterns rather than noise.

4. Results

A total of 591 flood reports in Trelleborg between 2006 and 2023 were analysed to assess how rainfall characteristics, property type and sewer system configuration relate to flood frequency and recurrence. Flood reports were unevenly distributed over time, with several years showing substantially higher numbers of reported cases.

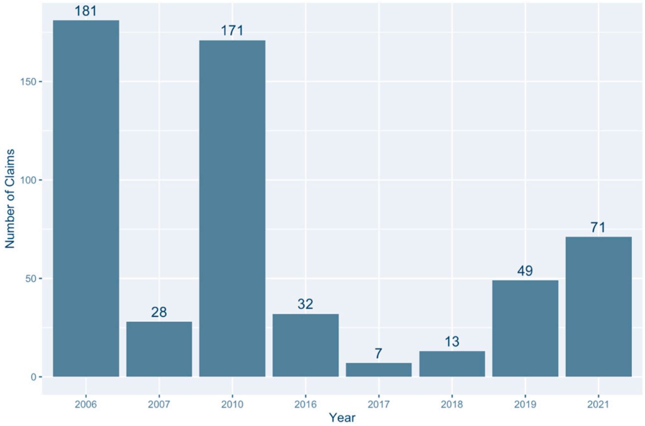

Fig. 3. Annual distribution of flood reports in Trelleborg (2006–2023).

4.1. Overview of flood reports

The temporal distribution of flood reports (Fig. 3) reveals three pronounced peaks in 2006, 2010, and 2021, which together account for approximately 75% of all documented cases. The most severe year was 2006, with 181 reports (34%), followed by 2010 (171 reports, 29%) and 2021 (71 reports, 12%). In contrast, 2017 and 2018 recorded the fewest reports, with only 7 and 13 cases, respectively.

Overall, flood reports were concentrated in a small number of years rather than exhibiting a gradual long-term increase over the study period. The dominance of a few high-impact years limits the ability to robustly assess long-term trends in flood reporting using this dataset. The pronounced peaks indicate periods of substantially elevated flood reporting, consistent with episodic exceedance of system capacity during intense rainfall events. Not all rainfall events resulted in comparable flood impacts, indicating that reported flooding is highly sensitive to specific combinations of rainfall intensity and duration. For example, some events with relatively high short-duration intensities but low total rainfall produced only a limited number of reported cases. This helps explain why only a small number of years exhibit pronounced peaks in flood reports, while other years with rainfall events show substantially fewer incidents. The 2017 event illustrates this pattern, as it had relatively high short-duration rainfall intensities but resulted in only a small number of reported flood cases. This indicates that rainfall intensity alone does not fully explain flood impacts, which likely depend on a combination of factors, including rainfall characteristics, and local infrastructure conditions.

Spatially, the majority of flood reports were concentrated in the central and eastern parts of the city (Fig. 4). These patterns indicate a strong spatial association between flood reporting and areas served by the combined sewer network. Despite its limited spatial extent, the results show that the combined sewer zone exhibits the highest density of flood reports, with several hexagon cells recording more than 50 reports. This concentration indicates that properties connected to the combined system experienced disproportionately frequent flooding events under certain conditions. In contrast, flood reports in areas served by separated sewer systems were more spatially dispersed and occurred less frequently.

Taken together, the temporal and spatial patterns demonstrate that flood reporting is unevenly distributed across the city and is associated with both infrastructure type and location. These patterns provide the basis for the subsequent analyses examining how rainfall characteristics, sewer system configuration, and property type relate to flood frequency and recurrence.

4.2. Characteristics of potential influencing drivers

4.2.1. Static drivers: Property type and sewer system type

Flood reports were unevenly distributed across property categories (Fig. 5). Houses accounted for a consistently higher proportion of reported flooding events compared with other property types. However, flood reports were recorded for all property categories, indicating that property type alone does not fully explain observed flooding patterns.

Fig. 5 illustrates the joint distribution of flooded properties by property type and sewer system configuration. Flooded properties were more frequently reported in areas connected to separate sewer systems, particularly among houses and apartments. In contrast, flooding in combined sewer areas was more commonly associated with apartments, consistent with the concentration of multi-dwelling buildings in older urban districts. Business properties were absent from the combined sewer category, indicating that commercial areas are primarily located within newer developments served by separate systems.

4.2.2. Dynamic driver: Rainfall

Fourteen rainfall events were identified based on reported flood dates. Fig. 6 shows a general correspondence between higher rainfall amount and increased numbers of reported flooded properties, although this relationship is not consistent across all events.

Table 4 summarizes rainfall conditions on reported damage dates, including total rainfall amount, event duration, and maximum

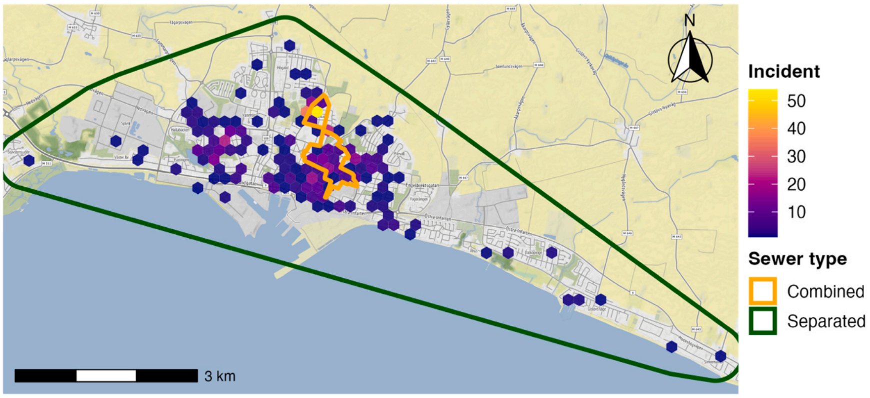

Fig. 4. Spatial distribution of flood damage reports in Trelleborg using hexagonal binning. Orange lines outline areas predominantly served by combined sewer systems; green lines represent zones served by separated sewer systems.

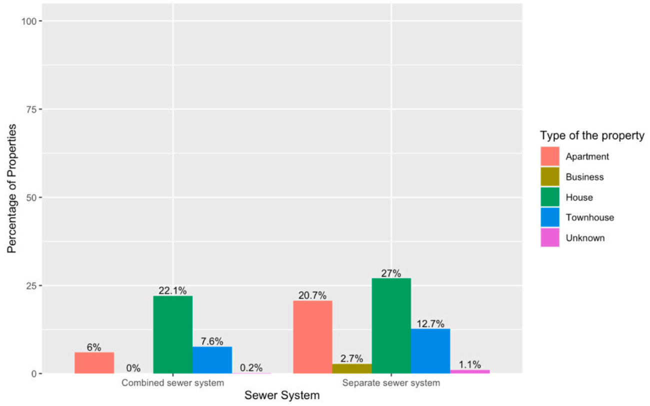

Fig. 5. Percentage of flood reports in each property category, grouped by sewer system type (combined and separated), Trelleborg (2006–2023).

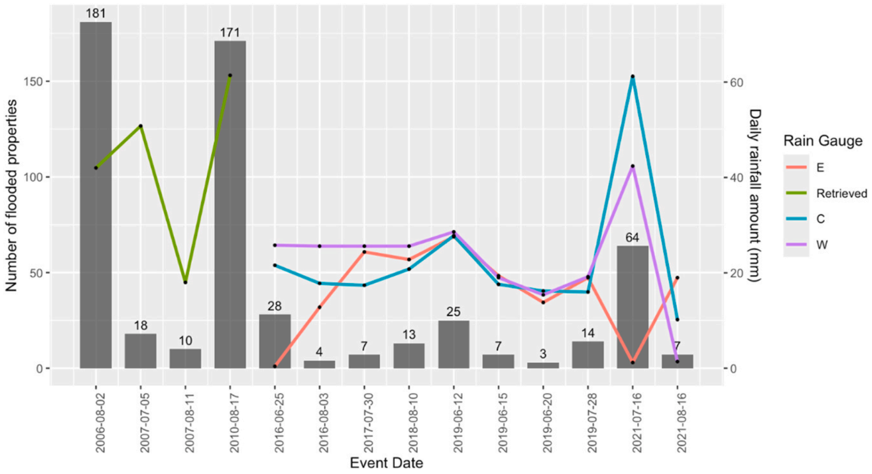

Fig. 6. Daily rainfall amount and number of flooded properties across 14 major events in Trelleborg (2006–2023).

Table 4
Summary of documented flood events and associated rainfall characteristics (2006–2023).

	Flood Event Date	Number of flood reports	Total rainfall amount (mm)	Rainfall event duration (min)	Event intensity (mm/h)	Max intensity (15 min) (mm/h)	Max intensity (30 min) (mm/h)	Max intensity (60 min) (mm/h)
1	2006–08–02	181	26	27 min	52.0	19.8	10.8	5.4
2	2007–07–05	18	46	878 min	3.2	10.2	10.2	9.0
3	2007–08–11	10	10	27 min	20.0	36.6	19.8	9.6
4	2010–08–17	171	56	336 min	10.0	33.0	25.8	21.6
5	2016–06–25	28	24	81 min	17.8	57.6	40.2	22.8
6	2016–08–03	4	23	107 min	12.9	45.0	34.2	22.2
7	2017–07–30	7	11	17 min	39.3	42.6	22.2	10.8
8	2018–08–10	13	25	82 min	18.2	67.2	42.6	23.4
9	2019–06–12	25	23	125 min	11.1	71.4	37.8	20.4
10	2019–06–15	7	18	71 min	15.3	48.0	30.6	17.4
11	2019–06–20	3	16	41 min	23.5	42.6	29.4	16.2
12	2019–07–28	14	19	67 min	17.0	67.8	36.0	18.6
13	2021–07–16	64	53	103 min	30.8	65.4	51.6	42.6
14	2021–08–16	7	1	66 min	0.9	2.4	1.2	1.2

recorded rainfall intensity (15-, 30-, and 60-minute) over different time windows. For example, the event on 2 August 2006 generated 181 flood reports following 26 mm of rainfall over 27 min, whereas the event on 5 July 2007 resulted in only 18 reports despite a higher total rainfall amount of 46 mm distributed over approximately 15 h. Similar patterns are observed for high-intensity events such as 2006 and 2010, where elevated rainfall intensities were associated with large numbers of reported flooded properties (181 and

171 reports, respectively).

Approximately 45% of all reported flood cases occurred during events where 60-minute rainfall intensities were below the nominal 10-year design criterion. Swedish guidelines specify a functional requirement corresponding to approximately a 10-year return period (Svenskt Vatten, 2016), but the effective performance of urban drainage systems depends on system configuration and operational measures. Older combined sewer systems are often originally designed for lower return periods (approximately 2–5 years), but in practice their performance may be enhanced through additional storage volumes, retention basins, and system upgrades implemented by municipalities. As a result, flooding observed below the nominal 10-year rainfall threshold does not necessarily indicate failure relative to design intent but rather reflects the interaction between rainfall characteristics and system capacity.

4.3. Univariate analysis of drivers

4.3.1. Static drivers of basement flooding

Chi-square analysis showed that sewer system type was significantly associated with flood frequency, grouped into categories of number of events per property (Likelihood Ratio $\chi^2 = 14.555$, df = 1, $p = 1.36 \times 10^{-4}$), although the effect size was modest (Cramer's V = 0.214). In contrast, property type showed a weaker and less consistent association with flood frequency. Sewer system type and property type were treated as fixed property-level attributes linked to each reported flood case. Results are summarized in Table 5.

These results suggest that while static infrastructure attributes such as sewer system type and property type are associated with flood frequency, their individual explanatory power is limited. This analysis was based on the observed dataset, where each property's attributes were linked directly to reported flood incidents. This is consistent with the descriptive patterns observed in Section 4.2.2, where houses and areas connected to combined sewer systems showed a higher frequency of flooding reports. However, these patterns do not imply strong predictive capacity on their own, indicating that additional factors, particularly rainfall characteristics, play a dominant role in determining flood frequency.

4.3.2. Dynamic drivers of basement flooding

Rainfall intensity differed significantly between properties flooded once and those experiencing recurrent flooding (i.e., two or more events) across all analysed durations.

The results in Table 6 show that rainfall intensities at 15-, 30-, and 60-minute durations differ significantly between one-time and recurrent flooding events. The pronounced effect at the 60-minute duration suggests that flooding is most sensitive to sub-hourly to hourly rainfall intensities. In contrast, event-based comparisons presented in Section 4.2.2 show that higher total rainfall amounts do not necessarily correspond to higher numbers of flood reports, as illustrated by the comparison between events such as 2 August 2006 and 5 July 2007, where higher total rainfall did not correspond to higher numbers of flood reports when distributed over longer durations. This indicates that rainfall intensity, particularly over shorter durations, plays a more critical role than total event volume in influencing whether properties experience flooding once or recurrently. Together, these results show that while Table 6 demonstrates a strong statistical relationship between rainfall intensity and flood recurrence, total event volume does not show a comparable relationship, indicating that intensity is the more critical factor in explaining flood outcomes.

4.4. Interpretive analysis of drivers

4.4.1. Poisson regression tree

The tree structure shown in Fig. 7 was derived using the methodology described in Section 3.3. The pruned Poisson regression tree (Fig. 7) identified 60-minute rainfall intensity as the primary splitting variable associated with flood frequency. The main patterns can be summarized as follows: (i) a threshold at 21 mm/h separates lower and higher predicted flood frequencies; (ii) properties connected to combined sewer systems below this threshold showed the highest predicted flood frequency; and (iii) at higher rainfall intensities, flooding was more often associated with single events rather than recurrent flooding.

The first split occurred at 21 mm/h, separating properties with higher and lower predicted flood frequencies in Trelleborg (Fig. 7). Properties connected to combined sewer systems and exposed to 60-minute rainfall intensities below this threshold formed the group with the highest predicted flood frequency, with a predicted mean of 5.2 flood events across 13 properties (8% of the dataset). In contrast, properties connected to separated sewer systems below the same threshold had a predicted mean of 2.3 flood events (12 properties, 7%).

These threshold values represent data-driven split points identified by the regression tree, which partition the dataset into groups with different predicted flood frequencies. They are selected by the algorithm as the values that best separate the data into subgroups with distinct flood event rates. They can be interpreted as empirical rainfall thresholds reflecting observed system performance, indicating intensity levels at which the frequency and recurrence of basement flooding change.

Above the 21 mm/h threshold, the tree further divided properties according to flood event intensity. Properties exposed to both

Table 5
Results of Chi-square test and Cramers' V for property type and sewer system type. Statistical significance was assessed at $\alpha = 0.05$.

	χ^2	df	p-value	Cramer's V
Sewer type	14.555	1	1.36×10^{-4}	0.214
Property type	10.054	4	0.0395	0.171

Table 6
Wilcoxon rank-sum test results comparing rainfall intensities between properties flooded once and those experiencing recurrent flooding. Statistical significance was assessed at $\alpha = 0.05$.

Variable	Wilcoxon W	p-value	Interpretation
15-min intensity	16,474.5	2.01×10^{-8}	Significant
30-min intensity	18,147.0	9.35×10^{-15}	Highly significant
60-min intensity	19,793.5	2.2×10^{-16}	Extremely significant
Event intensity	17,075.5	2.55×10^{-10}	Highly significant

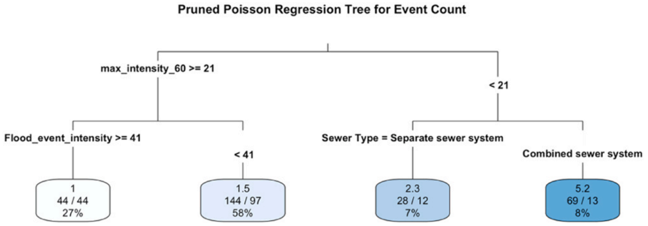

Fig. 7. Pruned Poisson regression tree predicting the mean number of flood events per affected property. The tree is based on splits in 60-minute rainfall intensity (mm/h), flood event intensity (mm/h), and sewer system type. Threshold values (e.g., 21 mm/h) indicate rainfall intensities associated with changes in predicted flood frequency. Each terminal node displays the predicted mean number of flood events per property, the total number of events and number of properties (events/properties), and the percentage of the total dataset. For example, properties connected to separated sewer systems and exposed to 60-minute rainfall intensities below 21 mm/h have a predicted mean of 2.3 flood events based on 12 properties (7% of the dataset).

high sustained and flood event intensity (≥ 41.4 mm/h, rounded in the tree) had a predicted mean of 1.0 flood event (44 properties), whereas those exposed to lower flood event intensity had a predicted mean of 1.5 flood events (144 properties). The threshold of 41.4 mm/h represents a data-driven split point selected by the algorithm to distinguish between properties experiencing predominantly single flood events and those with a higher likelihood of recurrent flooding. These results indicate that properties associated with the highest rainfall intensities were primarily linked to single flood events rather than recurrent flooding.

Overall, the regression tree indicates that sustained rainfall accumulation over 60 min is more strongly associated with predicted flood frequency than flood event intensity. This likely reflects the response of the drainage system, where sustained rainfall over longer durations leads to system surcharge and increases the tendency for recurrent flooding at the same property. In contrast, short-duration rainfall intensities (e.g., 15-minute) are more often associated with single flood events that do not result in recurrent flooding at the same property. The results also highlight the influence of drainage infrastructure, with combined sewer systems associated with higher predicted flood frequency than separated systems under comparable rainfall conditions. However, flooding was also observed in separated systems under moderate to high rainfall intensities, indicating that these systems do not fully eliminate flood risk.

4.4.2. Classification decision tree

The classification tree distinguishes between properties flooded once and those experiencing recurrent flooding. This classification forms the basis for deriving conclusions about flood recurrence, by identifying combinations of rainfall intensity and property characteristics associated with repeated flooding at the property level. Here, recurrent flooding refers to properties that appeared in the flood report dataset on two or more separate dates during the study period.

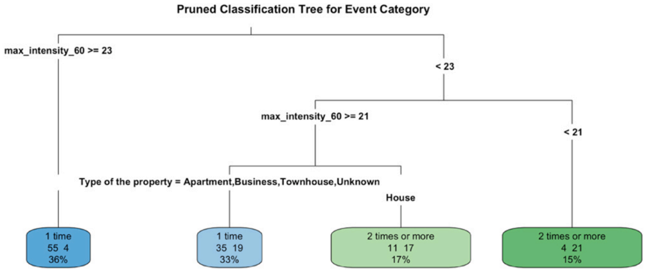

Fig. 8. Pruned classification tree distinguishing properties flooded once versus those experiencing recurrent flooding (≥2 events), based on 60-minute rainfall intensity (mm/h) and property type. Each terminal node shows: (i) the predicted class ("1 time" or "2 times or more"), (ii) the number of properties in each class (flooded once and recurrent flooding, respectively), and (iii) the percentage of the total dataset represented by the node. For example, for houses exposed to 60-minute rainfall intensities between 21 and 23 mm/h, the node shows 11 properties flooded once and 17 properties experiencing recurrent flooding (total n = 28), corresponding to 17% of the dataset. Since recurrent flooding is more frequent in this node, it is classified as "2 times or more.".

Fig. 8 shows the results of the pruned classification tree. The tree partitions properties based on 60-minute rainfall intensity and property type. The root node split occurred at 23 mm/h, above which properties were predominantly associated with single flood events. Below this threshold, a secondary split was identified at 21 mm/h, followed by property type as a key differentiator.

In the 21–23 mm/h rain intensity range, houses showed a higher occurrence of recurrent flooding, with 17 properties experiencing recurrent flooding compared to 11 properties flooded once. This indicates an interaction between rainfall intensity and property form, where property characteristics modify flood outcomes under comparable rainfall conditions. In contrast, apartments, townhouses, and commercial buildings within the same range were more often associated with single flood events, with 35 properties flooded once and 19 experiencing recurrent flooding. At intensities below 21 mm/h, recurrent flooding was also more common, with 21 properties experiencing recurrent flooding compared to 4 flooded once, indicating vulnerability even under moderate rainfall conditions.

The model achieved an overall accuracy of 76.5%, with sensitivity and specificity both around 0.76, indicating balanced performance in distinguishing single from recurrent events. The exclusion of sewer system type from the classification tree suggests that, while sewer configuration influences overall flood frequency, recurrence is more strongly driven by rainfall intensity and property type.

5. Discussion

The identification of empirically derived rainfall thresholds has important implications for urban flood risk management. Both tree-based approaches consistently identified 60-minute rainfall intensity as the dominant rainfall driver of basement flooding in Trelleborg. All rainfall durations (15-, 30-, and 60-minute intensities, as well as event intensity) were included as candidate predictors in the tree-based models, and 60-minute intensity was consistently selected as the primary splitting variable. This indicates that, among the tested rainfall metrics, 60-minute intensity provided the greatest explanatory power in partitioning the dataset and distinguishing between different flood outcomes. This convergence strengthens the evidence that the 60-minute timescale represents a critical duration and threshold for basement flooding in the city. This finding is also consistent with previous studies that emphasize the role of 60-minute rainfall accumulation in generating urban flood damage and insurance losses (Blumenthal and Nyberg, 2019). Importantly, basement flooding was frequently observed at intensities below the nominal 10-year, 60-minute design criterion, indicating that actual system performance under real conditions may differ from nominal design criterion based on return periods (Svenskt Vatten, 2016). These results highlight the need to supplement hydraulic design values with thresholds derived from observed performance.

Although separated sewers dominate the network, flooding remained common under moderate rainfall, indicating that separation alone does not eliminate risk. Combined systems, however, were more susceptible, with recurrent flooding happening at lower rainfall intensities. These findings point to the importance of addressing legacy infrastructure, routine maintenance, and the cumulative impact of urban densification on drainage performance. The result further suggest that separated systems remain vulnerable when affected by infiltration, maintenance deficits, or increased imperviousness.

Beyond sewer type, our results demonstrate that flood recurrence cannot be explained by any factor alone but emerges from interactions between dynamic drivers (rainfall exposure) and static drivers (property characteristics). While sewer configuration was an important determinant of overall flood frequency, property type played a role in explaining recurrence, confirming that structural form modifies vulnerability under similar rainfall conditions. Understanding these interactions, and addressing them through adaptation measures, requires interdisciplinary expertise spanning hydrology, urban drainage engineering, and building design.

The use of event count as a response variable assumes consistent and complete reporting; however, underreporting of flood claims, particularly for minor or uninsured events, may introduce bias. The model further treats all observations as temporally and spatially independent, without accounting for infrastructure changes, land-use development, or spatial autocorrelation that may influence flood clustering. Decision trees are also sensitive to small changes in the input data. To address the potential instability of tree-based models, we evaluated the robustness of the results using a train/test split procedure. The dataset was randomly divided into equal halves for training and testing. The tree models were trained using 10-fold cross-validation to determine the optimal pruning level and subsequently evaluated on the independent test set.

The classification tree showed a consistent structure between the training and test sets, with the same sequence of splitting variables and similar threshold values. Model performance on the test set was high, with an accuracy of 93.4%, sensitivity of 100%, and specificity of 77.6%. Similarly, the Poisson regression tree identified the same dominant predictors and showed stable performance (test MSE = 0.88).

Additional analysis using the full dataset with cross-validation confirmed consistent variable importance rankings, splitting variables, and threshold values. These results indicate that the main patterns identified by the tree-based models are robust, although some variability in exact threshold values remains.

Finally, while tree structures reveal key interactions, they may oversimplify complex hydrological processes that could potentially represented by ensemble or physically based models.

Topographic factors such as slope and elevation were not explicitly included in this analysis, as the study focuses on sewer surcharge-driven basement flooding rather than surface runoff processes. In this context, topographic effects are partly reflected in the design and operation of the drainage network. The analysis is based solely on reported flood incidents and does not include information on properties that did not experience flooding during rainfall events. As a result, the absence of reports cannot be interpreted as absence of flooding, which limits the possibility of constructing a binary flooded/not flooded dataset or analysing near-miss events. This also limits the ability to identify potential missed or near-miss events, such as high-intensity rainfall events that did not result in reported flooding.

Despite these limitations, the robustness of our conclusions is strengthened by applying a comprehensive analytical framework that combined univariate tests with two complementary tree-based models. Both the Poisson regression tree and the classification tree consistently identified 60-minute rainfall intensity as the critical driver of basement flooding, while also highlighting the modifying role of sewer system and property type. This convergence across approaches increases confidence in the identified thresholds and interactions and therefore provides useful insights for urban flood risk management and adaptation planning.

Nature-based solutions such as bioswales, retention basins, and permeable pavements offer promising runoff mitigation, but their long-term effectiveness depends on adequate maintenance (Bahrami et al., 2024). Hybrid strategies that combine engineered drainage upgrades with distributed green infrastructure are therefore essential.

At the policy level, Sweden's 2024 national climate adaptation strategy calls for stronger municipal mandates and legal clarity in stormwater governance (Swedish Government, 2024). At the European scale, the EU Floods Directive (2007/60/EC) and the EU Strategy on Adaptation to Climate Change (European Commission, 2021) emphasize the integration of climate resilience into local planning. Threshold-based approaches, as demonstrated here, can complement these frameworks by providing transparent, site-specific benchmarks for risk assessment.

Finally, integrating empirical thresholds with real-time rainfall monitoring and short-term forecasting could strengthen early-warning systems. Such operational use would enable municipalities to activate protective measures, such as temporary storage or backflow prevention, when thresholds are exceeded. In this way, threshold-based analysis can bridge the gap between design practice, climate adaptation policy, and on-the-ground resilience planning.

6. Conclusion

Analysis of 17 years of flood reports in Trelleborg identified a critical 60-minute rainfall intensity threshold of approximately 21–23 mm/h, above which both flood frequency and recurrence increased sharply. Importantly, many flood events were observed below the rainfall levels corresponding to the functional requirement of approximately a 10-year return period used in Swedish practice, indicating that flooding frequently occurred under rainfall conditions below nominal design criterion.

Decision-tree modelling showed that rainfall intensity was the dominant dynamic driver of flooding, while static attributes such as sewer system type and property characteristics further conditioned outcomes. Combined sewer systems and older detached dwellings (built before 1970) exhibited disproportionately high recurrence, underscoring the interaction between hydrometeorological drivers and legacy infrastructure.

Methodologically, this study demonstrates how empirical, threshold-based analysis using decision-tree models can complement hydraulic simulations by capturing real system behaviour under observed rainfall. The approach is transferable to other urban contexts with post-event data, offering a transparent way to identify locally relevant thresholds and interactions.

Future research should extend this framework by incorporating fine-scale topography, land use, and building age, while also addressing spatial dependence and reporting biases. Integration with real-time monitoring and forecasting would further enhance its operational value. In doing so, empirical thresholds can help align design criterion with observed performance and support the development of adaptive, data-informed strategies for urban flood resilience.

CRediT authorship contribution statement

Lars Nyberg: Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition. **Shifteh Mobini:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Yiheng Du:** Writing – review & editing, Visualization, Methodology, Formal analysis, Conceptualization. **Behnaz Pirzamanbein:** Writing – review & editing, Visualization, Software, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Funding

This study was funded by the Swedish Research Council for Sustainable Development FORMAS under grant number 2021–02380. Pirzamanbin received financial support from Trelleborg Municipality under the Kompetensfonden Trelleborg 2024 for this research.

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.

Acknowledgments

We sincerely thank Water and Wastewater Department at Trelleborg Municipality for providing access to the data, and for GIS support. Their cooperation and contributions have been invaluable to this research.

Data Availability

The rainfall data is available but the flooded properties are confidential.

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