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Spatial variability of combined sewer overflow responses to rainfall events in Brussels, Belgium

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Abstract

Brussels' complex sewer network, with around hundred regularly-spilling combined sewer overflows (CSOs), contributes significantly to its surface water courses pollution, threatening compliance with the European Water Framework and the new Urban Wastewater Treatment Directives. Identifying which specific rainfall events trigger different CSO occurrences is essential for implementing solutions like real-time control. However, many studies on CSOs rely on sparse or low-resolution rainfall data. This study investigates CSO occurrences for rainfall events in 2023 and 2024 using high-resolution rainfall data in the Brussels Capital Region, specifically radar-based precipitation with 1 km spatial and 5-minute temporal resolution. Nine overflow locations were selected, which discharge into two different surface water bodies at varying frequencies. We quantify overflow frequency and duration, and link these to rainfall event metrics. Future work will include more overflow locations, and will aim at identifying specific rainfall patterns that disproportionately contribute to CSO at the different locations.

Highlights

- Use of high-resolution rainfall (1 km resolution radar product and 16 rain gauges) and combined sewer overflow monitoring data.
- Insights in CSO frequency and duration and nine different overflow sites.
- Exploratory analysis suggests rain gauge rainfall depth correlates more strongly with CSO durations than radar-derived rainfall depth aggregated by subcatchment.

Introduction

Urban drainage systems face growing challenges due to aging infrastructure, urban population growth, impermeabilization, and intensified rainfall due to climate change (Perry et al., 2024). To prevent overloading wastewater treatment plants and mitigate flooding, combined sewer overflows (CSOs) discharge untreated excess water into nearby water bodies, degrading water quality (Hvitved-Jacobsen, 1982; Petrie, 2021).

Efficient implementation of solutions to mitigate CSO's, such as real-time control, requires a detailed understanding of the urban drainage system. However, its inherent complexity makes robust modelling challenging (Salvadore et al., 2015). Moreover, the accuracy of models depends heavily on the quality of input data, especially rainfall (Cristiano et al., 2017).

Many studies on CSOs rely on sparse or low-resolution rainfall data (Bizer & Kirchhoff, 2022; Gogien et al., 2022; Jean et al., 2018; Mailhot et al., 2015; Rodriguez et al., 2023), yet rainfall is variable in space and time, particularly during intense events (Maier et al., 2020). Moreover, cities' heterogeneous land use and non-linear sewer systems produce an even more variable spatial response. Understanding which specific rainfall patterns trigger which CSOs is key for efficient real-time control (Piadeh et al., 2022).

In this study we examine which CSO occurrence patterns occur in response to rainfall events in Brussels, Belgium. More specifically, we look at the importance of including rainfall spatial variability, and how to compute the best rainfall time series.

Case study

Our study focuses on the Brussels-Capital Region in Belgium, a highly urbanized area of 161 km² with a population of 1.25 million in 2024. Brussels has a combined sewer system that transports both wastewater and stormwater to two wastewater treatment plants, where a total annual volume of 150 million cubic meters is treated (Hydria, 2023).

Brussels' complex and aging sewer network spans around 2000 kilometres and includes multiple stormwater basins. The city's varied topography, with over 100 meters of elevation difference and numerous valleys, further complicates sewer flow dynamics. Around 100 CSO locations discharge into surface waters, contributing to about 45% of the organic matter in these waters and threatening the 'good ecological status' required by the European Water Framework Directive (Bruxelles Environnement, 2023). Reducing CSOs is a priority in the regional Water Management Plan 2022-2027, and Brussels must comply with the new EU Directive (EU) 2024/3019, which requires taking measures to limit stormwater overflow pollution to 2% of the annual wastewater load during dry weather flow, a challenging target.

The Senne River, Brussels' main river, receives most CSO discharges. The Woluwe and Linkebeek rivers also receive CSOs, though to a lesser extent. Smaller rivers like the Molenbeek, Ukkelbeek, and Kerkebeek are fully integrated into the sewer system. The Brussels Canal acts as a water buffer for the Senne during high water and receives CSOs during extreme events. A map of the case study area, showing the watercourses, subcatchments, and CSO locations, is provided in Figure 1.

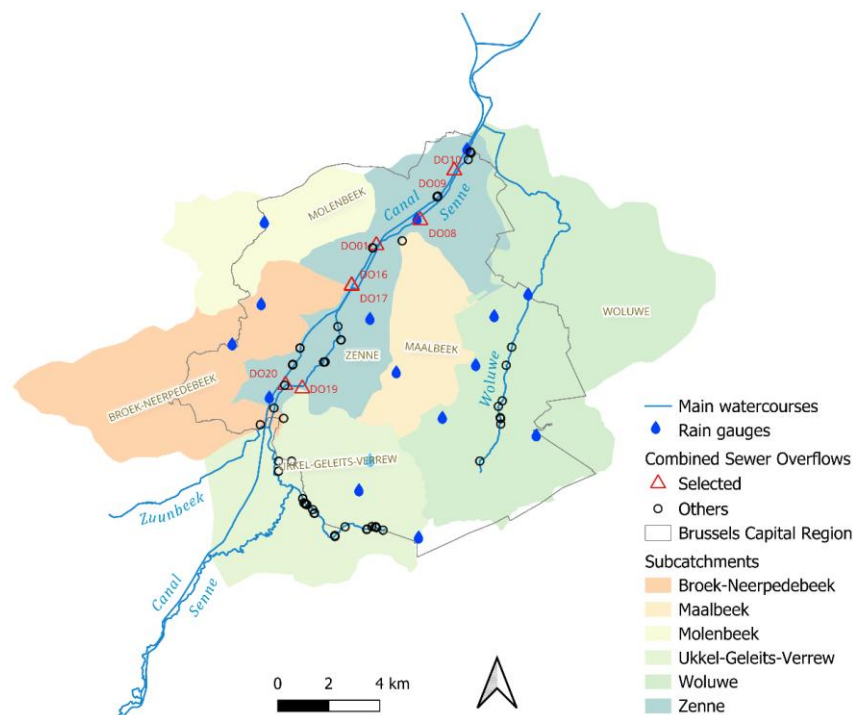


Figure 1. Map of the case study, showing the watercourses, the subcatchments and the locations of the combined sewer overflows.

Methodology

Sewer overflow data

The Brussels sewer network is equipped with sensors that measure water levels and flows in collectors, storm basins and at overflow locations, as part of the Flowbru monitoring network (available at www.flowbru.be). All data is recorded at intervals of at least five minutes.

Nine overflow locations were selected for this analysis based on the availability of continuous sensor records for most of 2023–2024 and on expert knowledge on overflow occurrence.

Sensor data was validated by automatically flagging suspicious, inconsistent, or missing values, which were then reviewed through a visual inspection. When appropriate, flagged values were corrected, replaced or filled. A binary overflow / no overflow time series, with a resolution of 5 minutes, was derived for each overflow location. Where multiple sensor datasets are available for a single site, they were combined to maximize completeness.

The selected sites are given in Table 1, along with the percentage of missing data in the final binary overflow time series. Their locations are indicated with red triangles in Figure 1.

Table 1. Selected overflow locations for the analysis, with percentage of missing data.

Location	Missing data
DO01 – Molenbeek Senne	12.1%
DO02 – Molenbeek Canal	10.8%
DO08 – Nouveau Maelbeek	0.3%
DO09 – Marly Senne	0.7%
DO16 – Paruck Senne	3.5%
DO17 – Paruck Canal	13.6%
DO19 – Charroi	0.3%
DO20 – Industriel	0.3%
DO29 – STEP Nord	0.3%

Precipitation data

As precipitation data, we use both a radar-based precipitation product and rain gauge measurements. The radar-based precipitation product used is the reprocessed RADCLIM dataset (up to November 2023) and the real-time operational product RADQPE (from December 2023 onwards) of the Royal Meteorological Institute (RMI) of Belgium. They have a 1-km spatial resolution, with a 5-minute temporal resolution. Both datasets use the advanced clutter filtering and gauge adjustment methods developed by Goudenhoofdt & Delobbe (2016) and improved by Journée et al. (2023).

In addition to the radar-based product, precipitation measurements from the Flowbru monitoring network are used. The network comprises 16 rain gauges distributed across the Brussels Capital Region, with records at 5-minute intervals. The locations of the gauges are shown in Figure 1.

Rainfall events were identified using the rain gauge precipitation time series, which are less noisy than the radar data. Two events are considered separate if no rainfall was recorded at any rain gauge for at least four consecutive hours between them.

Analysis

We analysed the time series of rainfall events and of CSO occurrences by computing descriptive statistics for both datasets. Furthermore, we quantified the correlation between CSO duration and rainfall depth per rainfall event, where rainfall depth was calculated using multiple approaches: (i) mean and individual measurements from the rain gauges, and (ii) radar-derived depth aggregated by subcatchment. The subcatchments, delineated in Figure 1, were previously defined using ground elevation and sewer network data (Seyoum et al., 2020). As radar data were available only for 2023 at the time of analysis, radar-derived rainfall depths do not yet incorporate events from 2024.

We took mostly an event-based approach instead of looking at the daily scale, to avoid the artificial separation of continuous rainfall episodes at midnight, and to improve correspondence between rainfall and CSO occurrences.

All data preprocessing, statistical analyses, and visualizations were conducted in Python, primarily utilizing the *pandas*, *geopandas*, *numpy*, *xarray*, *matplotlib* and *plotly* libraries.

Results

Sewer overflows

Table 2 presents the number of overflow days and total overflow duration for 2023–2024. The results confirm a high overflow frequency at all locations, ranging from 3 % to 36 % of overflow days in the study period. Considering there were 416 rain days over the two years, locations DO01 and DO09 experienced overflows on more than 50% of these rain days. These high values highlight the scale of the challenge faced in Brussels.

Table 2. Days with combined sewer overflows at nine selected overflow locations, with overflow duration statistics.

Location	Overflow days	Total duration (h)	Mean duration \pm SD (HH:MM)	Median duration (HH:MM)	Max duration (HH:MM)
DO01 – Molenbeek Senne	261 (36%)	1560 (8.9%)	06:00 \pm 05:55	03:55	24:00
DO02 – Molenbeek Canal	112 (15%)	236 (1.3%)	02:05 \pm 02:20	01:25	17:25
DO08 – Nouveau Maelbeek	121 (17%)	531 (3.0%)	04:25 \pm 03:30	03:35	21:30
DO09 – Marly Senne	252 (34%)	1412 (8.0%)	05:35 \pm 06:00	03:30	24:00
DO16 – Paruck Senne	112 (15%)	211 (1.2%)	01:55 \pm 02:50	00:55	20:55
DO17 – Paruck Canal	58 (8%)	102 (0.6%)	01:45 \pm 01:20	01:30	05:10
DO19 – Charroi	176 (24%)	474 (2.7%)	02:40 \pm 02:45	01:45	18:30
DO20 – Industriel	23 (3%)	42 (0.2%)	01:50 \pm 02:00	01:00	08:20
DO29 – STEP Nord	67 (9%)	175 (1.0%)	02:35 \pm 02:45	01:55	16:55

Note: Percentage of total days (731) and of total hours (17 544) in parentheses. These do NOT take into account missing data.

Rainfall events

Table 3 gives the statistics for the 330 recorded rainfall events in 2023-2024, calculated with a minimum dry period of 4 hours between each event at all rain gauges. With annual rainfall totals of 975 mm in 2023 and 1 095 mm in 2024, both years were wetter than the climatic norm, likely resulting in a greater number and longer duration of overflow events.

Table 3. Statistics of the 330 rainfall events recorded in 2023-2024 in Brussels (4h dry period).

P13 (2023-2024) – 330 events	Mean \pm SD	Minimum	Median	Maximum
Mean depth (mm)	6.2 \pm 7.7	0.1	3.1	55.9
Event duration (HH:MM)	13:15 \pm 10:40	00:05	10:45	98:05
Rain duration (HH:MM)	06:35 \pm 06:20	00:05	04:35	48:05
Max intensity 5-min (mm)	1.5 \pm 1.8	0.1	1.0	19.8
Max intensity 30-min (mm)	3.5 \pm 4.2	0.2	2.1	39.2

Event-based rainfall and sewer overflow analysis

Table 4. Overflow occurrence and frequency for the 330 rainfall events at the nine overflow locations.

Location	Events with overflow (%)
DO01 – Molenbeek Senne	208 (63%)
DO02 – Molenbeek Canal	94 (28%)
DO08 – Nouveau Maelbeek	101 (31%)
DO09 – Marly Senne	202 (61%)
DO16 – Paruck Senne	92 (28%)
DO17 – Paruck Canal	51 (15%)
DO19 – Charroi	149 (45%)
DO20 – Industriel	20 (6%)
DO29 – STEP Nord	57 (17%)

Table 4 presents overflow occurrence on rainfall event basis, complementing the daily overflow frequencies in Table 3. Table 4 shows that high overflow frequencies are also seen at the event scale, with locations such as DO01 and DO09 that overflow for more than 60 % of the rainfall events.

Figure 2 presents correlation scatterplots between the mean rain gauge–based rainfall depth (averaged across all 16 gauges) and CSO duration. Dots are all the rainfall events, events with zero CSO duration being excluded. While the slope of the relationship varies among locations, a noisy linear trend is observed across all CSO sites. This suggests that the mean rain gauge depth is a useful predictor of event CSO duration. However, the presence of noise indicates that additional explanatory variables should be found. Looking at additional rainfall metrics and explicitly accounting for the spatial distribution of rainfall should help to reduce variability.

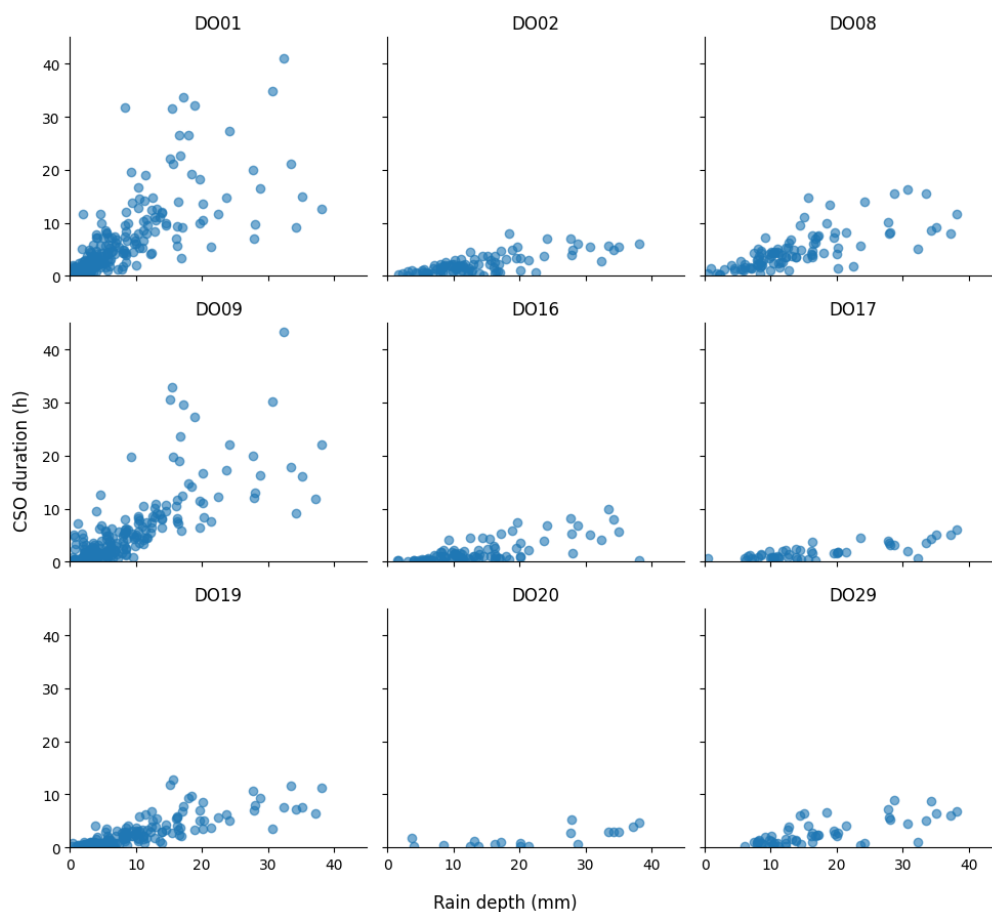


Figure 2. Scatterplots of CSO duration versus rainfall depth (averaged across all rain gauges) for the nine overflow locations for all 330 rainfall events. Events with zero CSO duration are not plotted.

To explore whether alternative rainfall representations improve predictive performance, we compared CSO durations against both rain gauge-based and radar-derived rainfall depths aggregated by subcatchment. Figure 4 shows the radar-derived subcatchment-averaged rainfall depths for event 89 (26 August 2023). As illustrated in Figure 3, correlations between CSO durations and rainfall depth across events are generally higher for rain gauge-based measurements than for radar-derived subcatchment averages. While this could currently suggest that rain gauge data provide a more reliable estimate than radar-based data, it is important to note that the radar data used here correspond to the raw product without any preprocessing. Furthermore, alternative spatial and/or temporal rainfall aggregations may improve the performance of the radar-based estimates.

For DO01 and DO02, which specifically drain the Molenbeek catchment, the highest or comparable correlations are obtained for the Molenbeek subcatchment and for the adjacent Broek-Neerpedebeek subcatchment, located just southwest of Molenbeek (downwind of the prevailing wind direction) – see Figure 1. A consistent spatial pattern is also observed for DO29, located in the northern part of the study area, which shows its lowest correlations with the Ukkel subcatchment in the south and with the Pluvio IRM [mm] gauge situated there. These observations highlight rainfall spatial distribution influences CSO response.

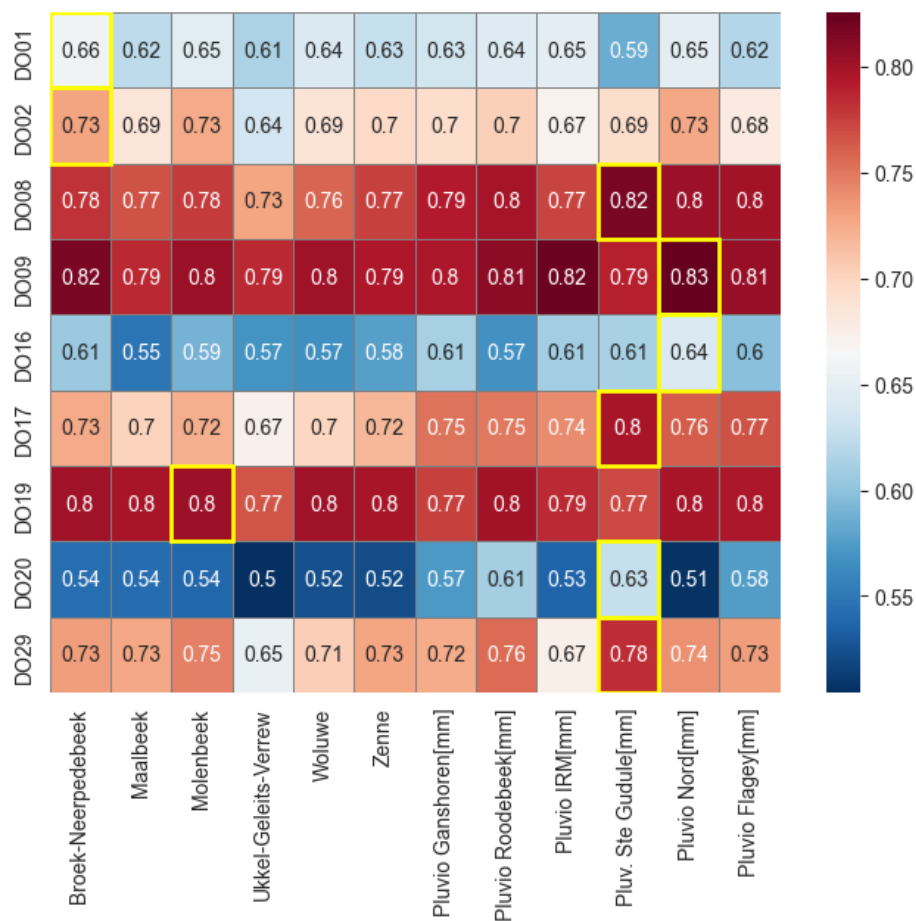


Figure 3. Correlation coefficients between CSO duration at the nine overflow locations and rainfall depth for all 330 rainfall events. Radar-derived rainfall depths averaged by subcatchment are shown in the first six columns, while rainfall depths measured by rain gauges are presented in the last six columns. Maximum correlation for each overflow location is highlighted in yellow.

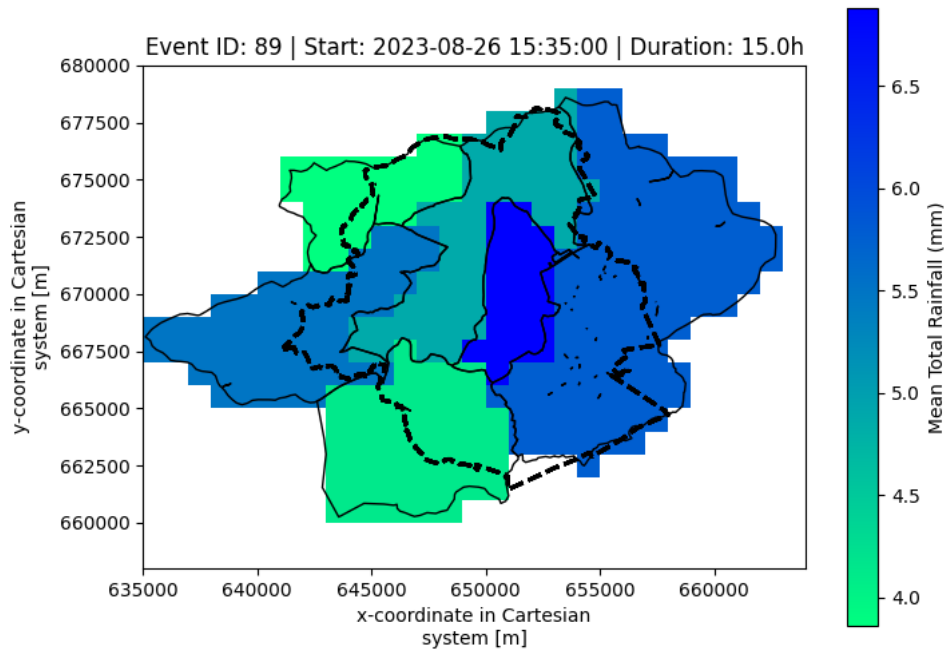


Figure 4. Map of the subcatchment-averaged rainfall depths for event 89. The bold black dotted line outlines the Brussels Capital Region, while thin black lines delineate the six subcatchments. Colour shading represents the rainfall depth assigned to each radar pixel.

Perspectives

Ongoing work will expand the analysis to include additional overflow locations and delve deeper into the rainfall spatial distributions. We will investigate specific rainfall patterns that disproportionately drive CSO at individual sites.

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