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Spatiotemporal analysis and classification of flood-generating processes in the District of Abidjan using satellite-based rainfall estimates

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Keywords: urban flooding, extreme rainfall, District of Abidjan, flood-generating processes

Supplementary material for this article is available online

Abstract

Urban flooding is one of the most frequent and impactful natural disasters that significantly impacts communities in major cities of West Africa. Understanding the spatial and temporal variations of floods is essential for effective disaster management associated with them. This study presents the first comprehensive evaluation of satellite rainfall estimates (SREs) across the District of Abidjan, utilising an enhanced urban rain gauge network from 2019 to 2022. Using multiple SRE products, namely IMERG (EARLY and FINAL runs) and CHIRPS, we analyse the dynamics of urban flooding from 1990 to 2022, examine flood-generating processes, and assess seasonal and interannual flood variability through a geo-historical approach. In terms of SRE product performance, IMERG-EARLY stands out at the daily scale, whereas CHIRPS clearly performs better in detecting extreme rainfall values. Moreover, the findings reveal that approximately 210 flood events occurred in the District of Abidjan, with the majority (146, representing 70%) occurring in June. These events resulted in more than 350 casualties, including 170 deaths and 180 injuries, as well as considerable material and economic damages. Heavy rainfall events (> 30 mm day^{-1}) constitute the most significant share across all datasets and municipalities, underscoring their critical role in triggering floods. Moreover, these flood events are classified to identify the different flood drivers: excess rainfall, prolonged rainfall, and short rainfall. Thus, the results revealed that nearly 75% of the identified flood events were linked to excessive or short-duration rainfall episodes, driven by soil saturation and intense precipitation occurring before and/or during the flood events. These findings could contribute to the development of effective flood risk management strategies, including early warning systems and policy measures that enhance urban resilience.

1. Introduction

Understanding the variability of extreme precipitation in the current climate under global warming is gaining international attention, as these events exhibit significant spatial and temporal fluctuations (IPCC 2022). These events exhibit pronounced spatial and temporal variability and are especially impactful in West African (WA) cities, where they threaten socio-economic development, environmental sustainability, and disaster risk management (Douglas et al 2008, Douglas 2017).

In WA urban areas, extreme precipitation often results in flash floods and landslides, leading to significant economic losses and social disruption (Douglas et al 2008, Fofana et al 2022, Miller et al 2022, Coulibaly et al 2024). Many countries in the region, including Côte d′Ivoire, remain highly vulnerable to these hazards due to a combination of climate dynamics and rapid, often unregulated urbanisation (Kpanou et al 2021, IPCC 2022). Additionally, human-induced factors such as deforestation, poor land-use planning, and infrastructure deficiencies further amplify flood risk (Di Baldassarre et al 2010). Coastal cities such as Abidjan (Côte d′Ivoire), Accra (Ghana), Cotonou (Benin), and Lomé (Togo), which host between 21% and 38% of their national populations, are particularly exposed to pluvial flooding (Hungerford et al 2019, Kpanou et al 2021).

The rising frequency of flood events since the 1960s is closely tied to population growth, land-use change, and urban sprawl—particularly into flood-prone zones with inadequate drainage systems (Di Baldassarre et al 2010, Yao et al 2024). Furthermore, land subsidence, often accelerated by excessive groundwater extraction and infrastructure loading, has been identified as an additional factor contributing to increased flood vulnerability in the region (Nicholls et al 2008). Consequently, climate change, population growth, and urbanization in flood-prone areas will exacerbate flood hazards and exposure levels (Hirabayashi et al 2021).

Since 2009, the District of Abidjan has been increasingly affected by devastating flood events (Coulibaly et al 2024). Informal settlements, often located in high-risk zones, are especially vulnerable, lacking the infrastructure and emergency systems necessary for flood mitigation (Douglas et al 2008, Adelekan 2010). This highlights the urgent need for targeted urban planning strategies and flood resilience policies. Informal settlements—often located in high-risk zones—are especially vulnerable, lacking the infrastructure and emergency systems necessary for flood mitigation (Douglas et al 2008, Adelekan 2010). This highlights the urgent need for targeted urban planning strategies and flood resilience policies.

A key component of urban flood management is the implementation of early warning systems, which enhance urban resilience and reduce flood-related risks. However, the successful implementation of early warning systems depends on a thorough understanding of past flood events, including their underlying causes and consequences, to design reliable and well-adapted alert mechanisms.

Despite growing concern, urban flood mechanisms in Abidjan remain poorly documented and understood, particularly with respect to the meteorological triggers. While existing research has focused largely on land-use changes and socio-demographic factors (e.g., Eba et al 2021, Fofana and Kra 2025), limited attention has been given to the types and dynamics of rainfall events that lead to flooding. For example, Coulibaly et al (2024) found that changes in the number of rainy days significantly influence flood risk in Yopougon, one of the District of Abidjan′s municipalities. However, broader city-wide assessments linking precipitation typologies to flood occurrences are still lacking. Investigating these factors is essential for assessing the impacts of climate change, reducing uncertainties in extreme flood estimations, and providing valuable insights into urban flood occurrences (Hirabayashi et al 2013, Winsemius et al 2016).

Tramblay et al (2021, 2022) highlighted the strong association between soil moisture and annual flooding in African river basins, identifying soil saturation as a key driver of flood. However, rainfall intensity and drainage infrastructure deficiencies likely play more significant roles in flood generation in highly urbanized catchments like the District of Abidjan. Moreover, to date, few, if any, studies have specifically evaluated the performance of satellite rainfall estimates over the urban area of Abidjan. To address this critical gap, this study aims to assess the performance of satellite-based rainfall products through comparison with ground-based station data for the period 2019–2022. Then, based on flood events in the District of Abidjan, this study compiles a comprehensive database from recent decades and analyses the associated flood-generating processes using the tested satellite rainfall products.

2. Data and methods

2.1. Data

2.1.1. Study area

The District of Abidjan is one of the fastest-growing cities in West Africa. It is the largest city in the country and the third most populous French-speaking city in the world, following Paris and Kinshasa (Zhu et al 2012). The District of Abidjan is a coastal area located in the south-eastern part of Côte d′Ivoire, between latitudes 5°20′ and 5°60′ North and longitudes 3°50′ and 4°20′ West (figure 1). The District of Abidjan consists of 13 municipalities. It covers an area of 57,735 hectares, characterized by significant industrialization, rapid urbanization, and a population estimated around 6,321,017 inhabitants, representing 21.5% of Côte d′Ivoire′s total population (RGPH 2022). The climate of the is influenced by the monsoon (humid oceanic wind) with alternating dry and wet seasons. The rainfall includes major and little rainy seasons (Yao et al 2024). The major

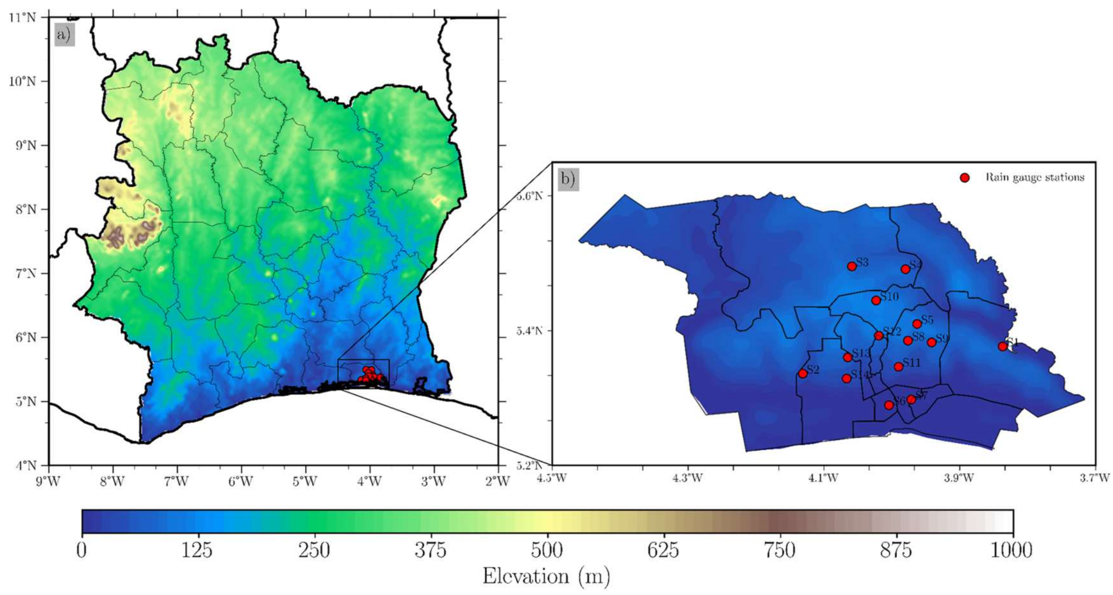

Figure 1. Study area topography (shading, in meter) of Côte d′Ivoire (a) and the station locations (red dots) in the District of Abidjan (b).

rainy season extends from April to July, peaking in June (monthly average ~ 600 mm), with a high probability of severe floods occurring, while the little rainy season occurs from October to November (Coulibaly *et al* 2024).

2.1.2. Station daily rainfall data

Daily rain gauge (RG) stations are provided by the EVIdENCE 'Évènements pluvieux extrêmes, Vulnérabilités et rIsques environnementaux : iNondation et Contamination des Eaux′ project (Hereafter Evidence, Zahiri *et al* 2023) from 2019 to 2022. In this study, we selected rainfall data from 14 stations across the District of Abidjan (figure 1 and table S1 in the supplemental material), ensuring the most extended common observation period available. These station measurements serve as reference data for evaluating satellite-based rainfall products.

2.1.3. Satellite precipitation products

Due to the lack of and sparse network of *in situ* precipitation measurements, satellite-based rainfall data are valuable products for precipitation studies over large areas and long periods. With the increase in the number of satellite sensors and imaging technology, many promising satellite products, recently published and revised, providing valuable distributed information on sub-daily rainfall data, are available for many applications (Yuan *et al* 2019). This study used Integrated Multi-satellitE Retrievals for Global Precipitation Measurement (GPM-IMERG) and Climate Hazards Group Infrared Precipitation with Stations version 2 (CHIRPS V2).

GPM-IMERG is the level 3 multi-satellite precipitation algorithm of Global Precipitation Measurement (GPM), which combines all available constellation microwave precipitation estimates, infrared satellite estimates, and monthly gauge precipitation data (Huffman *et al* 2020). The passive microwave (PMW) estimates are calculated using a more recent version of the Goddard Profiling (GPROF) algorithm. Then, a seasonal Global Precipitation Climatology Centre (GPCP) calibration is applied to the PMW to provide high spatio-temporal resolution global precipitation data. The temporal resolution is 30 min, and the spatial resolution is $0.1^\circ \times 0.1^\circ$.

We used IMERG V07B early (IMERG-EARLY, hereafter) and IMERG V07B final (IMERG-FINAL, hereafter). IMERG-EARLY provides rapid, low-latency precipitation estimates, making it ideal for applications such as weather monitoring and disaster response with latency of about 4 h. To enhance the accuracy of IMERG, several algorithmic improvements including monthly gauge-based calibration and data optimizations have been implemented in IMERG-FINAL compared to IMERG-EARLY. IMERG-FINAL has a 3.5-month latency and uses ground gauge data monthly for a more precise calibration (Huffman *et al* 2023).

CHIRPS v2 (CHIRPS, hereinafter) is a quasi-global dataset providing daily precipitation estimates (Funk *et al* 2015). CHIRPS is based on a global monthly precipitation climatology (CHPclim), thermal infrared (TIR) cold cloud duration (CCD), daily and monthly RG data and more than 30 years of quasi-global rainfall dataset. Spanning 50°S - 50°N (and all longitudes), starting in 1981 to the present, CHIRPS incorporates 0.05° resolution satellite imagery with *in situ* station data. The *in situ*, publicly available rainfall station data (e.g., Abidjan

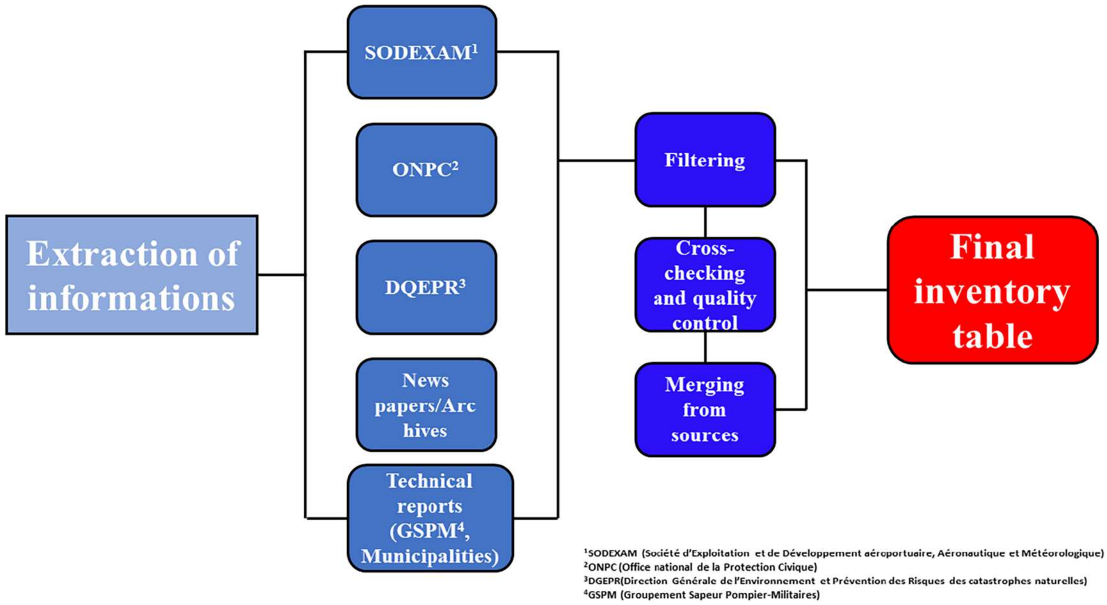

Figure 2. Steps in flood events data inventory development process.

airport) are used for creating CHPCLim and to disaggregate it into to pentads to create gridded rainfall time series for trend analysis and seasonal drought monitoring. It is initially computed in a pentad (5 days), and all other time steps are either aggregated (over periods of ten days or more) or disaggregated (to daily values) using cold cloud duration data. We re-gridded CHIRPS to the IMERG grid. In addition, some Evidence stations are located within the same CHIRPS/IMERG pixel. In such cases, we averaged the daily rainfall from all RG belonging to that pixel and compared the mean value to the corresponding satellite estimated pixel value (e.g., Maranan *et al* 2020, Ageet *et al* 2022, De Waal *et al* 2025). Thus, including multiple stations, when available, enhances spatial rainfall representation within a pixel and improves satellite products performance assessment (De Waal *et al* 2025).

2.1.4. Soil moisture data

We used soil moisture data from the fifth generation of the European Center for Medium-range Weather Forecasts (ECMWF) ERA5-Land (Muñoz-Sabater *et al* 2021). It provides high-resolution data with a spatial grid of approximately 9 km and a temporal resolution of one hour. The soil moisture is available for four different soil layers, corresponding to 0–7 cm for layer 1, 7–28 cm for layer 2, 28–100 cm for layer 3, and 100–289 cm for layer 4. Soil development is shaped by various factors, including key soil properties such as storage capacity, infiltration capacity, and depth suitable for its application. The study of Tramblay *et al* (2021) in Africa showed that the deeper soil layers 3 and 4 yield a more delayed response of soil moisture to a rainfall event, and similar results are obtained with soil moisture from the soil layers 1 and 2 with a light improvement for soil layer 2. Therefore, this study uses the second soil layer for all further analyses.

2.2. Methods

2.2.1. Flood events database: geohistorical approach

The availability of flood event data at the municipal level is crucial for understanding flood dynamics and characteristics, assessing population exposure and vulnerability, and improving the accuracy of models and analyses in flood risk assessments (Eldho *et al* 2018). To derive critical insights into risk and vulnerability, it is essential to collect an extensive flood dataset encompassing various aspects of flooding. To collect data on flood events, this study employed a geohistorical approach. Indeed, a geohistorical approach emphasizes the integration of historical flood events with spatial and geographical context, adhering to specific criteria (Anon 2024, Bruckmann *et al* 2019). The data collection and processing follow a strict workflow as presented in figure 2. The approach consisted of three stages (e.g., Da 2021): the first stage involved extracting information from various identified sources; the second stage involved verifying the information; and the third stage involved creating a final table inventory. Thus, in this study flood data were obtained from five main sources: (i) Reports on climate conditions in Côte d'Ivoire (SODEXAM, Société d'Exploitation et de Développement Aéroportuaire, Aéronautique et Météorologique) (ii) Flood reports from ONPC (Office National de la Protection Civile); (iii) flood intervention reports from GSPM (Groupement des Sapeurs Pompier-Militaire);

(iv) Environmental Departments of each Municipality; and (v) about 250 articles from Newspapers reporting floods in the District of Abidjan were reviewed. The collected data were then filtered to isolate only urban flood events. For each event, the following details were recorded: date (year, month, and day), location, cumulative rainfall during the event, and associated impacts (material and human damage). The flood events from various sources (press articles, civil protection reports, municipal archives and institutions) were cross-checked to confirm the occurrence, date(s), and location(s) of each event (flood-event single day). Some events can span over two days, e.g., late night until the following morning. Such events are considered a single flood event. For example, this includes a flood event in Attecoube on 4–5 June 2024. However, multiple flood events can be occurred on a single day across different municipalities, and each such event is counted individually for each municipality.

Moreover, to ensure reliability, an event was only recorded if confirmed by at least two independent sources. This approach fits squarely within a framework that contextualizes floods through a diachronic analysis while considering the available sources, their composition biases, and the information′s discontinuities (Martin *et al* 2015). Thus, limitations related to information discontinuities necessitate for great caution when comparing floods over the long-term period. Discontinuities in sources may arise, varying quantitatively and qualitatively over time and across different locations (Boudou 2015, Bruckmann *et al* 2019). For example, following the political and military crisis that began in 2002, institutional instability and limited media coverage may have affected the documentation of flood events.

Additionally, the continuous migration of populations from the interior of the country to Abidjan intensified during the post-electoral period of 2010–2011, thereby increasing demographic pressure on the city. Furthermore, in recent years, media coverage has improved, supported by local platforms, social media, and greater institutional awareness. The growing media focus on climate change has likely increased the visibility of flood events, including those previously underreported. As a result, the pre-processing mentioned above was done to check the relevance of the information.

Despite the aforementioned limitations, historical records constitute a reliable source of data to characterize past flood events, as they document these events and their changes over long-time scales (Wetter 2017, Wilhelm *et al* 2019). Moreover, this approach seems relevant despite the lack of instrumental data (e.g., discharge/flood level) and archives dedicated to natural disasters in the District of Abidjan.

2.2.2. Event-based classification of flood generating processes

The classification methodology is applied to all historical individual flood events identified in section (2.2.1). This approach is based on Tramblay *et al* (2022) adapted from Stein *et al* (2020) studies. Flood events in communes are classified according to three hydrometeorological generating processes: excess rainfall, short rainfall, and prolonged rainfall, which are adapted herein to better account for the effects of antecedent soil moisture before the flood event (see figure S1 in Supplemental material). Thus, hereafter the term ‘flood-generating processes′ refers to types of rain/showers leading to flood events (e.g., Tramblay *et al* 2022).

- Excess rain

An excess rain event occurs when soil moisture is already high (i.e., Ssat > Tsm) and the 7-day rainfall total (P7) exceeds the historical mean. This situation indicates an elevated flood risk due to wet antecedent conditions combined with above-average rainfall.

- Prolonged rain

A prolonged rain event is defined as occurring when the total rainfall amount over seven (7) consecutive days (P7) exceeds the 90th percentile of accumulated 7-day rainfall, with the stipulation that no single day dominates this period; that is, Pmax $\leqslant (2/3) \times$ P7. This signifies sustained, distributed rainfall across multiple days.

- Short rain:

A short rain event occurs when the maximum single-day rainfall within a 7-day window (Pmax) exceeds the 90th percentile of all such historical maxima, and the rainfall is intensely concentrated on that day, i.e., Pmax > (2/3) of the total 7-day rainfall amount (P7). This indicates a high-intensity, short-duration rainfall episode.

2.2.3. Classification of flood-inducing rainfall

The rainfall flood-induced at a daily scale were categorized as light rain (<10 mm), moderate rain ($\geqslant$ 10 mm and <30 mm), heavy rain ($\geqslant$30 mm and <50 mm), and severe rain ($\geqslant$50 mm) adapted from Kacou *et al* (2023). This classification has the advantage of integrating national thresholds used by the Ivorian meteorology service for extreme rainfall warning alert systems. This classification aims to identify the most suitable flood-inducing precipitation category in the District of Abidjan.

Table 1. Contingency table for comparing the rainy (⩾ 0.2 mm) days in RG and satellite estimates.

	Rain gauge ⩾ 0.2 mm	Rain gauge <0.2 mm
Satellite ⩾0.2 mm	Hit (H)	False Alarm (F)
Satellite <0.2 mm	Miss (M)	Correct rejection (R)

2.2.4. Evaluation metrics for satellite rainfall products

Evaluation metrics are divided into two processes. The first process assesses the ability of satellite products to detect rainy days, which are defined here as days with daily rainfall amounts greater than 0.2 mm day^{-1} based on the contingency table (table 1). In addition to continuous metrics that measure the accuracy of satellite rainfall estimates (SRE), it is essential to investigate their capability for detecting precipitation occurrence. Therefore, three categorical metrics, including probability of detection (POD), probability of false alarm (POFA), bias in detection (BID), and Heidke skill score (HSS) (Maranan *et al* 2020). POD quantifies the ability of satellite products to detect rainy episodes as recorded by the RGs and is perfect when POD = 1. Similarly, POFA is the fraction of false alarms relative to all rainfall occurrences in satellite products. Among them, POD is the correct forecast rate, while POFA is the wrong rain probability (Wilks 2011).

The second group of metrics are employed for precipitation intensity assessment. It includes Pearson′s correlation coefficient (r), mean error (ME), percent bias (PB), mean absolute error (MAE), and root-mean-square error (RMSE) to assess the satellite product′s accuracy for rain rates.

3. Results

3.1. Evaluation satellite precipitation estimates over the District of Abidjan

Figure 3 presents the evaluation metrics based on point-to-pixel comparison between satellite products and RG for the period 2019–2022. While the spread of values in figure 3(a) does not show significant differences across stations, IMERG-EARLY exhibits the largest bias (−29%), indicating a clear underestimation of rainfall compared to RG. IMERG-FINAL also shows a substantial negative bias, though less pronounced. CHIRPS exhibits lower bias (−6.30%) values with less variability, indicating that it performs more consistently (figure 3(a)). Besides, IMERG-EARLY shows the lowest MAE (3.77) (figure 3(b) and table 1), but at ME level, the best score (−0.33) is found with CHIRPS, and it demonstrates least stable systematic error, compared to IMERG products (figure 3(c)). RMSE values range from approximately 8.64 mm day-1 to 9.51 mm day−1 for all stations considered here. It is clear that the performance of the satellite products varies considerably from station to station (figure 3(d)), with correlation coefficients (COR) of 0.70, 0.66 and 0.52 for IMERG-EARLY, CHIRPS and IMERG-FINAL respectively. This indicates that IMERG-EARLY better captures observed precipitation’s temporal and spatial variability, highlighting its relative capacity to provide realistic and reliable estimates (figure 3(e) and table 2). All stations show a good POD score (figure 3(f)) with values ranging from 0.53 to 0.76, as reported in table 2. The ability of all satellite products to detect a rainy day as reported in the RG is generally satisfactory using the contingency table (table 1). However, all the products are prone to false alarms and tend to overestimate rainfall frequency. For example, CHIRPS excels with a POFA of 0.18, the lowest among the three products (figure 3(g)). Moreover, CHIRPS accurately represents actual rainfall occurrences with the lowest value (figure 3(h)). Then, the Heidke Skill Score (HSS) combines multiple aspects of predictive performance. IMERG-EARLY and IMERG-FINAL products have a score of 0.38 and outperform CHIRPS (0.34) (figure 3(i) and table 2). The current results show that IMERG-EARLY and IMERG-FINAL have both the highest HSS, meaning they may have the best skill in predicting rain events.

Overall, during the period 2019–2022, IMERG-EARLY shows the best performance in terms of correlation, the lowest RMSE, and the highest detection capability (POD), although it exhibits a stronger negative bias over the District of Abidjan. CHIRPS performs better in terms of bias and false alarms but shows higher day-to-day errors and lower detection rates. IMERG-FINAL falls in between but does not consistently outperform IMERG-EARLY.

It is worth noting that this work has been conducted over a limited period (2019–2022) and in a local area that may not allow a full conclusion. Further investigation may help to fully address this question. However, this is beyond the scope of this study.

3.2. Performance of satellite products in extreme rainfall event characterization

The ability of satellites to capture and detect extreme rainfall is analyzed in figures 4 and 5. Here, we define an extreme event as daily rainfall exceeding the 95th percentile on rainy days in the RG and satellite products.

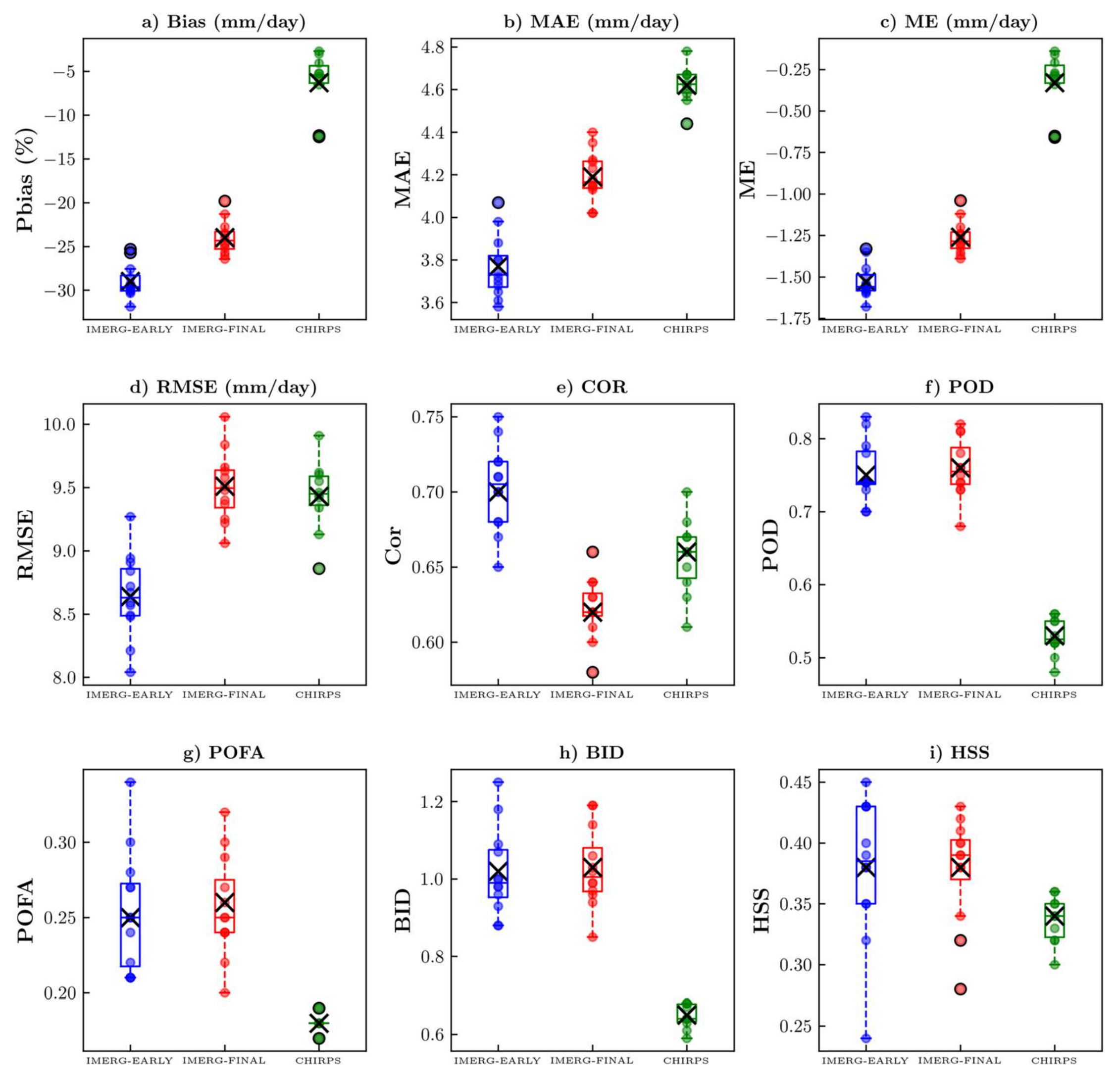

Figure 3. Boxplots showing the performance of the satellite products on a daily time scale across all the stations. Each circle represents a station's value, and the black star shows the mean between 2019–2022.

Table 2. Scores for daily scale indices evaluation for all the satellite products. The best performance for each metric is given in bold font.

	Bias	MAE	ME	RMSE	COR	POD	POFA	BID	HSS
IMERG-EARLY	−29	**3.77**	−1.53	**8.64**	**0.70**	**0.76**	**0.25**	1.02	**0.38**
IMERG-FINAL	−23.98	4.19	−1.26	9.51	0.62	0.75	0.26	1.03	**0.38**
CHIRPS	**−6.30**	4.62	**−0.33**	9.43	0.66	0.53	0.18	**0.65**	0.34

Regarding the 95th percentile (figure 4(a)), RGs are the highest among all, with values reaching up to 55 mm day−1 at some stations. IMERG-EARLY significantly underestimates rainfall intensity compared to observations, with values ranging from 25 to 35 mm day. It appears less capable of capturing high-intensity events over the District of Abidjan during the period 2019–2022. However, IMERG-FINAL and CHIRPS show an improvement compared to IMER-1G-EARLY, ranging from 30 to 40 mm day-1 and 35 to 45 mm day-1, respectively. Therefore, CHIRPS shows the best agreement with RG among the three products. As for the 95th percentile, we observe the same trends at the 99th percentile level (figure 4(b)).

The performance of SREs capturing extreme rainfall varies significantly across the stations (figure 5). All satellite-based products exhibit significant underestimations of daily extreme rainfall (>95th percentile) as shown in figures 5(a)-(d) and table 3. With RMSE between 11.18 mm day^{-1} and 12.4 mm day^{-1} (table 3), IMERG-EARLY, IMERG-FINAL, and CHIRPS underestimated extreme rainfall by about 33.34%, 30.48% and 13.82% respectively (figure 5(a) and table 3). Among the different products presented, the highest correlation

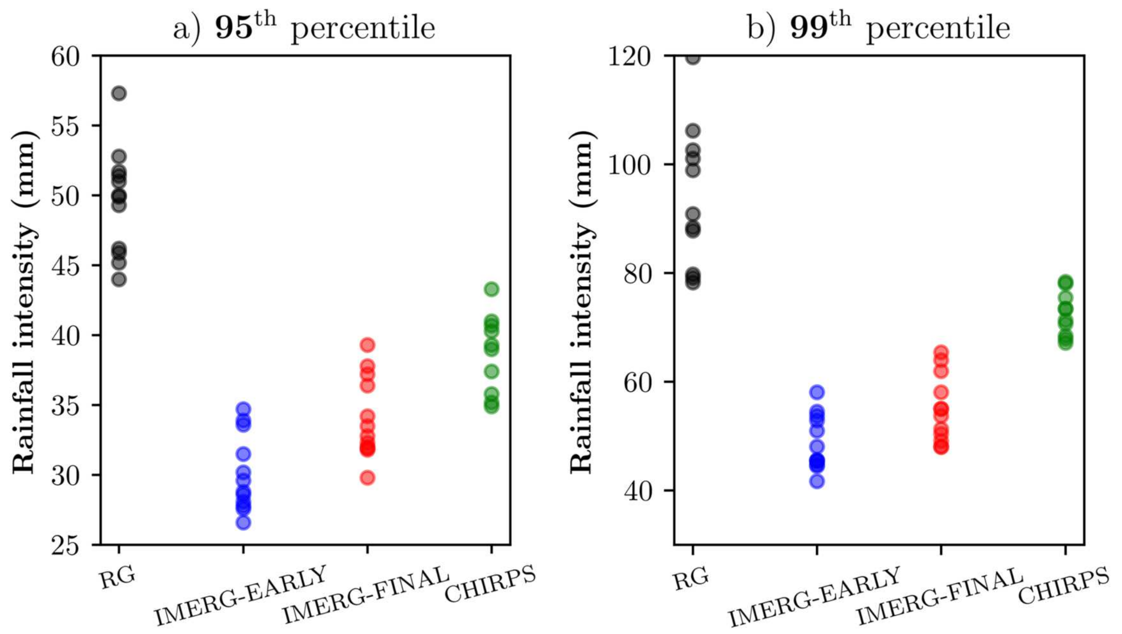

Figure 4. 95th percentile (a) and 99th percentile (b) of daily extreme rainfall from RG, IMERG-EARLY, IMERG-FINAL and CHIRPS data from 2019 to 2022.

between the satellite product and RG is found at IMERG-EARLY level (Cor = 0.67), followed by CHIRPS (Cor = 0.63) and finally IMERG-FINAL shows the weakest performance with a Cor = 0.59 (figure 5(e) and table 3). Moreover, the performance of the SRE declines for extreme events compared to the full daily scale (cf figure 3). In addition, all products miss between 60% to 70% of the daily extreme events reported by the RGs where the POD ranges between 0.29 and 0.40 for CHIRPS. In contrast, the POFA tended to increase (figure 5(g)) at CHIRPS and IMERG-FINAL level. Additionally, they underestimate the frequency of extreme rainfall events (BID $<$ 1) (figure 5(h)), with the best score provided by CHIRPS (BID = 0.69, table 3).

3.3. Spatiotemporal variability of flood events and impacts related

Figure 6 illustrates the spatiotemporal variability of flood events and their associated impacts in the District of Abidjan from 1990 to 2022, analyzed using a geohistorical approach (see section 2.2.1). A total of 210 individual urban floods were documented from various sources, revealing a significant increase in flood frequency over the years. Between 1990 and 2009, flood occurrences were relatively low (25 events), with notable years such as 1996 and 2009 recording 5 and 8 events, respectively. 2000, 2001, 2003, 2004, and 2006, experienced almost no flooding. However, from 2010 onward, the number of flood events surged significantly in the District of Abidjan. The important number of floods was observed in 2014 with 37 events followed by 2021 recording 29 events. In 2022, 15 flood events were recorded during the first rainy season alone as data collection ceased mid-year (there were potentially more flood events, but went unrecorded).

Over the same period, 170 flood-related fatalities were recorded, averaging six (6) deaths per year (figure 7(a), red curve). Fatalities remained relatively low from 1990 to 2004, except for 1996, which saw 28 deaths. From 2005 onward, fatalities increased significantly, with 34 deaths in 2014, 22 in 2009, and 16, 21, and 20 deaths in 2016, 2018, and 2020, respectively. More than 70% of the recorded fatalities occurred in the last decade (2012–2022), highlighting the increasing severity of flood events in recent years.

As shown in figure 6(b), seasonal variability indicates that most flood events occurred in June, accounting for 146 cases (70%). May and October contributed 22 and 21 events, respectively, while April and July saw 12 events (6%). Over 80% of all flood events occurred in April–July, corresponding to the major rainy season, characterized by the highest cumulative rainfall and peaking in June, with ~ 600 mm. An additional 12% of events occurred in September, October, and November, aligning with the short rainy season. Isolated events were reported during the major dry season (December–February), with only 5 cases recorded during this period, underscoring the irregularity of extreme precipitation events.

Spatially, figure 6(c) highlights that flood events affected all areas of the District of Abidjan except Brofodoumé (no data). The most affected communes were Cocody (47 events, 22%) and Yopougon (42 events, 20%), followed by Abobo (26 events, 12%), Attecoube (25 events, 11.7%), and Adjame (16 events, 7.5%) as well as Bingerville (16 events, 8%). Less affected communes included Treichville, Marcory, Plateau, and Songon. Indeed, Plateau and Treichville are the two oldest communes of Abidjan, around which the city gradually

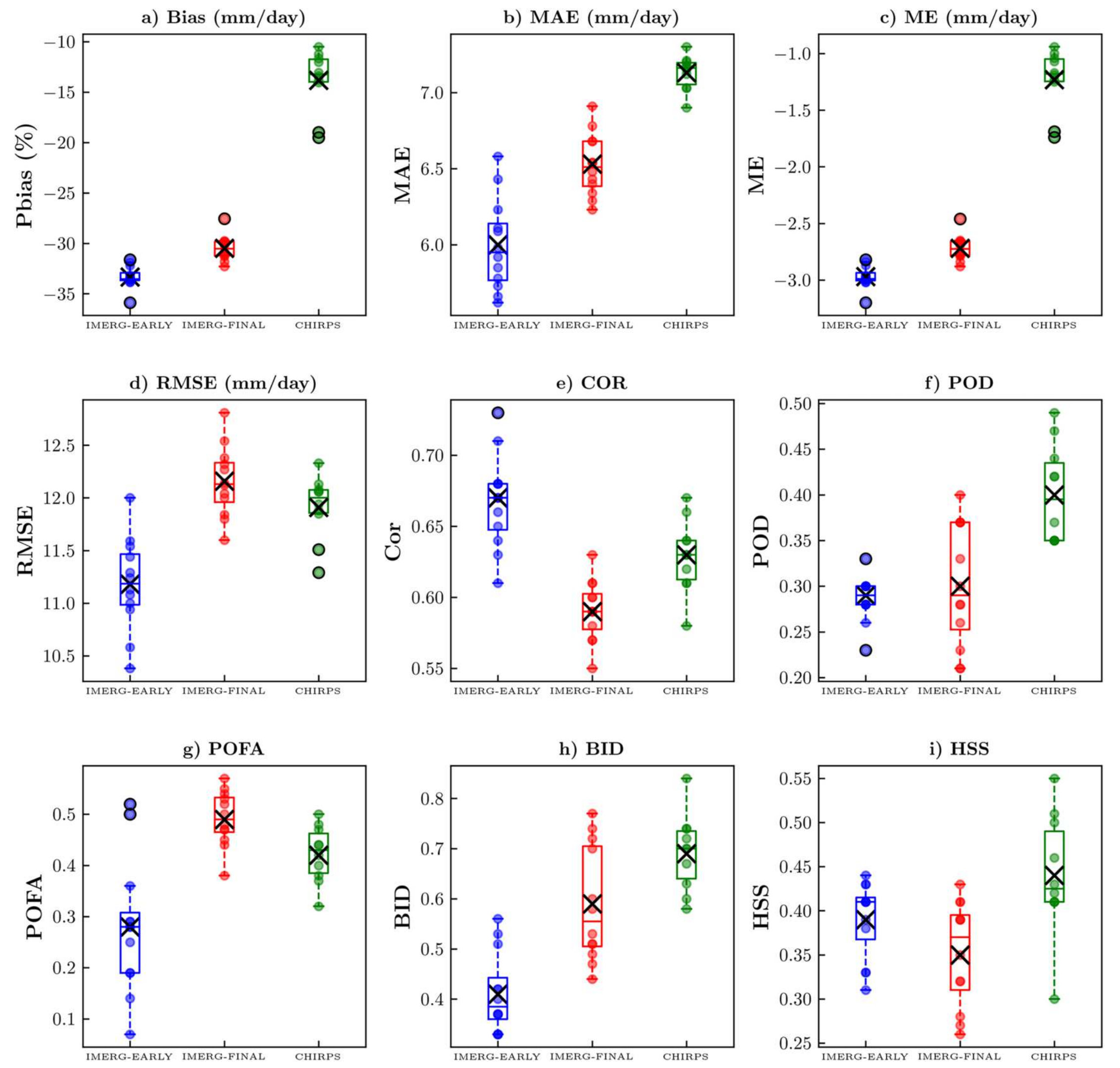

Figure 5. As in figure 3, but for extreme events. A hit occurs when both the RG and the satellite product record rainfall exceeding the 95th percentile of RG rain days (2019–2022). The cross indicates the mean value over the 2019–2022 period.

Table 3. As in table 2, but for daily extremes events (i.e., rainfall amount > 95th percentile in rainy days subset of RGs) applied on rainy days (⩾0.2 mm) from 2019 to 2022. The best performance for each metric is given in bold font.

	bias	MAE	ME	RMSE	COR	POD	POFA	BID	HSS
IMERG-EARLY	−33.34	**6.00**	−2.97	**11.18**	**0.67**	0.29	**0.28**	0.41	0.39
IMERG-FINAL	−30.48	6.53	−2.72	12.16	0.59	0.30	0.49	0.59	0.35
CHIRPS	**−13.82**	7.13	**−1.23**	11.91	0.63	**0.40**	0.42	**0.69**	**0.44**

expanded. Due to their historical significance and economic and administrative importance, they benefit from better-planned infrastructure, including a relatively efficient drainage system to limit water accumulation during heavy rainfall. Plateau city, in particular, serves as the city′s administrative and financial center, with urban planning measures in place to mitigate the impact of extreme precipitation.

The concentration of flood events in highly urbanized areas, particularly Cocody and Yopougon, could be attributed to several factors. The Cocody city, despite being a residential commune with several essential infrastructure, is characterized by many sloping areas as reported by (Danumah 2016). These topographical features facilitate the rapid flow of rainwater toward lower-lying regions, where it can accumulate and lead to flooding (Danumah *et al* 2016). Additionally, the rapid urbanization of specific neighborhoods without proper drainage infrastructure has increased the commune′s vulnerability to heavy rainfall.

The recorded flood events resulted in material damage and loss of life in the affected areas. The analysis of flooding-related fatalities and injuries reveals significant spatial disparities among communes (figure 6(d)).

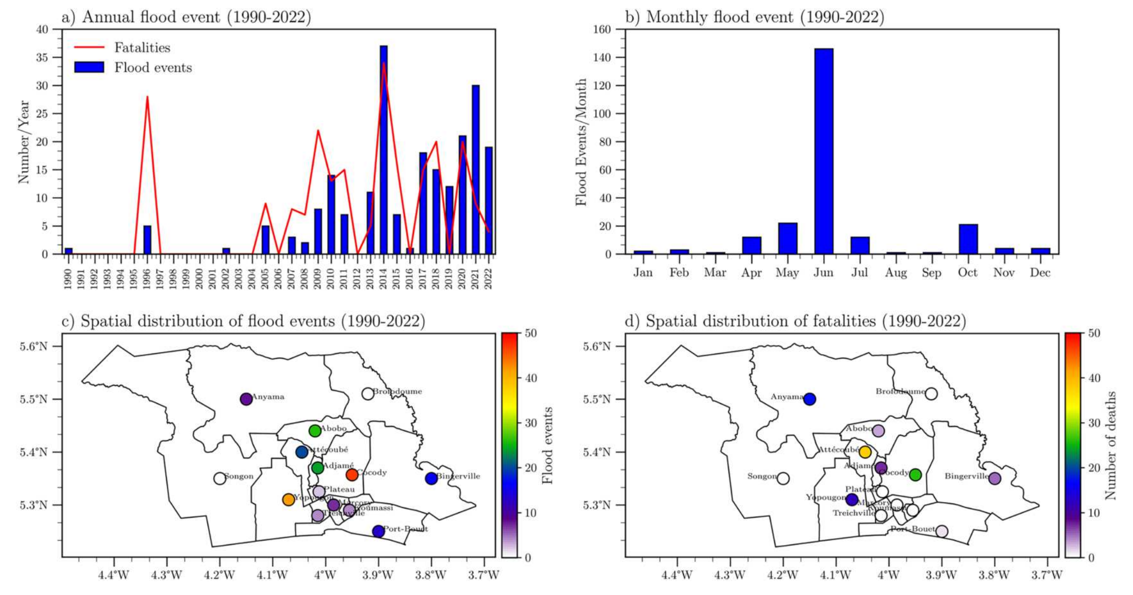

Figure 6. Spatiotemporal variability of flood events and impacts related to the District of Abidjan from 1990 to 2022. (a) Annual flood events (blue bar) and fatalities (red curve line). (b) Monthly flood event. (c) Spatial distribution of flood events. (c) Spatial distribution of fatalities.

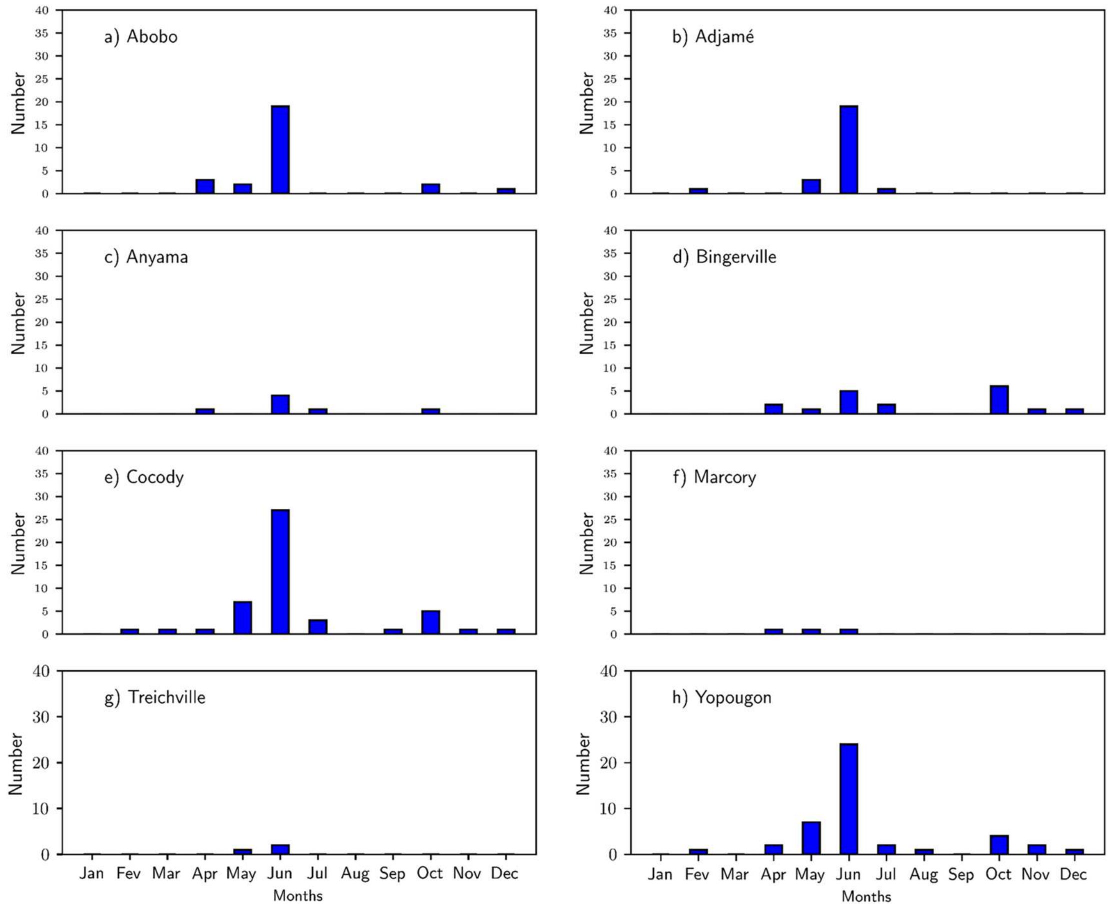

Figure 7. Monthly occurrence of flood in each municipality in the 1990–2022 period.

Cocody recorded the highest number of deaths (66 fatalities, 38%), attributed mainly to its rapid urban expansion into flood-prone areas, which exacerbates vulnerability. Attecoube followed with 38 deaths (22%), highlighting that hilly, low-income neighbourhoods are prone to landslides and inadequate drainage. While

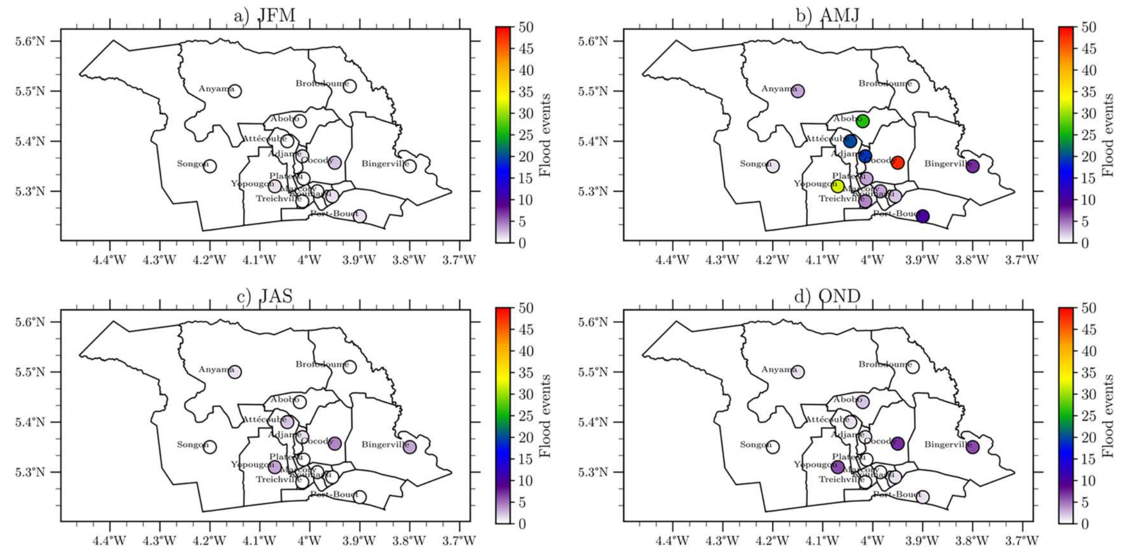

Figure 8. Seasonal distribution of floods events in the 1990–2022 period. (a) JFM, (b) AMJ, (c) JAS, (d) OND.

fatalities were lower in Anyama (17 deaths, 10%), Port-Bouet (14 deaths, 9%), and Yopougon (13 deaths, 8%), these areas still faced considerable human losses.

In contrast, the highest number of injuries was reported in Abobo (82 injuries), suggesting different flood dynamics, potentially involving widespread but less fatal incidents. Cocody (38 injuries), Anyama (17 injuries), Port-Bouet (14 injuries), and Yopougon (13 injuries) also saw significant injury rates, indicating the broad human impact of flooding across various urban settings. Spatiotemporal analysis reveals an alarming increase in the frequency and severity of flood events in the District of Abidjan. unregulated urbanization, may have played a role in amplifying the impact and recurrence of flooding in these vulnerable communes (Danumah *et al* 2016). Although damage estimates have not been compiled for some floods, significant material and infrastructure damage (including houses, roads, schools, shops, and cars) has been reported.

3.4. Monthly and seasonal flood occurrence in each municipality

Figure 7 presents the seasonal variation in the frequency of flooding events across different areas of the District of Abidjan. From April, corresponding to the beginning of the rainy season, floods have already appeared, with peaks in June (averaging 10 events per year in the District of Abidjan). Indeed, June is the month that records the most flooding, with an increase in cases in the different communes. We have recorded 18 cases in Abobo (figure 7(a)), 18 cases in Adjame (figure 7(b)), 37 cases in Cocody (figure 7(e)), and 25 cases in Yopougon (figure 7(h)). However, unlike the other zones, Bingerville experiences a peak in flooding in October (figure 7(d)), which corresponds to the rainiest month of the short rainy season. In addition, Cocody appears to be the most affected, as it experiences flooding cases almost every month (figure 7(e)). Most of the flooding occurred in each zone during the primary rainy season. Indeed, the rains during this season are often stormy and are characterized by high intensities, as Maranan *et al* (2018) and Djakouré *et al* (2024) noted. These studies identify several types of precipitation systems (MCS, unorganized local thunderstorms) responsible for rainfall in West Africa during the summer monsoon season.

As expected, flooding in the various municipalities occurs on a seasonal scale as shown in figure 8, primarily in April, May, and June. Seasonal flood occurrence in AMJ reaches 164 cases (i.e. 78% of the total annual cases) (figure 8(c)), including 142 cases for June alone (cf figure 6(a)). In figure 8(d), the OND season highlights 26 cases (i.e. 12% of the total annual cases) of floods that occurred, of which almost 21 cases occurred in October (cf figure 6(a)). Then came the JAS season with 14 cases (7% of the total annual cases) (figure 8(c)). Finally, the JFM is the least essential season for flooding, with only 6 cases (3% of the total yearly cases) (figure 8(a)). It is worth noting that these records occurred at the peak of the West African Monsoon season over the respective stations, which can be attributed to their location along the coast where vital moisture from the Gulf of Guinea fuels thunderstorm development as well as land and sea surface temperature variations producing heavy rainfall (Kacou *et al* 2023).

3.5. Characterization of flood-inducing precipitation

This section presents the flood-inducing precipitation based on event-classification rainfall defined in section (2.2.3) between 2001 and 2022. We focus our analysis mainly on the six (6) municipalities that are the

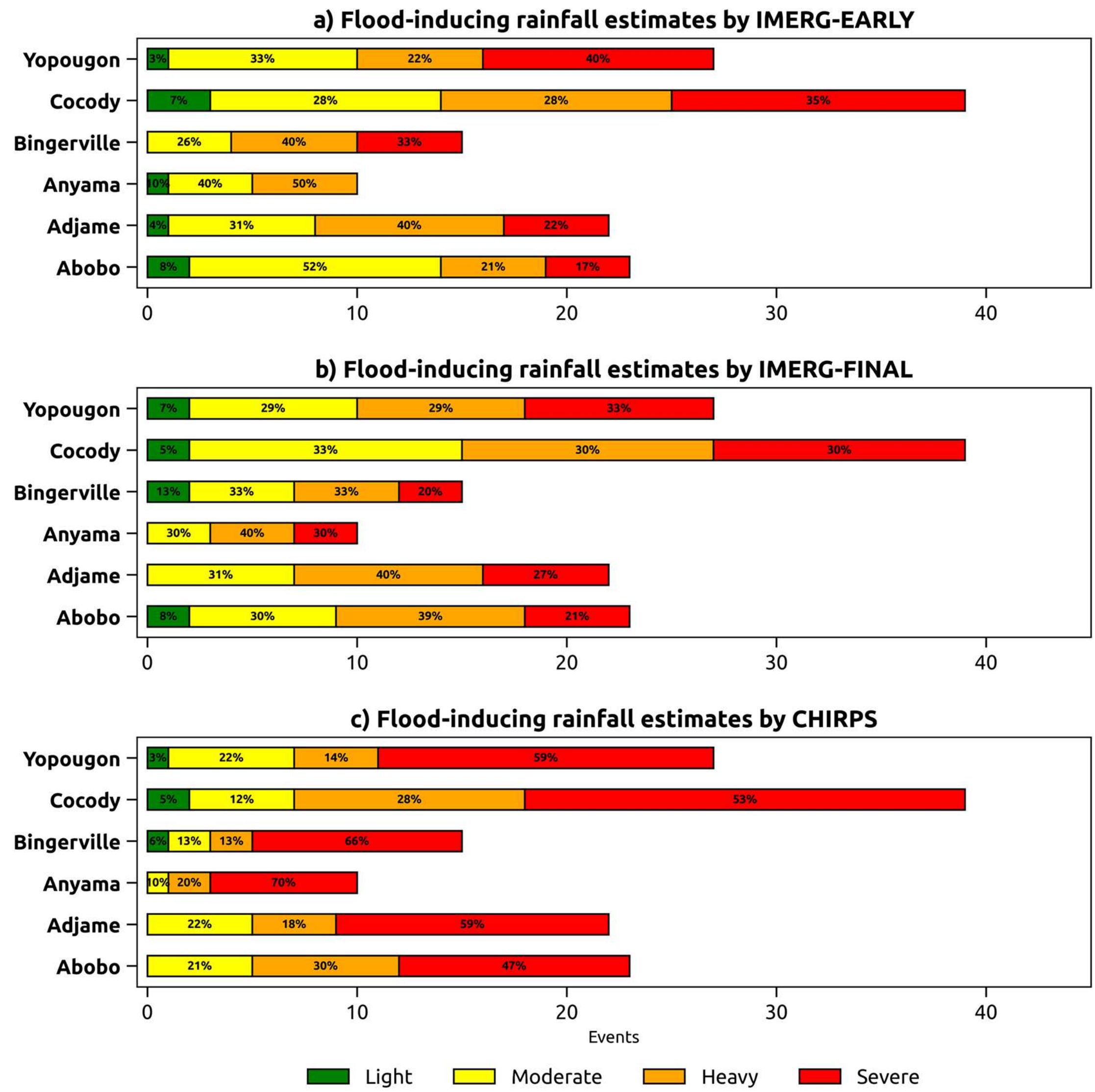

Figure 9. Flood-inducing rainfall estimates by satellite products during 2001–2022 period. Green, yellow, orange and red represent light rain (<10 mm), moderate rain (⩾10 mm and <30 mm), heavy rain (⩾30 mm and <50 mm), and severe rain (⩾50 mm) respectively.

most affected by floods (cf figure 6(a)), namely Abobo, Adjame, Anyama, Bingerville, Cocody and Yopougon. Over this period (2001–2022), Cocody recorded 38 cases, Yopougon 28 cases, Abobo and Adjame recorded 24 cases, and Bingerville and Anyama recorded 16 cases and 10 cases respectively. The classification is based on individual flood events identified at each commune according to the satellite products used. From IMERG-EARLY (figure 10(a)), severe rainfall events dominate in Cocody (35% of the total recorded), while Yopougon records the highest proportion (40%). Heavy rainfall events are the most reported in Bingerville (40%), Anyama (40%), and Adjame (40%). The flood-inducing rainfalls that are caused by light make a small contribution. Figure 10(b) highlights that heavy rainfall intensities contribute the highest percentages to Abobo (40%), Adjame (40%), Anyama (40%), and Bingerville (35%). However, Yopougon shows similar results as figure 9(a), with a high contribution of severe rainfall intensity of 33%. In figure 9(c), CHIRPS shows a significant increase in severe rainfall events for most municipalities compared to the IMERG datasets, with the highest proportions, e.g., in Yopougon (59%), Cocody (53%), Bingerville (66%), and Anyama (70%). In addition, Cocody and Yopougon consistently experience the highest number of severe rainfall events, indicating a high vulnerability to extreme rainfall-induced floods. Bingerville also exhibits a high percentage of severe events, particularly in CHIRPS. On the other hand, Anyama has a unique pattern, with heavy events dominating in CHIRPS compared to severe events in IMERG. Moreover, IMERG-EARLY and IMERG-FINAL present relatively similar distributions, though IMERG-EARLY emphasizes a slightly higher percentage of severe events. While CHIRPS shows a significant increase in severe rainfall events for most municipalities compared to the IMERG datasets, suggesting different classification thresholds or detection biases as

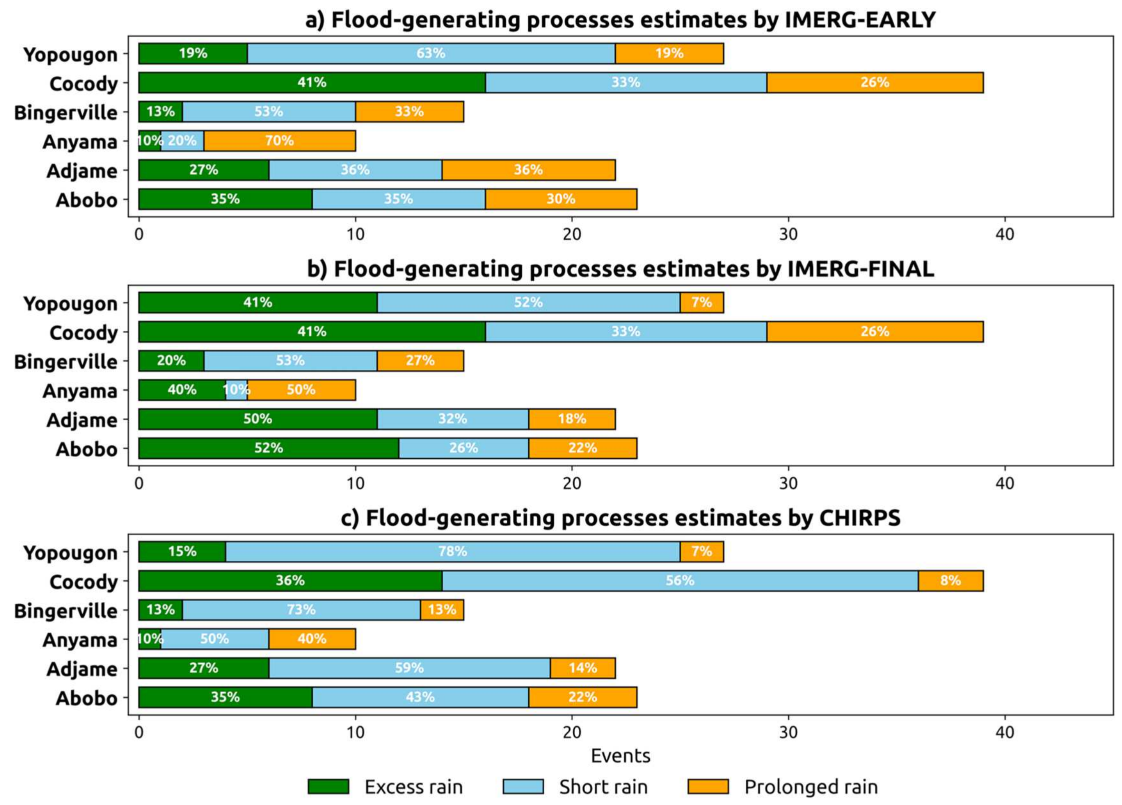

Figure 10. Event-based flood generating processes during the 2001–2022 period over 6 municipalities: Cocody (39 events), Yopougon (27 events), Abobo (23 events), Adjame (22 events), Bingerville (15 events), and Anyama (10 events).

highlighted in figure 4 and table 3. Severe rainfall events account for the largest share across all datasets and municipalities, underscoring their critical role in triggering floods.

3.6. Classification of flood-generating processes in District of Abidjan

In this part, we classified the identified flood events into one of three hydrometeorological generating processes (see (2.2.2)): excess rainfall, short rainfall, prolonged rain across the six municipalities (Yopougon, Cocody, Bingerville, Anyama, Adjame, and Abobo) most affected (cf figures 6(c)–(d)–8) reflecting spatial variability and local urban characteristics. The classification criteria are based on the information about potential causal factors (total rainfall daily amount, soil moisture) that occur shortly before the event. IMERG-EARLY (figure 10(a)) shows that short rain dominates in most municipalities, particularly in Yopougon (63%), Bingerville (53%), and Abobo (35%). Excess rain plays a significant role in flood events in Cocody (41%). Regarding prolonged rain, it remains relatively minor in Yopougon (19%) and Cocody (26%), contributing to 70% of flood events in Anyama.

Similarly, IMERG-FINAL (figure 10(b)) reflects the same overall trend but with slight variations. Short rain remains the dominant factor in flood events in Yopougon (52%) and Bingerville (53%), while excess rain accounts for 41% in both Yopougon and Cocody, and reaches 52% in Abobo. Prolonged rain plays a moderate role, particularly with 50%, 18%, and 27% of flood events in Anyama, Adjame, and Bingerville, respectively. However, CHIRPS amplifies the contribution of short rain, particularly in Yopougon (78%), Bingerville (73%), and Anyama (50%) flood events (figure 10(c)). Excess rain still contributes significantly to Abobo (35%) and Cocody (36%) flood events. Prolonged rain plays a notable role in Anyama (40%), whereas it is lower in most other municipalities, such as Yopougon (7%) and Cocody (8%), in terms of flood events.

This analysis highlights the prevalence of short rainfall as the primary driver of urban flooding in municipalities such as Yopougon and Cocody, where impermeable surfaces exacerbate the impact of intense rainfall. Excess rain, which often results from saturated soil, is a major contributor in Abobo and Adjame, indicating poor drainage systems in these areas. Although less frequent, prolonged rain remains critical in municipalities like Anyama (figures 10(a)–(c)), where it can lead to soil saturation and prolonged flooding. A dominant flood-generating process here is the flood process that occurs most often. Thus, IMERG-EARLY, on average, indicates that the contribution of excess rain is approximately 24%, 40% for short rain, and 36% for prolonged rain. For IMERG-FINAL, excess rain reaches 41%, short rain accounts for 34%, and prolonged rain accounts for 25%. However, CHIRPS identified flood types as having about 23% excess rain, 60% short rain, and 17% rain.

When assembling all this information, we find that, across the District of Abidjan, including all datasets, the proportion of excess rain reaches 45%. Short rain accounts for 29%, and 26% of events are attributed to prolonged rain. Therefore, two main types of flood-generating mechanisms can be identified across the District of Abidjan. The first one is short rain (45%), highlighting the importance of rainfall intensities associated with the different events as depicted in figure 10, followed by excess rain (29%) over saturated soil on average for all municipalities. The results indicated that nearly 75% of floods are driven by excess rainfall or short rainfall episodes.

These two processes (i.e., excess rainfall and short rain) are caused by either soil saturation or rainfall intensity occurring before or during the flood event, which indicates their respective roles in the flood triggering mechanism. The differing contributions of these processes, as captured by IMERG-EARLY, IMERG-FINAL, and CHIRPS datasets, highlight the need for tailored urban flood management strategies.

3.7. Temporal analysis of flood-inducing precipitation occurrences

This section presents a comparative temporal analysis of rainfall-induced flooding using data from multiple satellite-based datasets. To better understand the occurrence of such events, daily rainfall amounts exceeding the 95th percentile for each year were identified as extreme rainfall (black dots) and compared with precipitation recorded during documented flood events (red dots) (figures S2–4 in the Supplemental material). The objective of this analysis is to determine how extreme rainfall events correspond to flood occurrence. The figures S2–S4 in the Supplemental material show the distribution of daily rainfall intensities (mm day^{-1}), categorized as flood-inducing (red dots), no flood-inducing (black dots), and missing flood data (blue bars). The horizontal dashed lines represent the 95th percentile (lower threshold, blue) and 99th percentile (upper threshold, pink), which serve as benchmarks for identifying extreme rainfall events.

IMERG-EARLY (figures S2–4 in the Supplemental material, left column) reveals that a significant number of flood days fall below the 95^{th} percentile, as several red dots appear under the blue threshold line (95^{th} percentile) across municipalities such as Abobo (figure S2a in the Supplemental material), Adjame (Figure S2d in the Supplemental material), Cocody, and Yopougon (figure S3 in the Supplemental material). IMERG-FINAL (figures S2–4 in Supplemental material, middle column) provides higher daily rainfall estimates than IMERG-EARLY. In contrast, CHIRPS (figures S2–4 in the Supplemental material, right column) show higher values than both IMERG products.

On one hand, this analysis corroborates the previous finding (see section 3.2) that satellite-based precipitations struggle to accurately capture extreme rainfall events in the District of Abidjan, highlighting limitations in their ability to represent localized showers e.g. under convective conditions (e.g., Maranan *et al* 2020) (cf figure 4 and table 3). On the other hand, it suggests that some events may be caused by short-duration rain events (lasting only a few hours), relevant for urban flash floods that are poorly captured at the daily scale (mm day^{-1}). Moreover, this highlights a key limitation in relying on daily-scale thresholds to detect urban floods, particularly in settings where brief, intense rainfall over saturated surfaces can trigger flooding even when daily rainfall totals appear moderate. In addition to extreme rainfall, we also emphasize the role of other contributing factors discussed in previous sections such as land use and land cover changes which can amplify flood risk. Furthermore, urban flooding may result from saturated soils, blocked drainage systems, or elevated groundwater levels, even in the absence of extreme rainfall. Together, these findings underscore the complexity of flood-generating mechanisms across the District of Abidjan (see figure 10).

4. Discussion

In sections (3.1) and (3.2), we evaluated SRE products in the District of Abidjan over the period 2019–2022. Despite a strong negative bias −33.34% (figure 5(a)), IMERG-EARLY shows lower absolute errors (figure 5(b)) compared to IMERG-FINAL and CHIRPS slightly better performance for extreme rainfall detection, consistent with earlier findings (e.g., Monsieurs *et al* 2018, Ageet *et al* 2022). However, CHIRPS presents a much lower bias (−13.82%) and higher correlation values (figure 5(e)), suggesting a better ability to capture the spatial and temporal distribution of extreme rainfall events.

Djakouré *et al* (2024) highlighted that extreme rainfall in the District of Abidjan is most related to oceanic and atmospheric mesoscale convective systems (MCS).

For this reason, satellite-based rainfall underestimates convective rain amounts because it fails to capture extreme rainfall′s magnitude and timing. This discrepancy is likely due to the inherent limitations of satellite sensors in capturing the rapid evolution of convective systems, particularly in regions with intense local precipitation (Maranan *et al* 2020, Djakouré *et al* 2024).

Furthermore, it is important to note that the analysis of SRE products is based on point-to-pixel perspective (e.g., Maranan *et al* 2020, De Waal *et al* 2025) which may inherently affect the accuracy and the comparability of the extreme rainfall rates between the SREs and RGs (Ageet *et al* 2022).

The high population density and the proliferation of informal settlements further amplify the risks of flooding, making rainwater management more challenging. Moreover, the frequent occurrence of floods in recent years (figure 6) can result from a combination of demographic growth and the intensification of extreme precipitation (Danumah *et al* 2016, IPCC 2022, Yao *et al* 2024).

Notably, the increased precipitation intensities are also partly linked to a rainfall recovery driven by natural factors, such as decadal variability associated with climate change (Sanogo *et al* 2015, Nicholson *et al* 2018). Seasonal trends reveal a strong correlation between flooding and the main rainy season, while the spatial distribution of fatalities highlights the vulnerability of specific communes, such as Cocody and Yopougon (e.g., Coulibaly *et al* 2024, Yao *et al* 2024). Furthermore, rapid urban development and increasing population density have significantly impacted the frequency and intensity of flood events by altering land-use patterns (e.g., Li *et al* 2016, Gosset *et al* 2023). The expansion of impervious surfaces, such as roads and buildings, has reduced natural water absorption, leading to increased surface runoff and overwhelming drainage systems as highlighted by Song *et al* (2015) and Li *et al* (2016). In areas like Cocody and Yopougon, urban sprawl has encroached on natural floodplains, disrupting the hydrological balance, while in Attecoube, informal settlements on steep slopes have heightened susceptibility to flooding and landslides. Similarly, in Anyama, rapid expansion into low-lying and uneven terrain has exacerbated flood risks.

The high population density and the proliferation of informal settlements further exacerbate the risks, making rainwater management even more challenging, thereby amplifying the risks of flooding. The frequent occurrence of floods in recent years can result from a combination of demographic growth and the intensification of extreme precipitation (Danumah *et al* 2016, IPCC 2022, Yao *et al* 2024). Notably, the increased precipitation intensities are also partly linked to a rainfall recovery driven by natural factors, such as decadal variability associated with climate change (Sanogo *et al* 2015, Nicholson *et al* 2018).

These transformations, driven by demographic pressure and unregulated urbanization, may have played a role in amplifying the impact and recurrence of flooding in these vulnerable communes (Danumah *et al* 2016). Although damage estimates have not been compiled for some floods, significant material and infrastructure damage (including houses, roads, schools, shops, and cars) has been reported.

The rising trend of floods in the District of Abidjan is part of a broader pattern seen in many West African capitals (Douglas *et al* 2008). Fofana *et al* (2022) underscore the significant link between extreme rainfall events and flash floods in Bamako in the last decade of the study period from 1982 to 2019.

5. Conclusion

The main purpose of this study is to evaluate the performance of the SRE products through comparison with ground-based station data for the period 2019–2022. Then, based on a flood event occurring in the District of Abidjan from recent decades, analyse the associated flood-generating processes. Analysing historical disaster events is crucial for understanding current risk levels and assessing how disaster risks evolve. While disaster databases provide valuable insights into trends, the criteria for event inclusion remain a critical factor in their reliability and accuracy. We found systematic differences and errors in the satellite-based estimate products that make them suitable for different applications at different spatial and temporal scales.

The rationale for using different SRE products is to determine whether the conclusions obtained vary depending on the data set, given that there is no benchmark or reference data set for the District of Abidjan region. We agree that the period may appear relatively short; this is mainly due to the limited availability of rain gauge station data, which constitutes one limitation of this study. More available data from both RG and SRE products will be needed to strengthen the assessment and enhance the reliability of the results.

Despite this limitation, our findings indicate that the performance of the satellite products declines for extreme events ($>95^{th}$ percentile) compared to rainy events ($\geqslant 1$ mm) across all satellite products in the District of Abidjan. Nevertheless, based on statistical metrics presented in tables 2–3, both IMERG-EARLY and CHIRPS appear as the most reliable products for the characterization of extreme rainfall over the District of Abidjan during the evaluation period (i.e., 2019–2022).

In recent decades, the District of Abidjan has experienced recurrent flooding, resulting in significant damage and numerous losses of life. Thus, over this period (1990–2022), 210 urban flood events were documented, causing nearly 170 fatalities. The analysis of these events shows that flood characteristics vary across space, depending on flood-generating mechanisms.

The District of Abidjan experienced two years with elevated numbers of flood events in 2014 and 2021, with 37 and 29 cases, respectively, compared to an average of 7 events per year from 1990 to 2020. Most flood events (146 representing 70% of the total events) occur in June, the peak of the main rainy season.

In terms of spatial occurrence, the most affected communes were Cocody (47 events, 31%) and Yopougon (42 events, 18%), followed by Abobo (29 events, 14%). Danumah *et al* (2016) had identified these areas as vulnerable to flood risk. These areas have undergone substantial urban expansion over the past two decades, which may have increased their vulnerability to flood risk through uncontrolled expansion of impermeable surfaces. This has led to increased surface runoff and a rapid hydrological response to heavy rainfall. When combined with the lack of maintenance of these systems and the limited institutional capacity of urban administrations to manage such challenges, the risk of urban flooding is significantly amplified. Nevertheless, rainfall intensity (cf figure 10) has also been identified as important factor that could influence flooding.

Regarding the characterization of flood-inducing precipitation, IMERG-EARLY and IMERG-FINAL present relatively similar distributions most dominated by heavy rainfall ($>$30 mm day^{-1}). However, IMERG-EARLY emphasizes a slightly higher percentage of severe events. Meanwhile, CHIRPS shows a significant increase in severe rainfall events for most municipalities compared to the IMERG datasets. Severe rainfall events (exceeding 50 mm day^{-1}) constitute the largest share across all datasets and municipalities, underscoring their critical role in triggering floods. This classification could be a limiting factor in attributing flood events to extreme rainfall, as another factor exacerbating flood risk lies in the distribution of daily precipitation. Therefore, it is essential to have a clear understanding of the flood-generating mechanisms across the District of Abidjan.

The results revealed that nearly 75% of floods are caused by excessive or short-duration rainfall episodes. Excess rainfall could indeed have a contribution by soil saturation; however, the short rainfall may be linked to intensities, not necessarily soil saturation highlighting their role in triggering floods. These findings are consistent with the results of Tramblay *et al* (2022), which show that 75% of flood events are dominated by excess rain in West Africa. Heavy rainfall with high antecedent soil moisture has also been identified as a dominant driver of floods worldwide (Berghuijs *et al* 2016, 2019, Wasko *et al* 2020, Tramblay *et al* 2021). That said, we acknowledge that this result has its limitations, as Di Baldassarre *et al* (2010) have shown that it′s challenging to distinguish the effects of climate change from those of human activities. To identify a clear climate signal in floods, we require reliable long-term runoff data that accurately reflects natural and runoff conditions.

However, this study provides valuable insights into the underlying causes of urban flooding in the District of Abidjan, offering a foundation for improving flood risk assessments and informing decision-making processes that can lead to more effective and sustainable flood management strategies in the District of Abidjan.

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Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: https://disc.gsfc.nasa.gov/; https://www.chc.ucsb.edu/data/chirps.

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