



Linking rainfall spatial organization and distributed travel times to critical flood-contributing areas in a mountainous urban catchment.

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Abstract.

Extreme rainfall events can produce different flood responses depending on how rainfall is organized across a catchment and how this organization interacts with the drainage system. This study examines the spatial and temporal characteristics of four high-magnitude rainfall events and their associated flood responses in the Medellín River–Aula Ambiental catchment in the Valle de Aburrá, Colombia. The analysis combines weather radar observations, measurements from a dense network of rain gauges, and high-frequency river level and discharge records. The events were characterized according to rainfall magnitude, spatial distribution, temporal evolution, displacement, and location within the catchment. These characteristics were then examined in relation to rainfall distribution across areas with contrasting degrees of urbanization and to the timing of rainfall relative to the observed river response.

The results indicate that the spatial organization and movement of rainfall can play an important role in shaping the magnitude and timing of the hydrological response. Events with rainfall concentrated along the drainage network or over highly urbanized areas produced a more spatially synchronized contribution to the river response, whereas rainfall occurring in less urbanized or less hydraulically connected parts of the catchment contributed differently to the observed response. The analysis also shows that the area contributing to the flood peak can vary substantially among events, highlighting the dynamic nature of rainfall–catchment interactions.

The findings suggest that rainfall accumulation alone may not fully describe the potential hydrological response of a high-magnitude event. The location, movement, and spatial organization of rainfall provide additional information for interpreting flood response in urbanizing catchments. Future research could investigate these relationships using larger event samples and synthetic rainfall generation, while incorporating distributed travel times and a wider range of rainfall spatial configurations to further examine their implications for flood response.



1. Introduction

1.1 Spatial and temporal organization of rainfall matters

Extreme rainfall events exhibit pronounced spatial and temporal variability, particularly in mountainous catchments where precipitation is influenced by elevation, topography, and slope orientation relative to prevailing atmospheric circulation (Leonard & Whipple, 2021; Poveda et al., 2025; Gomez-Rios et al., 2023). These patterns are hydrologically relevant because they determine where and when runoff is generated. During extreme events, recurrent or concentrated rainfall can enhance runoff, erosion, and sediment transport, while increasing hydrological connectivity across mountainous and urbanized catchments (Solano-Rivera et al., 2019; Velásquez et al., 2020).

This effect is amplified in highly urbanized catchment, where impervious surfaces reduce infiltration and increase the efficiency of runoff transfer toward drainage networks (Huong & Pathirana, 2013; Semadeni-Davies et al., 2008; Deng et al., 2025). Consequently, rainfall location relative to impervious areas and drainage pathways can influence not only runoff volume but also the timing of its downstream propagation. Previous studies have shown that the spatial distribution and movement of precipitation relative to the drainage network can modify the magnitude and timing of peak discharge (Douinot et al., 2016; Emmanuel et al., 2015; Ghimire et al., 2021). The rainfall centroid provides a compact representation of storm spatial organization and its displacement through time (Amengual et al., 2021; Cristiano et al., 2017), while weather radar provides the spatial and temporal resolution required to characterize these dynamics (Berne & Krajewski, 2013).

1.2 Travel time and hydrological connectivity

The hydrological effect of rainfall organization depends on the connectivity between runoff-generating areas and the drainage network. Hydrological connectivity controls the efficiency with which water generated over hillslopes is transferred toward channels and downstream reaches, with some areas acting as preferential runoff pathways that disproportionately influence flood response (Ali & Roy, 2010; Bracken & Croke, 2007; Jencso et al., 2009). Travel time provides a temporal representation of this connectivity, describing how long runoff generated at different locations is required to reach the outlet (Michaelides, K. 2009; Dwivedi, D., 2025; Liu, Y., 2021).

Flow velocity varies throughout drainage networks as a function of slope, geometry, roughness, discharge, and contributing area, but hydraulic-geometric relationships can be used to estimate spatially distributed velocities and transit times where detailed hydraulic models are unavailable (McGuire & McDonnell, 2006; Gleason & Smith, 2014). In urban catchments, engineered drainage systems can further accelerate runoff transfer, making travel times particularly relevant to the rapid response of steep urban catchments (Reyes-Silva et al., 2020; Walsh et al., 2005, Agonafir C. et al., 2023). Thus, runoff generated at different locations may reach the outlet at different times, while rainfall occurring at different times and locations may produce runoff contributions that converge within the same stage of the hydrograph (Dharmarathne, G. et al, 2024; Ghomash, S. K. et al, 2022).

1.3 Gap: lack of dynamic coupling

Although rainfall organization and hydrological connectivity have been extensively studied, they are commonly analyzed as separate components of catchment response (Lu, M., 2023; Nikolopoulos, E. I., 2011; Oswald, C. J., 2023; Sigaroodi, S. K., 2016). Rainfall studies typically characterize intensity, accumulation, spatial variability, or storm movement, whereas routing approaches focus on runoff propagation through the drainage network. Consequently, there remains a need to explicitly link



the evolving spatial organization of rainfall with distributed travel times to determine which portions of a catchment contribute to a flood peak at a given stage of the hydrograph (Saghafian, B., 2002; Solano-Rivera, V., 2019).

This distinction is important because rainfall accumulation alone does not determine peak-flow magnitude. A storm with greater accumulation may generate a lower peak if runoff contributions are temporally dispersed, whereas a storm with lower accumulation may produce a larger peak when rainfall organization and travel times favor the simultaneous arrival of runoff from spatially distributed areas. The effective contributing area is therefore dynamic, changing throughout the event according to rainfall location, storm movement, drainage connectivity, and runoff travel times.

1.4 Objective and hypothesis

This study aims at developing a framework to investigate the dynamic coupling between rainfall organization and distributed travel times in the Medellín River–Aula Ambiental catchment (W1), a highly urbanized mountainous area in the Aburrá Valley, Colombia. High-resolution weather-radar observations are used to characterize the spatial and temporal organization of rainfall and storm movement, while a distributed travel-time field represents the spatial variability of runoff propagation through the drainage network. These components are coupled to identify the portions of the catchment whose runoff contributions become synchronized with critical stages of the flood hydrograph.

The analysis considers both recurrent spatial rainfall patterns, characterized by a high probability of occurrence, and rainfall patterns associated with extreme flood events, which may be rare or have low recurrence. Their relationships with impervious surface coverage and rainfall-centroid dynamics are subsequently evaluated. Analysis evaluates their relationship with impervious surface coverage and rainfall-centroid dynamics. This dual characterization also allows the identification of two hydrologically relevant zones: Z1, associated with rainfall concentrations during extreme flood events, and Z2, representing areas of recurrent rainfall occurrence. Distinguishing these zones provides a spatial basis for evaluating whether areas that frequently receive rainfall also coincide with sectors that become particularly important during extreme flood response.

We hypothesize that flood response is controlled not only by rainfall magnitude, but by the degree of temporal synchronization between spatially distributed runoff generation and catchment travel times. Specifically, rainfall events whose location and movement favor the alignment of runoff contributions from highly connected and impervious areas are expected to produce larger and more concentrated flood peaks, even when their total rainfall accumulation is lower.

2. Study Region and data

The city of Medellín and the Aburrá Valley Metropolitan Area are located in the Central Cordillera of the Colombian Andes, between approximately 6.0°–6.5°N and 75.3°–75.6°W. The metropolitan area occupies a narrow, highly urbanized valley where expansion has progressively extended toward the surrounding hillslopes. The valley extends approximately 64 km from south to north, with a width ranging from 3 km to 18.2 km between opposite drainage divides. Population density is approximately 359 inhabitants ha⁻¹ (AMVA-EAFIT, 2018). The hydrological system is organized around the Medellín River, which flows predominantly south to north and receives runoff from numerous tributary catchments. The basin covers approximately 1,251 km² and has an elongated configuration, with a main channel extending approximately 104 km across an elevation range of 1,300–2,800 m a.s.l. (Fig. 1a).

The combination of steep terrain and extensive urbanization strongly influences the hydrological response. Most tributary catchments have slopes ranging from 15% to 45% and varying impervious surface coverage, reaching approximately 80% in



highly urbanized sectors. Imperviousness increases runoff generation and accelerates its transfer to the drainage network, while urban expansion has modified natural flow pathways through sewers, channels, and hydraulic structures. These conditions promote rapid runoff propagation toward the valley floor, where limited drainage capacity can increase flood susceptibility.

The climate of the Aburrá Valley is characterized by a bimodal rainfall regime with two wet and two relatively dry seasons. This seasonality is primarily associated with the meridional migration of the Intertropical Convergence Zone (ITCZ), while local topography and atmospheric circulation modulate convective activity throughout the year (Poveda et al., 2025; Gomez-Rios et al., 2023; Hoyos, C.D. et al., 2020; Herrera-Mejía and Hoyos, 2019). The main wet seasons occur during March–May (MAM) and September–November (SON), whereas relatively drier conditions prevail during December–February and June–August. Annual precipitation ranges from approximately 1,400 to 2,500 mm depending on location and elevation. Rainfall also exhibits a pronounced diurnal cycle, with peaks generally occurring during the afternoon and early morning and minimum rainfall between approximately 09:00 and 11:00 local time (Bedoya-Soto et al., 2019). This combination of rainfall variability, steep terrain, and urbanization provides favorable conditions for rapid hydrological responses and extreme flood events.

Within this setting, the Medellín River–Aula Ambiental catchment (W1) was selected as the main study area because continuous and reliable streamflow observations have been available since 2012 through the hydrometeorological monitoring network operated by the Early Warning System of Medellín and the Aburrá Valley (Ruiz-Carrascal, D., 2026). Two smaller urban catchments, Doña María (W2) and La Presidenta (W3), were also considered to evaluate the applicability of the framework across different spatial scales and degrees of urbanization (Table 1). Impervious surface coverage is approximately 16% in W1, 8% in W2, and 24% in W3, providing contrasting conditions for assessing the influence of rainfall organization and hydrological connectivity on flood response.

The hydrological relevance of these catchments is further evidenced by the frequency of reported flood events. According to records from the Early Warning System of Medellín and the Aburrá Valley (AMVA-SIATA 2026), 413 flood-related events associated with catchment W1, W2 and W3 were reported between 2012 and 2025 across the catchments listed in Table 1 (Fig. 1b). Of these, 46 were classified as producing moderate to severe impacts based on observed water depths. The annual distribution of events (Fig. 1c) broadly follows the regional bimodal rainfall regime, with most events occurring during the MAM and SON wet seasons. This correspondence highlights the sensitivity of the urban catchments of the Aburrá Valley to extreme precipitation and provides the hydrometeorological context for the analysis.

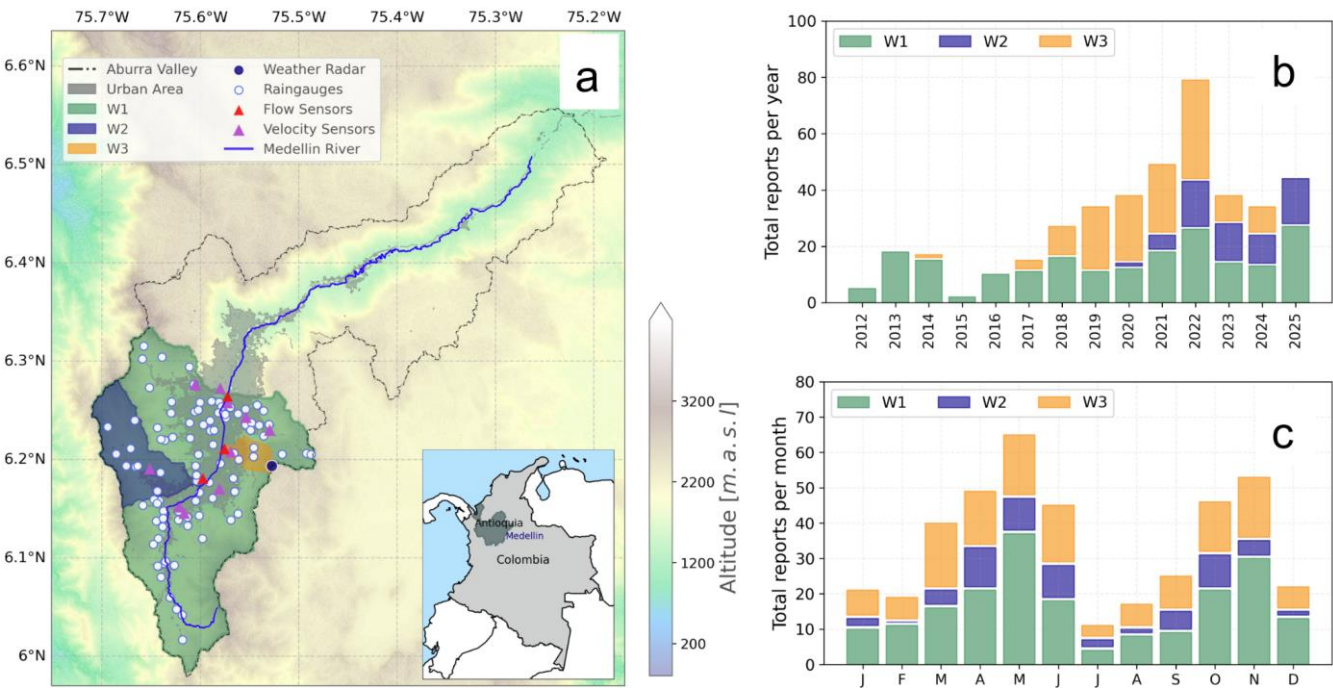


Figure 1. Study area and temporal distribution of reported flood events in the Aburrá Valley. (a) Location of the Medellín River–Aula Ambiental (W1), Doña María (W2), and La Presidenta (W3) catchments, together with the Medellín River, weather radar, rain gauges, and hydrological monitoring stations. The background represents the digital elevation model. (b) Annual number of reported flood-related events associated with urban drainage between 2012 and 2025 for the three study catchments. (c) Monthly distribution of reported flood-related events, highlighting the seasonal variability associated with the bimodal rainfall regime of the Aburrá Valley.

Table 1. Characteristics of the study subcatchments. The last column shows the number of reported flood events, and the asterisk indicates events exceeding the 90th percentile of peak level.

Subcatchment	Area (km ²)	Channel slope (%)	Impervious area (%)	Start of water level records	Number of reports
W1. Medellín River	470	2	16	2012	198 (21*)
W2. Doña María	73	5	8	2020	69 (10*)
W3. La Presidenta	15	17	24	2014	146 (15*)
				Total	413 (46*)



The physical processes governing runoff generation and flood propagation in the Aburrá Valley require hydro-meteorological observations with adequate spatial and temporal resolution. This study focuses on steep, highly urbanized catchments characterized by rapid hydrological responses; therefore, rainfall and flow observations must adequately resolve the relevant response timescales. Hydro-meteorological data for the 2012–2025 period were obtained from the Early Warning System of Medellín and the Aburrá Valley (SIATA), including two complementary sources of rainfall observations: remote sensing from a C-band weather radar and ground-based measurements from a network of rain gauges (Ruiz-Carrascal et al., 2026). The radar provides spatially distributed rainfall estimates over the study area at 5-min temporal and approximately 120 m spatial resolution; its application and processing in the Aburrá Valley are described in (Sepúlveda Berrío, J., 2015). The rain-gauge network provides 1-min observations from 93 sensors distributed across the study catchments.

Streamflow and surface-velocity observations, also provided by SIATA, are available at 1-min resolution and comprise three flow sensors and 12 surface-velocity sensors (Fig. 1a). Fig. 2a–2c show the distribution of peak water levels for the identified events in catchments W1, W2, and W3, respectively. Fig. 2d presents the available surface-velocity records, with monitoring stations ordered according to their contributing catchment area. This area-based classification is used in the subsequent analysis to characterize and parameterize surface-flow velocity across the drainage network.

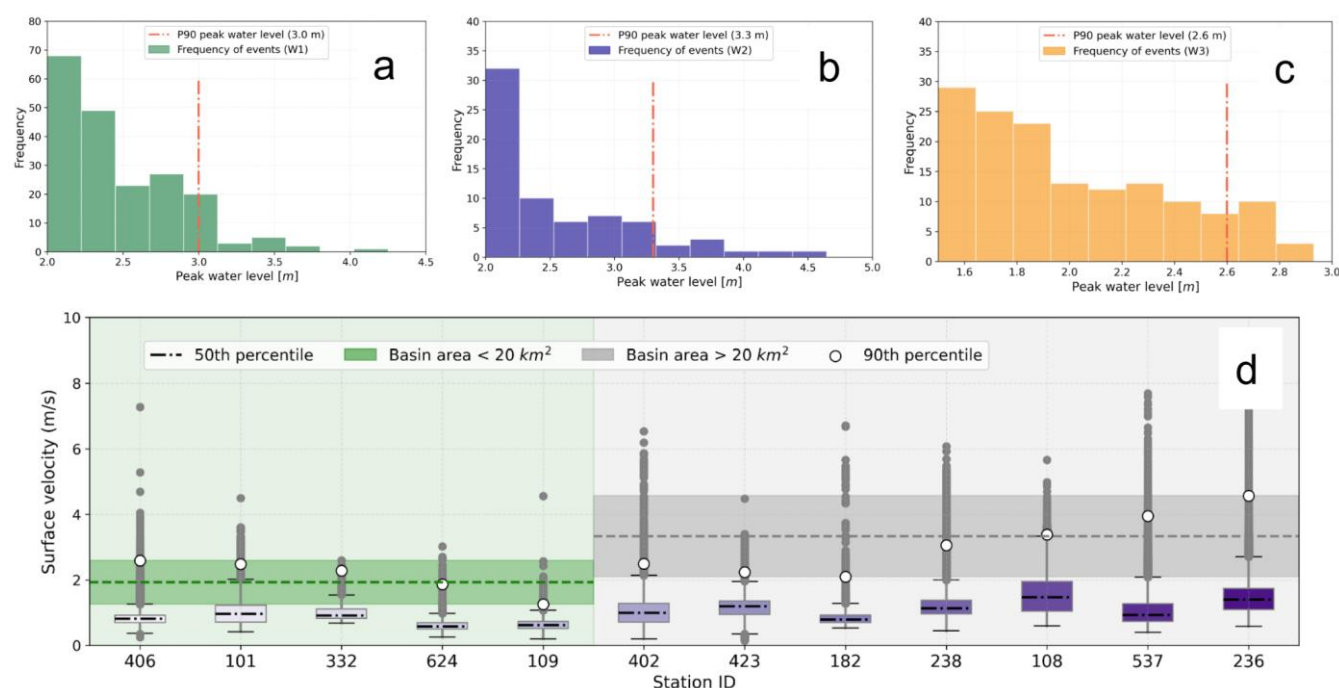


Figure 2. Distribution of peak water levels and surface-velocity observations across the study catchments. (a–c) Histograms of peak water levels for the identified events in W1, W2, and W3, respectively. The red dash-dotted lines indicate the 90th percentile of peak water level for each catchment, and the shaded bars represent the frequency of events. (d) Distribution of observed surface velocities across monitoring stations, grouped according to the contributing catchment area. Green and gray backgrounds represent catchment areas below and above 20 km², respectively. Boxplots summarize the observed velocity distributions, while dashed lines and open circles indicate the 50th and 90th percentiles, respectively. Velocity sensors are identified by their station IDs.



In addition to hydro-meteorological observations, a digital elevation model derived from NASA ALOS PALSAR data (2023) was used to characterize catchment topography and drainage pathways. A land-use map from Ruiz-Carrascal et al. (2026) was used to delineate impervious surfaces within the study catchments. Finally, the regional public utility company (EPM) provided detailed altimetric and planimetric information, as well as nodes and pipe parameters (e.g., diameter, roughness, altitude, length) and other relevant data. These data comprise georeferenced elevations, upstream and downstream node locations, and outfall coordinates connecting the sewer system to the surface drainage network. Together, these datasets provide the spatial and temporal information required to characterize rainfall organization, estimate distributed travel times, and evaluate their coupling with the observed hydrological response.

3. Methodology

To identify and characterize the critical zones controlling the hydrological response of the study catchments, a multi-stage methodological framework was developed. First, extreme hydrometeorological events were identified, considering only those with complete records from water level sensors, rain gauges, and weather radar. Next, the spatial and temporal characteristics of each event were analyzed to determine its localization, trajectory, and frequency (Alshammari et al., 2023; Ten Veldhuis et al., 2018; Zhou et al., 2021). Based on this analysis, travel times (isochrones) were estimated and validated throughout the drainage network, including both the urban storm sewer system and the natural stream network draining to the catchment outlet. Finally, the estimated travel times were used to delineate the specific catchment areas contributing to the observed peak flows during the selected extreme events.

3.1 Identification and characterization of flood events

Events were identified from historical water level records by extracting the timestamp of the peak stage for each high-flow event. This timestamp was used as the baseline to define the time window for collecting water level and precipitation data, ensuring a complete record of each event.

The duration of the analysis window was defined based on the catchment's Time of Concentration (T_c), which represents the time required for runoff generated in the most distant part of the catchment to reach the outlet. This parameter can serve as the effective time window to capture the representative distribution of rainfall within a catchment (Richard McCuen, 1984; McCuen, 2009; Michailidi et al., 2018). Empirical equations commonly recommended for urban catchments (Azizian, 2018; Mehta et al., 2022) were applied to the largest catchment (W1), yielding individual T_c estimates of 315 min (Kirpich, 1940), 256 min (Picking, 2005), and 260 min (Témez, 1987), with an average value of approximately 277 min. Given the similarity among the estimates, a standardized 5-hour (300-min) rainfall window was established as the operational period for all three analyzed catchments.

For the general characterization of rainfall events associated with flooding, all events described in Sect. 2 were considered. However, travel times were estimated using only those events for which the peak water level exceeded the 90th percentile of the historical record, a threshold selected to isolate hydrologically significant events while retaining a sufficient sample size for robust travel-time estimation across the three catchments. This selection criterion resulted in a database comprising water-level hydrographs, representing the hydrological response, together with rainfall hyetographs derived from both the rain-gauge network and weather radar, representing the hydrological forcing. A total of 21 events were analyzed for W1, 10 for W2, and 15 for W3.

3.2 Characterization of rainfall spatial organization



The identification of critical hydrological response zones was based on the spatial characterization of rainfall patterns across the study catchments, using an integrated analysis of weather radar and rain gauge observations. As illustrated in Fig. 3, the methodology consisted of four sequential steps: (1) characterization of rainfall patterns, (2) generation of rainfall probability maps, (3) spatial overlay and classification, and (4) threshold selection to delineate the critical hydrological response zones.

For the largest catchment (W1), weather radar observations covering the period 2014–2025 were used to characterize the spatial distribution of rainfall. Two complementary analyses were performed independently:

3.2.1 Recurrent rainfall

Daily rainfall accumulations from the complete radar record were analyzed to characterize the long-term spatial persistence of precipitation. For each radar pixel, daily accumulations were summed over the full record (2014–2024) to obtain a single total accumulated value per pixel. These pixel-wise totals were then converted into percentile values by ranking the accumulation at each pixel with the corresponding accumulations across the other pixels of the spatial grid, allowing the spatial recurrence of rainfall to be compared across the catchments. Pixels with higher percentile values represent locations where rainfall most frequently reaches high accumulations relative to the other pixels in the domain, and therefore define the typical rainfall pattern.

3.2.2 Flood-associated rainfall

The flood events described in Sect. 2 were considered (Table 1). For each event, rainfall accumulations during the 5-hour period preceding the observed peak water level were calculated for each radar pixel. These event-based accumulations were then summed over all flood events to obtain a single total accumulated value per pixel. As in the previous analysis, these pixel-wise totals were subsequently converted into percentile values by ranking the accumulated rainfall at each pixel relative to the corresponding accumulations across the other pixels of the spatial grid. Pixels with higher percentile values represent locations where rainfall accumulations are systematically higher relative to the other pixels in the domain during the selected flood-producing events, and therefore define the typical spatial rainfall pattern associated with these events.

The two percentile maps represent complementary aspects of the rainfall regime. The first describes the long-term spatial recurrence of precipitation, whereas the second characterizes the spatial distribution of rainfall associated with flood generation. These maps were subsequently overlaid to classify the catchments according to the joint occurrence of typical and flood-associated rainfall (Fig. 3).

This classification was performed using percentile thresholds applied independently to both percentile maps. The threshold percentile values were selected to maximize the hydrological contrast among the resulting zones based on two criteria: (i) the percentage of impervious surface coverage and (ii) the spatial distribution of storm centroids during flood events. The resulting classification identifies areas exhibiting different levels of hydrological response, from low-priority zones to critical areas with a high likelihood of contributing to flood peak generation.

The analysis considers both recurrent spatial rainfall patterns and rainfall associated with extreme flood events, evaluating their joint occurrence together with impervious surface coverage and rainfall-centroid dynamics. This dual characterization enables the delineation of two hydrologically relevant zones from the spatial overlay of both rainfall maps: Z1, which concentrates the highest impervious surface coverage (78%, 125 km²) and centroids of extreme events with peak water levels below the 95th percentile, and Z2, covering a smaller impervious area (22%, 35 km²) and concentrating centroids of the most extreme events, with peak water levels exceeding the 95th percentile. Distinguishing these zones provides a spatial basis for evaluating whether areas that frequently receive rainfall also coincide with sectors that become particularly important during



extreme flood response. The remaining portions of the catchment that do not meet the 60th-percentile threshold for either of the spatial criteria are assigned a lower priority for subsequent analysis. These areas represent comparatively lower values of the combined indicators used to delineate the zones Z1 and Z2.

3.2.3 Centroids and trajectories

To characterize the spatial organization and evolution of rainfall during flood events, rainfall centroids were computed at two temporal scales. A static centroid was calculated from the cumulative rainfall over the 5 hour analysis window, representing the overall spatial distribution of total accumulated during each event. Dynamic centroids were calculated from progressively accumulated rainfall at 5 minute intervals, allowing the temporal displacement of the rainfall center of mass to be tracked throughout the event.

Centroid coordinates were estimated by adapting the formulations proposed by Emmanuel et al. (2015) and Douinot et al. (2016), with the accumulation interval (Δt) defined according to the temporal scale. For the static centroid, Δt corresponded to the complete 5 hour analysis window, whereas for the dynamic centroids, rainfall accumulation was updated every 5 minutes, consistent with the temporal resolution of the rainfall data.

The dynamic centroids were used in this study to characterize the trajectory of rainfall events by tracking the progressive displacement of the rainfall center of mass throughout each event. The sequence of centroid positions provides a quantitative representation of storm movement, including its predominant direction and spatial progression across the catchment. In the context of this study, centroid trajectories were used to characterize the spatial dynamics of extreme rainfall events and to examine their relationship with catchment response and hydraulic travel times (see Sect. 4.3). This tracking analysis was restricted to events exceeding the 90th percentile of peak water level, allowing both the detailed kinematic paths and the overall trajectories of the most hydrologically significant events to be identified (Fig. 2).

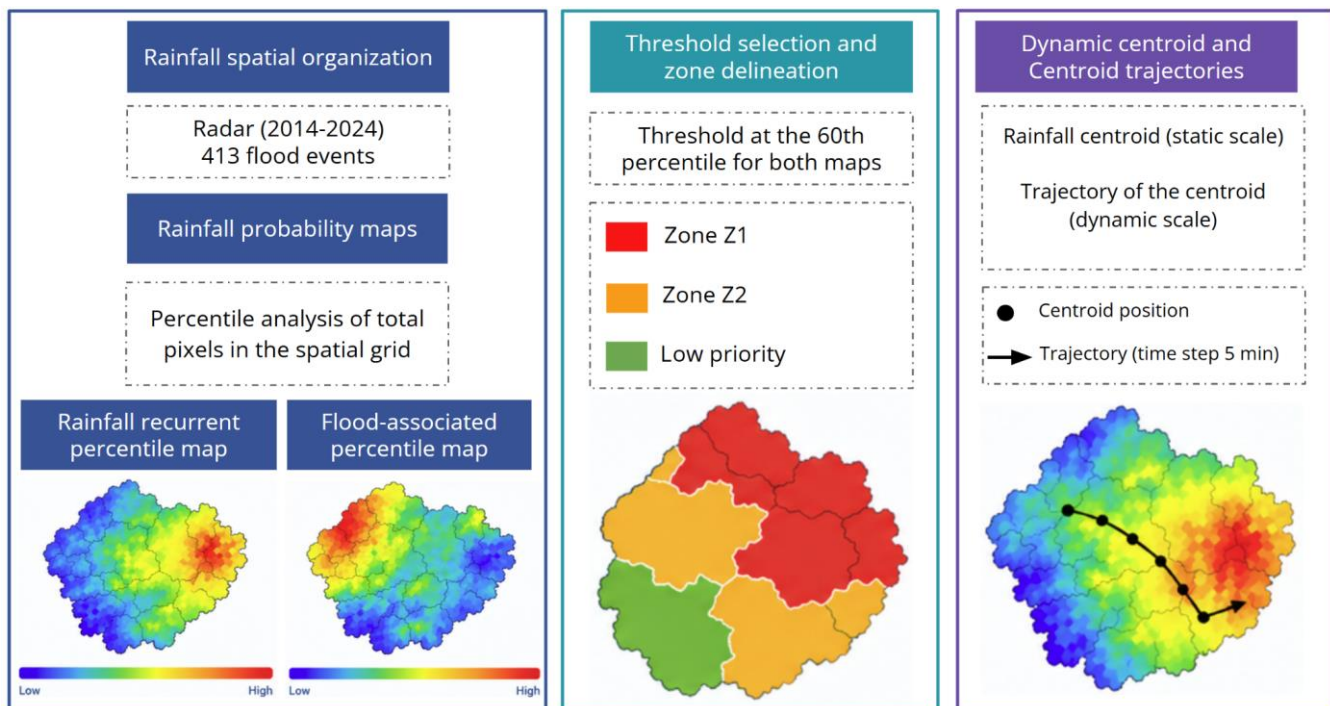




Figure 3. Methodological framework for characterizing rainfall spatial organization and hydrological response. Radar observations are used to derive spatial percentile maps of recurrent and flood-associated rainfall, which are combined to classify the catchment according to the joint occurrence of both rainfall patterns. Critical zones are delineated using thresholds selected from hydrological contrast, impervious surface coverage, and the spatial distribution of storm centroids. Static and dynamic centroids are then derived from cumulative and 5-min rainfall fields, respectively, and their trajectories are analyzed to characterize storm movement and its potential influence on the hydrological response.

3.3 Construction and evaluation of drainage-network travel times

To identify the specific catchment areas contributing to peak flow, this study proposes a methodological framework that maps each temporal increment of the hydrological response to a distinct spatial region within the catchment. This approach enables the determination of the spatial origin of runoff discharging through the outlet at any given time step. In urbanized catchments, this connectivity is amplified by storm sewer systems and impervious surfaces, which significantly reduce travel times and facilitate the rapid concentration of runoff (Dell’Aira & Meier, 2025; Reyes-Silva et al., 2020, Abedin, S. J. H., 2019).

Consequently, we propose the generation of a comprehensive travel time map that integrates the urban sewer system with the surface drainage network (comprising both Medellín River and its tributaries). This distributed travel time field serves as the fundamental analytical framework for diagnostic source-tracking. By coupling this spatial baseline with the kinematics of specific storm events, it is possible to isolate the exact geographical source areas contributing runoff to the hydrograph at any given temporal increment.

This procedure incorporates high-resolution official data on drainage infrastructure and a validation strategy utilizing temporal precipitation records (hyetographs) derived from weather radar and rain gauge networks. Fig. 4 presents the methodological framework, which is structured into four main phases:

3.3.1 Sewer

Residence times were estimated based on the physical characteristics (length, slope, and diameter) of each pipe segment. Flow velocity in urban systems is conventionally estimated using Manning’s equation (Chow, 1959). Due to its computational efficiency and minimal hydraulic data requirements, this approach is widely applied to characterize travel times in stormwater networks (Rossman & Bernagros, 2019 ; Yen & Asce, 2002). In this study, a simplified formulation of Manning’s equation, as described by McCuen (2009), Reyes-Silva et al. (2020), and Farina et al. (2023), was used to estimate travel times without explicitly specifying roughness coefficients. This simplified formulation assumes that slope and pipe geometry provide the primary controls on flow velocity, while the variability in roughness is not explicitly represented.

Finally, the cumulative residence time from any point in the network to the surface discharge point (T_{path}) was derived by summing the individual residence times of all pipes in the network (T_{pipe}) belonging to a defined path, as expressed in Eq. (1) and Eq. (2):

$$T_{pipe} = \frac{L_{pipe}}{D_{pipe}^{2/3} \cdot S_{pipe}^{1/2}}$$

(1)

$$T_{path} = \sum_{i=1}^N T_{pipe,i}$$

(2)



Where L_{pipe} is the length of the pipe in meters, S_{pipe} is the slope in m/m, D_{pipe} is the diameter in millimeters, and T_{pipe} is the residence time per pipe in seconds.

3.3.2 Surface network

The surface drainage network encompasses the hydraulic segments originating at storm sewer outfalls and extending through the tributary stream network to their confluence with the Medellín River, ultimately terminating at the catchment outlet. Travel time calculations within this surface drainage network were parameterized using empirical flow-velocity records from 12 monitoring stations located along the tributaries and 6 stations situated along the main stem of the Medellín River.

Extensive research has shown that spatial variations in flow characteristics can be effectively represented through hydraulic-geometric relationships, whereby velocity, top width, and mean flow depth exhibit systematic changes across the drainage network as a function of discharge and contributing area (McGuire & McDonnell, 2006; Gleason & Smith, 2014; Jencso et al., 2009). To account for these variations under high-flow conditions, a reach classification framework based on contributing drainage area was implemented, using drainage area as a proxy for channel slope and hydraulic capacity.

To characterize velocities under extreme flood conditions, the 90th percentile of the historical velocity record was calculated for each monitoring station. For tributary stream segments, these high-flow velocities were then regionalized according to the upstream contributing area at the downstream node of each reach. A critical threshold of 20 km² was established to distinguish between high-gradient headwater channels (<20 km²) and lower-gradient valley reaches (>20 km²). This empirical threshold was supported by a scale-dependent analysis that revealed distinct hydrological responses and peak-flow magnitudes across these drainage-area ranges.

For the segments comprising the Medellín River, where monitoring-station density is considerably higher, velocity values were regionalized using a spatial proximity approach. Each river reach was assigned the 90th-percentile velocity derived from the nearest operational monitoring station.

With the regionalized velocity fields defined and segment lengths established, the residence time for each surface watercourse section (T_{stream}) was calculated as the ratio of the reach length (L_{stream}) to its corresponding high-flow velocity (V_{stream}), as expressed in Eq. (3). The total surface drainage residence time (T_{path-s}) from any given outfall to the catchment outlet was subsequently determined by summing the transit times of all sequential reaches composing that specific drainage route, as Eq. (4).

$$T_{stream} = \frac{L_{stream}}{V_{stream}}$$

(3)

$$T_{path-s} = \sum_{i=1}^N T_{stream,i}$$

(4)

3.3.3 Composite travel time

The comprehensive hydraulic travel time map was compiled by superimposing the independent residence times derived for the sewer system (Sect. 3.3.1) and the surface drainage network (Sect. 3.3.2). By establishing a rigorous topological alignment between the discrete routing paths of both networks, the total time from any source node within the catchment to the ultimate outlet was quantified using Eq. (5):



$$T_{total} = T_{path} + T_{path-s} \quad (5)$$

Where T_{total} represents the total hydraulic travel time, T_{path} is the cumulative urban drainage pipe residence time Eq. (2), and T_{path-s} is the cumulative surface drainage network routing and residence time Eq. (4).

3.3.4 Validation.

Based on the multi-network framework described above, a distributed hydraulic travel time field, hereafter referred to as the hydraulic isochrone map, was generated for catchment W1. This field provides a deterministic approximation of runoff travel times by coupling the modified Manning formulation for sewer system with empirically derived high-flow velocities across the surface drainage network. To evaluate the performance of this framework and quantify its associated uncertainty, an empirical validation protocol was developed by comparing the theoretical routing times with observations derived from weather radar fields, rain-gauge hyetographs, and high-resolution hydrographs recorded at the catchment outlet.

The hydraulic travel time computed in Sect. 3.3.3 represents the transit time of a runoff parcel from its initial injection node to the catchment outlet under extreme hydrometeorological conditions. At the catchment scale, this metric can be related to the concept of basin lag time (T_L), traditionally defined as the time interval between the centroid of effective precipitation and the occurrence of the resulting peak discharge or stage at the outlet (Chow, 1962; Beven, 2012). Rather than being strictly equivalent, the two metrics provide complementary representations of catchment response: the hydraulic travel time describes the propagation of individual runoff contributions through the drainage network, whereas basin lag time represents the integrated temporal response of the catchment to a rainfall event.

This catchment-scale response integrates the transit times associated with multiple components of the hillslope-drainage continuum, including overland flow, subterranean sewer conveyance, and open-channel routing. By jointly analyzing event-based radar rainfall fields, rain-gauge observations, and outlet stage records, the accumulated response time associated with these processes can be empirically constrained. The resulting empirical benchmark was then compared with the theoretical travel time matrix derived in Sect. 3.3.3.

As a first-order approximation, overland flow transit time was initially assumed to be negligible relative to the internal drainage-network travel times. This assumption is consistent with the hydrological behavior commonly observed in highly urbanized catchments, where extensive impervious surfaces, steep local gradients, and dense drainage networks substantially reduce the length of the hillslope-to-network pathway (Walsh et al., 2005; Fletcher et al., 2013; Butler & Davies, 2024). Nevertheless, this assumption was not imposed as a fixed condition in the validation procedure. Instead, its potential influence was incorporated explicitly into the uncertainty analysis.

To assess the robustness of the initial isochrone map, an uncertainty envelope was constructed around the empirically derived response times. For each discrete time step of the deterministic routing model, the observed event responses were used to define a range of plausible travel times. The lower bound of this envelope represents a highly efficient or accelerated routing condition, whereas the upper bound represents a delayed response scenario, thereby allowing for situations in which overland flow contributions, hillslope storage, or other unrepresented processes may introduce additional travel time. Fig. 4 presents the schematic architecture of the proposed validation protocol, whose sequential steps are described below.

Step 1: Estimation of event-based lag times via weather radar rainfall: For each selected extreme hydrometeorological event (Sect. 2), raw weather radar fields were processed to resolve the spatiotemporal distribution of precipitation across the



catchment domain. To filter out non-representative, low-intensity background noise, a localized grid-cell threshold was established; for every radar pixel exhibiting a cumulative precipitation depth exceeding 2 mm, a discrete rain hyetograph was reconstructed at a 5-minute temporal resolution. The temporal centroid of precipitation (T_{cen}) for each individual pixel was subsequently computed via the mass-moment formulation expressed in Eq. (6).

$$T_{cen} = \frac{\sum_{i=1}^K T_i \cdot R_i}{\sum_{i=1}^K R_i} \quad (6)$$

Where T_i denotes the discrete timestamp on the hyetograph, R_i represents the corresponding rainfall intensity pulse at time T_i , and K is the total number of temporal increments within the storm duration.

To deduce the empirical basin lag time (T_{lag}) unique to each spatial grid coordinate, this localized centroid was cross-referenced against the precise timestamp of the peak water stage (T_{peak}) recorded at the catchment outlet. Lag time was estimated using the centroid of total rainfall rather than effective rainfall, consistent with the highly urbanized character of the catchment, where impervious surfaces generate near-instantaneous runoff response with minimal infiltration losses. This relation follows the classical hydrologic derivation of basin lag time as the temporal distance separating the center of mass of effective rainfall from the maximum peak of the streamflow hydrograph (Chow, 1962; McCuen, 1984), formulated in Eq. (7).

$$T_{lag} = T_{peak} - T_{cen} \quad (7)$$

Step 2: Estimation of point-based lag times via the rain gauge network: To supplement the remote-sensing radar fields, data from 107 active, in-situ rain gauges distributed across the catchment were processed. For each operational gauge registering precipitation during a target event, a point-level hyetograph was reconstructed at a 5-minute temporal resolution, and its corresponding rainfall centroid was resolved via the mass-moment formulation defined in Eq. (6). By calculating the temporal offset between these localized centroids and the corresponding outlet hydrograph peak, empirical point-based lag times were determined via Eq. (7). This step generated a secondary validation database indexing the specific event timestamp, gauge coordinate pairs (latitude and longitude), empirical lag time (T_{lag}), and total cumulative rainfall depth for each ground-based instrument.

Step 3: Geospatial intercomparison: To evaluate the predictive accuracy of the deterministic isochrone framework, a spatial comparison was conducted between the modeled network travel times (T_{total}) and the empirically observed lag times (T_{lag}). The geographic coordinates of each observational monitoring point, encompassing both the discrete rain gauge locations and the centroids of the weather radar grid cells, were coupled with the nearest topological node within the composite hydraulic network model (Sect. 3.3.3). This geospatial matching enabled a direct, point-to-node pairing of estimated and observed transport times. The paired dataset was subsequently mapped onto a bivariate scatter plot relative to a 1:1 ($Y=X$) line of identity, facilitating a visual and statistical diagnostic of systematic bias, correlation, and structural dispersion.

Step 4: Quantitative performance evaluation and uncertainty quantification: To rigorously assess the alignment of the scatter fields generated in Step 3, the modeling performance for each evaluated event was quantified using a robust suite of goodness-of-fit metrics standardly deployed in hydrological model verification. These metrics include Pearson's correlation coefficient (R), the root mean square error ($RMSE$), the Nash–Sutcliffe efficiency (NSE), and the Kling–Gupta efficiency (KGE) (Nash & Sutcliffe, 1970; Gupta et al., 2009; Knoben et al., 2019; Vrugt, J. A., 2022).

Concurrently, the dispersion of the observational points relative to the 1:1 identity line was analyzed to isolate the predictive uncertainty embedded within the deterministic travel time estimates. Following frameworks for uncertainty assessment in



distributed hydrological parameters, this residual error distribution was used to construct a 90% confidence interval around the computed isochrone fields.

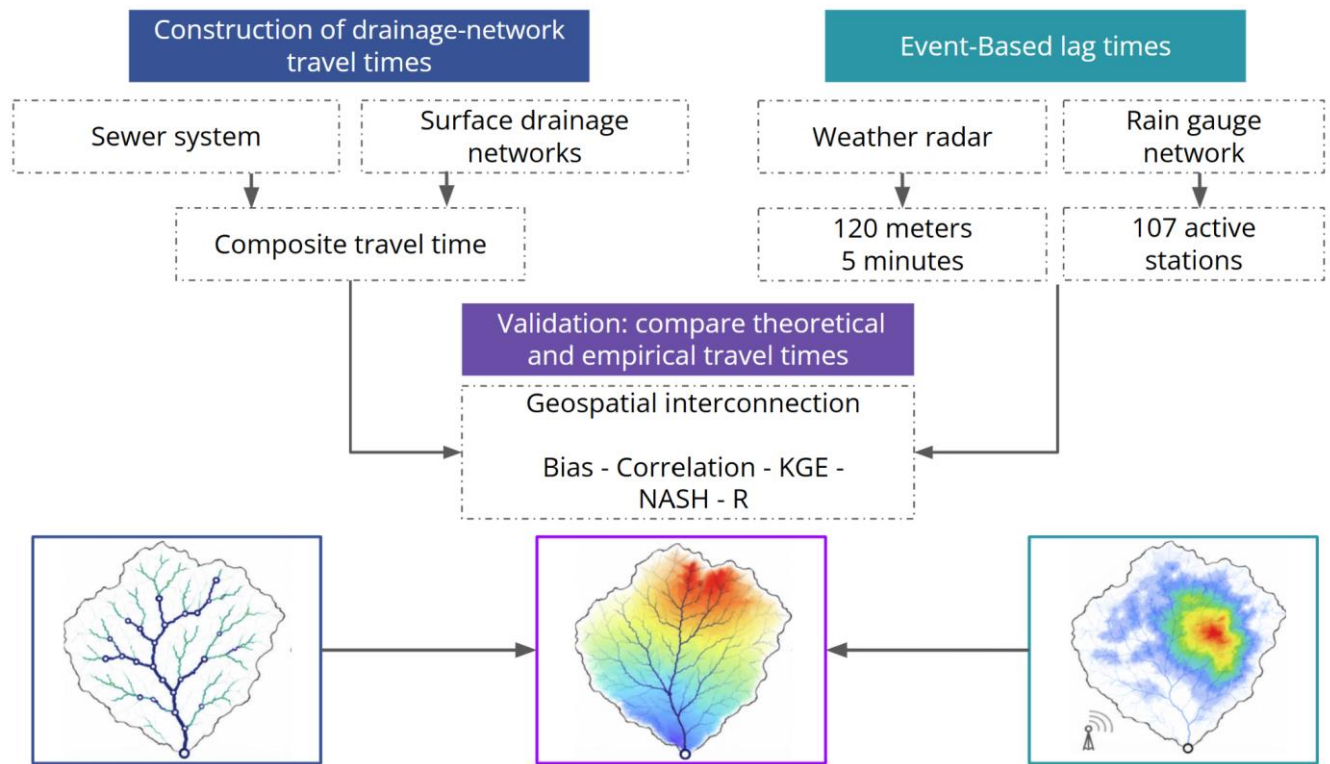


Figure 4. Methodological framework for the construction and validation of drainage-network travel times. Travel times are estimated separately for the sewer system and surface drainage networks, integrated to generate a hydraulic isochrone map, and subsequently evaluated using radar and rain-gauge-derived lag times, geospatial comparison, performance metrics, and uncertainty analysis.

3.4 Spatiotemporal coupling and dynamic contributing areas

For each target event, high-resolution quantitative precipitation estimations derived from weather radar grid cells were spatially coupled with the drainage network infrastructure. To ensure structural integration, radar grid centers were matched to their nearest topological node within the composite hydraulic model using a maximum search radius threshold of 300 meters. This spatial constraint ensures that the precipitation input is rigorously localized within the drainage network domain utilized in the theoretical transport estimation.

Following this spatial pairing, the temporal centroid of the precipitation hyetograph at each radar grid cell was designated as the baseline entry timestamp (T_0) for network routing. To explicitly bound the predictive uncertainty and temporal variability inherent in the catchment response, the ultimate arrival time of a runoff parcel at the catchment outlet was evaluated through three operational routing scenarios: a fast response (T_1), an expected response (T_2), and a slow response (T_3). These routing conditions were computed via Eq. (8), Eq. (9) and Eq. (10).



$$T_{1,i} = T_{0,i} + TV_{5,i} \quad (8)$$

$$T_{2,i} = T_{0,i} + TV_{50,i} \quad (9)$$

$$T_{3,i} = T_{0,i} + TV_{95,i} \quad (10)$$

Where:

- $T_{1,i}$, $T_{2,i}$, and $T_{3,i}$ represent the respective timestamps at the outlet associated with the fast, expected, and slow hydrological responses originating from node i .
- $T_{0,i}$ is the routing initiation timestamp (the precipitation centroid) at node i .
- $TV_{5,i}$, $TV_{50,i}$, and $TV_{95,i}$ denote the network travel times extracted from the error distribution at the 5th, 50th, and 95th percentiles, respectively, for node i .

To determine the geographic origin of streamflow contributions, the observed outlet hydrograph was continuously cross-referenced against the three space-time matrices derived from Eq. (8), Eq. (9) and Eq. (10). This integration identifies the specific subsets of nodes contributing to the total outflow discharge at any discrete temporal increment.

Consequently, the stage record or discharge value at any given clock time (t) is mapped to a dynamic, time-varying contributing area ($A_{s,t}$). This contributing matrix comprises all network nodes on the isochrone map whose calculated arrival windows enclose time t between the fast (T_1) and slow (T_3) boundary bounds, formulated as follows:

$$A_{s,t} = I_{map}[T_1 < t < T_3] = [N_1, N_2, \dots, N_i, \dots, N_n] \quad (11)$$

Where:

- $A_{s,t}$ is the set of active drainage network nodes contributing to the outlet discharge at time t .
- I_{map} represents the validated isochrone mapping matrix obtained in Sect. 3.4.
- T_1 and T_3 are the spatially distributed response-time fields corresponding to the 5th and 95th percentile routing envelopes, respectively.
- N_i denotes the discrete network nodes that satisfy the temporal transit condition ($T_1 < t < T_3$).

4. Results and Discussions

Travel times were estimated for the study catchments using the integrated hydraulic drainage network, composed of sewer system and surface drainage network, to characterize and delineate the areas contributing to streamflow during different stages of the hydrological response. This section is organized into three components: (i) the characterization of extreme rainfall events, (ii) the estimation of travel times, and (iii) the delineation of critical contributing areas for representative events selected as case studies.

4.1 Spatial organization of rainfall and critical zones



Figure 5a presents the flood-associated rainfall map, derived from rainfall accumulations during the five hours preceding the peak water level for the 413 selected flood events. The value assigned to each radar grid cell represents its percentile occurrence relative to the historical record analyzed. A value of 100% indicates that rainfall was recorded over that grid cell during all selected events, whereas a value of 0% indicates that no rainfall occurred at that location during any of the events.

Figure 5b shows the recurrent rainfall map, constructed from daily rainfall accumulations across the entire catchment during the 2014–2024 period, regardless of flood occurrence. Historical daily rainfall totals were standardized prior to the analysis so that grid cells with values of 100% represent the highest accumulated rainfall observed during the study period, whereas values approaching 0% correspond to the lowest rainfall accumulations.

Finally, Fig. 5c presents the combined map of flood-associated and recurrent rainfall zones, generated by applying a threshold corresponding to the 60th percentile in both maps. Grid cells exceeding this threshold in both the flood-associated (Fig. 5a) and recurrent (Fig. 5b) rainfall maps define the zone Z2. Conversely, grid cells exceeding the 60th percentile in the flood-associated rainfall map but remaining below this threshold in the recurrent rainfall map define the zone Z1. This zone is primarily located in the middle and lower portions of the catchment and largely coincides with highly urbanized areas, where impervious cover reaches approximately 78%.

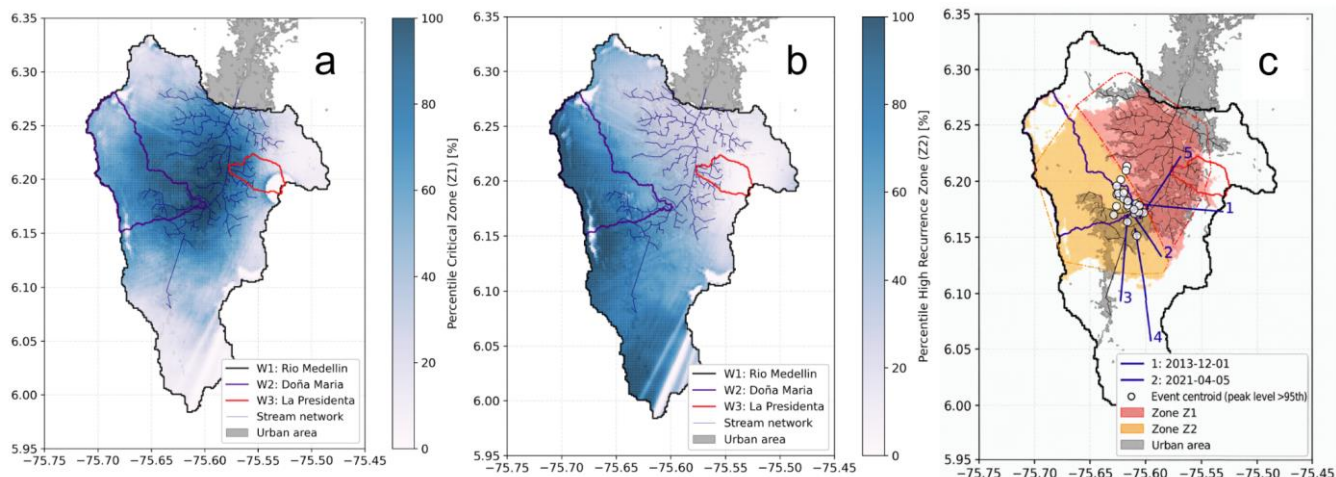


Figure 5. Spatial characterization of rainfall occurrence and critical source areas in the Medellín River–Aula Ambiental catchment (W1). (a) Flood-associated rainfall map derived from the cumulative precipitation during the five hours preceding the peak water level for the 413 selected flood events (Sect. 3.2.2). Values indicate the percentile of rainfall occurrence associated with flood-producing events. (b) Recurrent rainfall map derived from daily precipitation accumulated during the 2014–2024 period (Sect. 3.2.1). Values represent the percentile of historical rainfall recurrence. (c) Delineation of zone Z1 and zone Z2 using the 60th percentile threshold applied to both rainfall maps. Gray circles indicate the centroids of rainfall fields associated with events exceeding the 90th percentile of peak water level, while numbered labels identify the five representative case-study events. Urban areas and the hydraulic network are also shown.

Figure 5c also shows the rainfall centroids associated with events whose peak water level exceeded the 90th percentile (3 m). The spatial distribution of these centroids reveals a clear concentration within the zone Z2, suggesting that the most severe flood events are generally triggered by rainfall concentrated over this portion of the catchment. In addition, the trajectories of



the rainfall centroids (blue lines) are displayed for the five largest events in the historical record, whose peak water levels ranged from 3.4 to 4.2 m. These events were selected as case studies to evaluate the spatiotemporal coupling between rainfall evolution and travel times within the integrated hydraulic drainage network.

4.2 Drainage-network travel times and validation

Applying the methodology described in Sect. 3.3 yielded a travel-time map representing water movement through the integrated underground and surface drainage networks. The travel-time estimates were derived from the hydraulic characteristics for the sewer system and flow velocities for the surface drainage network. The resulting travel-time (Fig. 6a) and hydrological flow-path distance to the catchment outlet (Fig. 6b) maps are presented in Fig. 6. The spatial domain of these maps is defined by the extent of the integrated drainage network (sewer systems and surface drainage network). The estimated travel times exhibited an interquartile range (P25–P75) of 35–61 min, whereas the corresponding flow-path distances to the catchment outlet ranged from 6.8 to 13.5 km. Throughout this section, travel times extracted from the hydraulic travel-time map are referred to as simulated, whereas those derived from the monitoring observations are referred to as observed.

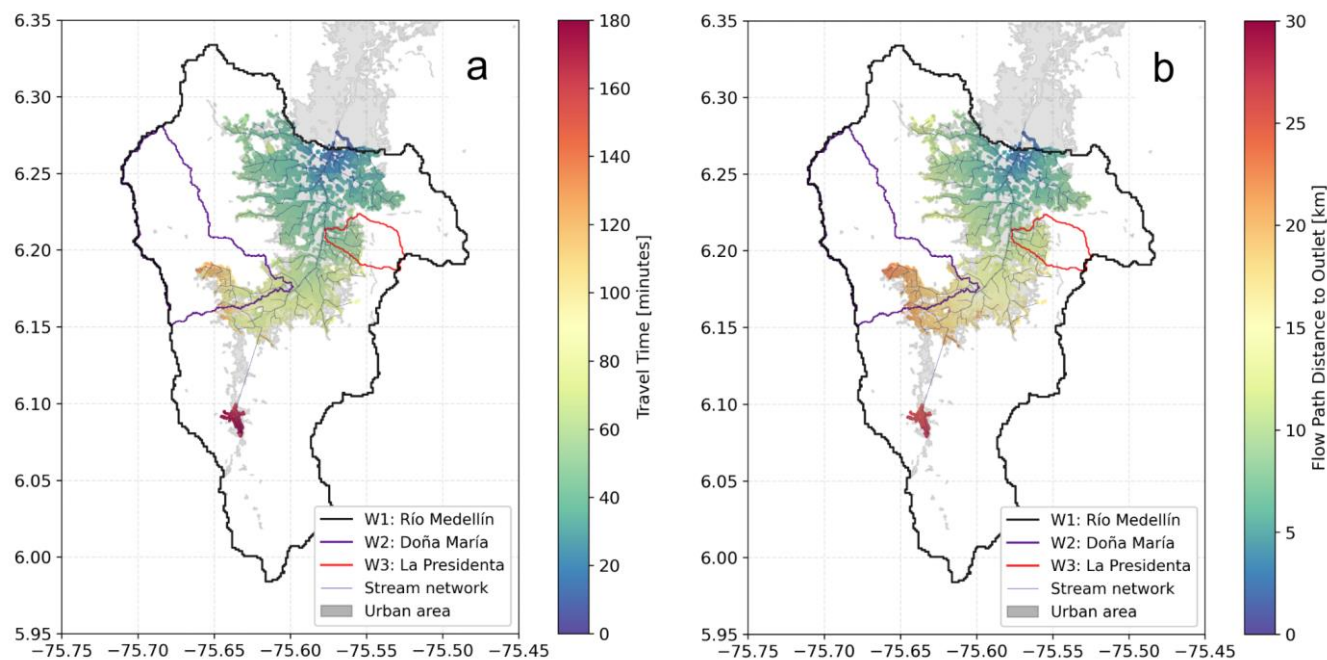


Figure 6. Spatial distribution of the hydraulic travel time and hydrological flow-path distance within the integrated drainage network of the Medellín River–Aula Ambiental catchment (W1). (a) Travel time from each network segment to the catchment outlet, estimated by combining the sewer systems and the surface drainage network. (b) Hydrological flow-path distance from each network segment to the catchment outlet. Both maps are defined exclusively along the hydraulic network and were derived from the network topology and hydraulic characteristics of the drainage system.

Figure 7A compares the observed and simulated travel times. Most model estimates are concentrated between 25 and 75 min, where the simulated values also show relatively close agreement with the observations. Overall, the model shows moderate performance, with a Kling–Gupta Efficiency (KGE) of 0.52, a coefficient of determination (R^2) of 0.55, and a root mean square error (RMSE) of 26 min. The RMSE envelope is illustrated in Fig. 7a around the 1:1 line, while Fig. 7b presents the



501 error distribution, which is centered near zero and closely follows a normal distribution with a mean of $\mu = 7.24$ min and a
 502 standard deviation of $\sigma = 25.65$ min.

503 To characterize travel-time uncertainty, a 90% uncertainty envelope was defined from the relationship between the
 504 hydrological flow-path distance from each network node to the catchment outlet and its corresponding travel time (Fig. 7c).
 505 The relationship is described by a mean exponential trend (solid blue line, $R^2 = 0.94$) and lower and upper bounds enclosing
 506 90% of the nodes. Each node in the drainage network is therefore assigned a travel-time interval, which is subsequently used
 507 for the spatiotemporal coupling analysis of extreme rainfall events.

508 Finally, Fig. 7d presents boxplots corresponding to the three travel-time estimates: the lower bound (5th percentile band), the
 509 mean estimate (50th percentile band), and the upper bound (95th percentile band). These distributions are shown for both the
 510 complete drainage network and the subnetworks corresponding to zone Z1 and zone Z2. For the complete network, the median
 511 travel times associated with the three bands are 36, 47, and 56 min, respectively. In contrast, the travel-time distributions for
 512 zone Z1 and zone Z2 are shifted toward opposite ends of the overall distribution. The Z1 subnetwork exhibits shorter travel
 513 times because of its proximity to the catchment outlet, its high degree of imperviousness, and the dense artificial drainage
 514 network that promotes rapid runoff conveyance. Conversely, the Z2 subnetwork is characterized by longer travel times,
 515 reflecting greater flow-path distances to the outlet, lower impervious surface coverage, and reduced flow velocities.

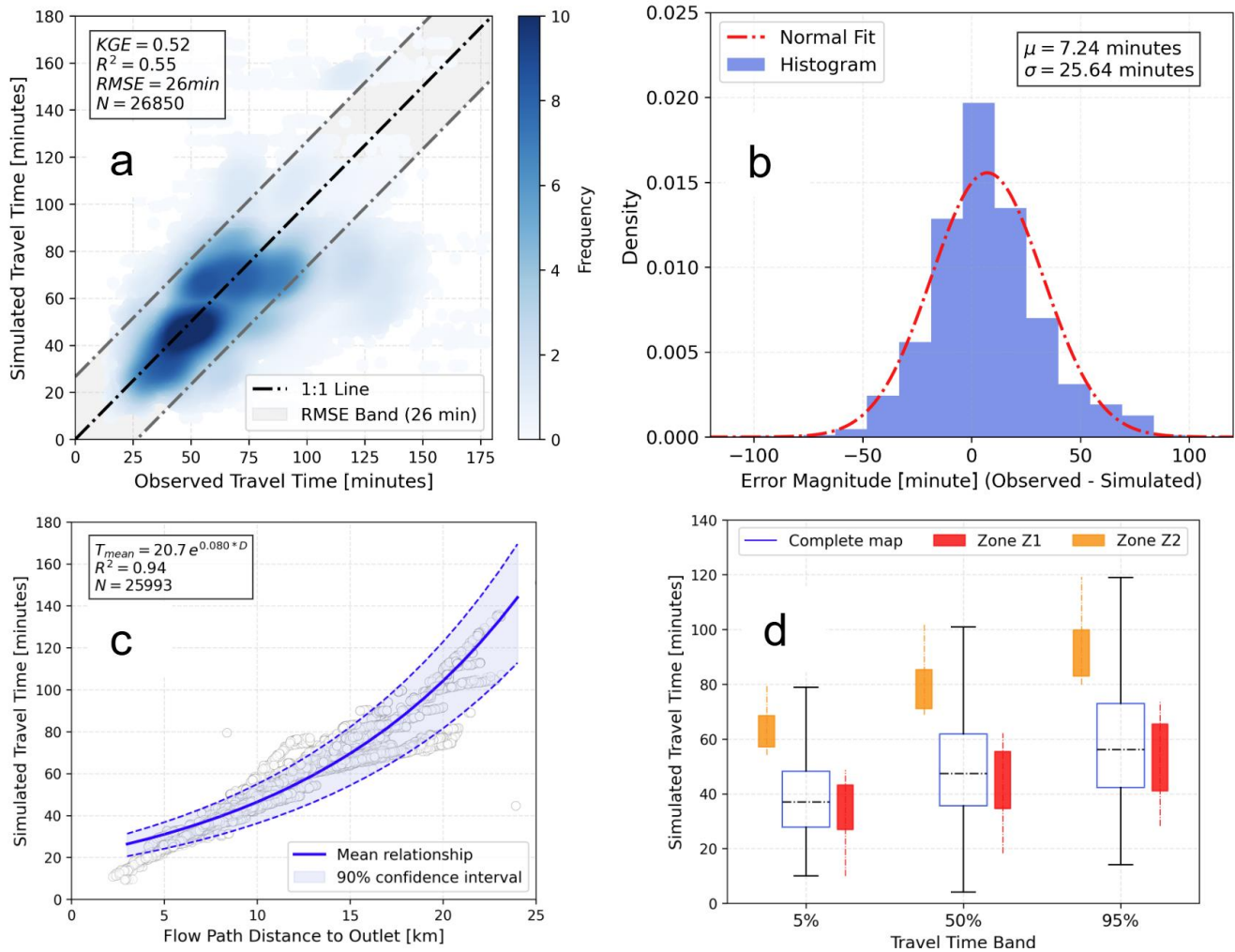


Figure 7. Validation of the simulated travel-time map using hydrometeorological observations. (a) Comparison between observed and simulated travel times for all analyzed events. The black dash-dotted line represents the 1:1 agreement, and the gray envelope corresponds to the RMSE (26 minute). Color intensity indicates the frequency of observations. (b) Distribution of travel-time errors (Observed vs. Simulated) and fitted normal distribution, with the estimated mean (μ) and standard deviation (σ). (c) Relationship between hydrological flow-path distance to the catchment outlet and simulated travel time. The solid blue line represents the mean exponential relationship, while the dashed lines delimit the 90% uncertainty envelope. (d) Distribution of simulated travel times for the lower (5th percentile), median (50th percentile), and upper (95th percentile) estimates, comparing the complete drainage network with the zone Z1 and the zone Z2.

4.3 Dynamic contributing areas during contrasting flood events

For catchment W1, two flood events, ranked among the five most severe events in the historical record, were selected for detailed analysis. These events exhibit contrasting spatiotemporal rainfall characteristics, providing an opportunity to evaluate



the influence of storm location, trajectory, and magnitude on the resulting hydrological response. In addition, one event was selected for each of the smaller catchments, W2 and W3, to evaluate the applicability of the framework at smaller spatial scales. The main characteristics of all selected events are summarized in Table 2.

Table 2. Selected events for the contributing area synchronization analysis.

Catchment	Event date	Peak stage (m)	Peak flow (m ³ /s)	Maximum cumulative rainfall (mm)	Contributing area to Qp (km ²)
W1	2013-12-01	4.2	734	43	57
W1	2021-04-05	3.6	642	89	16
W2	2025-04-25	3.9	314	50	3.7
W3	2026-01-28	2.6	99	79	2.1

Figure 8 presents the results for the flood events of 1 December 2013 and 5 April 2021, which produced peak discharges of 734 m³ s⁻¹ and 642 m³ s⁻¹, respectively. Fig. 8a and 8b show the rainfall hyetographs derived from the catchment rain-gauge network for each event. The two events exhibit contrasting temporal rainfall patterns in terms of both peak magnitude and hyetograph duration. The 5 April 2021 event extended over a longer period and reached higher instantaneous rainfall intensities, whereas the 1 December 2013 event was more concentrated in time. Despite these differences, both events exhibited a double-peaked rainfall structure, with most of the rainfall accumulation concentrated within an approximately two-hour period. Using both weather-radar grid cells and rain-gauge observations, the temporal centroid of each hyetograph was calculated and is indicated by the red dashed lines. These centroids were used as the reference time for estimating runoff travel times, representing the temporal origin from which rainfall-generated runoff was tracked through the integrated drainage network, comprising both the sewer system and the surface drainage network.

Figures 8c and 8d present the corresponding response hydrographs, including water level (solid black line) and streamflow (dashed red line), divided into the three hydrograph phases defined previously. The 1 December 2013 event exhibited a more temporally concentrated hydrograph, with a steeper rising limb and a more rapid attainment of peak discharge than the 5 April 2021 event, which showed a more gradual rise. The recession limbs also differed in their duration and in the timing of the return toward baseflow conditions. Because Phase 2 represents the peak-flow period defined as the 20-min interval before and after the discharge maximum, this phase accounted for a larger proportion of the hydrograph in the 1 December 2013 event than in the 5 April 2021 event. In the latter, the more extended hydrograph resulted in a greater relative contribution of Phases 1 and 3, encompassing the rising and recession limbs, respectively.

The direct runoff volume was estimated for each phase from the streamflow hydrograph. For the 1 December 2013 event, the runoff volume during the peak-flow phase (Phase 2) was estimated at 1.356×10^6 m³, representing approximately 42% of the total event runoff volume. In contrast, the 5 April 2021 event produced a Phase 2 runoff volume of 1.296×10^6 m³, equivalent to 31% of the total runoff volume. Despite the similar Phase 2 runoff volumes, the larger proportion of event runoff



555 concentrated within this phase in 2013 is consistent with the more temporally concentrated hydrograph and provides an
556 additional basis for comparing the synchronization of runoff contributions during the peak-flow period.

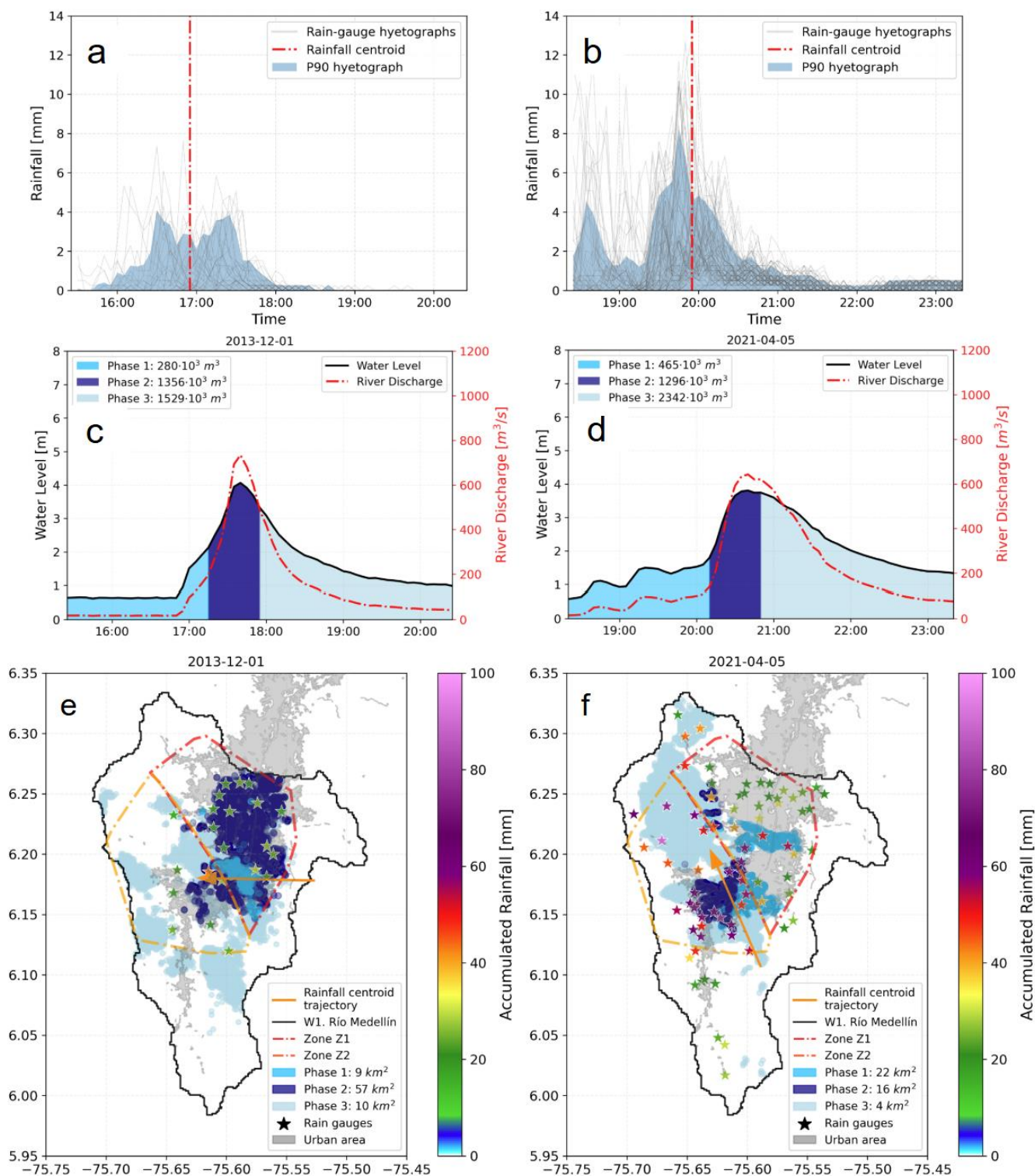




Figure 8. Spatiotemporal coupling between rainfall evolution and drainage-network travel times for the flood events of 1 December 2013 (left column) and 5 April 2021 (right column). (a–b) Rainfall hyetographs recorded by the rain-gauge network (gray lines), highlighting the P90 hyetograph (blue shading). The red dash-dotted line indicates the temporal rainfall centroid, which defines the reference time for travel-time estimation. (c–d) Observed water-level (black solid line) and river discharge (red dash-dotted line) hydrographs, divided into the rising limb (Phase 1), peak-flow (Phase 2), and recession limb (Phase 3). Shaded areas represent the direct runoff volume associated with each hydrograph phase. (e–f) Spatial distribution of accumulated rainfall and dynamic contributing areas associated with the three hydrograph phases. The orange arrow represents the rainfall-centroid trajectory, while the red and orange dash-dotted polygons delineate zones Z1 and Z2, respectively. Star symbols indicate rain-gauge locations, and gray shading denotes urbanized areas. The blue shades represent the spatial extent of the contributing areas associated with each hydrograph phase, with Phase 2 indicating the area synchronized with the peak-flow response. The corresponding event dates are indicated in each panel.

Figures 8e and 8f illustrate the spatial distribution of rainfall for the two selected events. Each grid cell is assigned to one of the three hydrograph phases according to the temporal synchronization between rainfall occurrence and the corresponding runoff travel time through the drainage network. This delineation of dynamic contributing areas allows the spatial extent of rainfall contributing to each hydrograph phase to be quantified and, in particular, identifies the location and magnitude of the area synchronized with peak discharge (Phase 2, shown in dark blue), which represents runoff contributions reaching the outlet during the most critical stage of the flood event. The figures also show rainfall accumulations measured at the rain-gauge stations and the overall rainfall centroid trajectory, representing the spatiotemporal evolution of each storm.

The two events exhibit marked differences in their spatial rainfall organization. The 5 April 2021 event produced rainfall accumulations exceeding 60 mm at 18 rain-gauge stations distributed across the catchment, whereas the 1 December 2013 event exhibited a more homogeneous rainfall distribution, with accumulations generally close to 20 mm. Despite the substantially lower rainfall accumulation, however, the 2013 event produced a higher peak discharge than the 2021 event. The travel-time framework indicates that the synchronized contributing area during the peak-flow phase reached approximately 57 km² in 2013, compared with only 16 km² in 2021.

During the 1 December 2013 event, the rainfall centroid propagated approximately along the main drainage axis in the eastern portion of the catchment (orange arrow in Fig. 8e). This trajectory favored the progressive accumulation of runoff contributions along the drainage network and increased the likelihood that runoff from different areas would reach the outlet within a relatively narrow temporal window. Moreover, most of the synchronized area was located within Z1, which is characterized by relatively high impervious surface coverage, further favoring rapid runoff generation and efficient drainage connectivity. In contrast, the 5 April 2021 event exhibited greater rainfall accumulation but a considerably smaller synchronized area, concentrated mainly in sectors with lower impervious surface coverage and largely associated with Z2. Its rainfall trajectory was predominantly transverse to the main drainage axis, reducing the temporal alignment of runoff contributions and distributing them over a broader portion of the hydrograph.

These contrasting responses highlight the distinction between rainfall magnitude and hydrologically effective rainfall organization. Total rainfall accumulation characterizes the magnitude of the atmospheric forcing, whereas peak-flow generation depends on how rainfall-generated runoff is spatially organized and connected to the drainage network, and on whether travel times allow contributions from different locations to reach the outlet within a sufficiently narrow temporal window.



The differences between the two events can be further examined through the distributions of travel times and hydrological flow-path distances to the catchment outlet, both of which are controlled by the spatiotemporal synchronization between the rainfall core and the contributing area associated with Phase 2 of the hydrograph. Fig. 9 compares these variables using boxplots for the three hydrograph phases and for zones Z1 and Z2. During the 1 December 2013 event, the runoff contributing to the peak-flow phase (Phase 2) was characterized by substantially shorter travel times and hydrological flow-path distances than the catchment-wide averages, with median values of 35 min and 7 km, respectively (Fig. 9a and 9c). This behavior reflects the concentration of the storm core near the catchment outlet, primarily within zone Z1, which promoted a high degree of synchronization between rainfall and hydrological response. In contrast, the 5 April 2021 event exhibited median Phase 2 values of 72 min and 17 km, respectively, much closer to the average conditions of the drainage network (Fig. 9b and 9d). In this case, the storm core was located within the transition zone between Z2 and Z1, resulting in longer runoff travel paths and a reduced synchronization of flow contributions during the peak-flow phase.

This distinction is particularly relevant in highly urbanized catchments, where efficient drainage connectivity and short travel times can strengthen the temporal coupling between rainfall forcing and outlet response. Consequently, rainfall events with substantially different spatial and temporal characteristics may produce contrasting hydrological responses, depending not only on rainfall accumulation but also on its alignment with the drainage network and the timing of runoff propagation. In this context, the distributed travel-time field provides a fundamental analytical layer for identifying the spatial zones that most strongly govern catchment response and for interpreting how rainfall organization translates into differences in peak-flow generation.

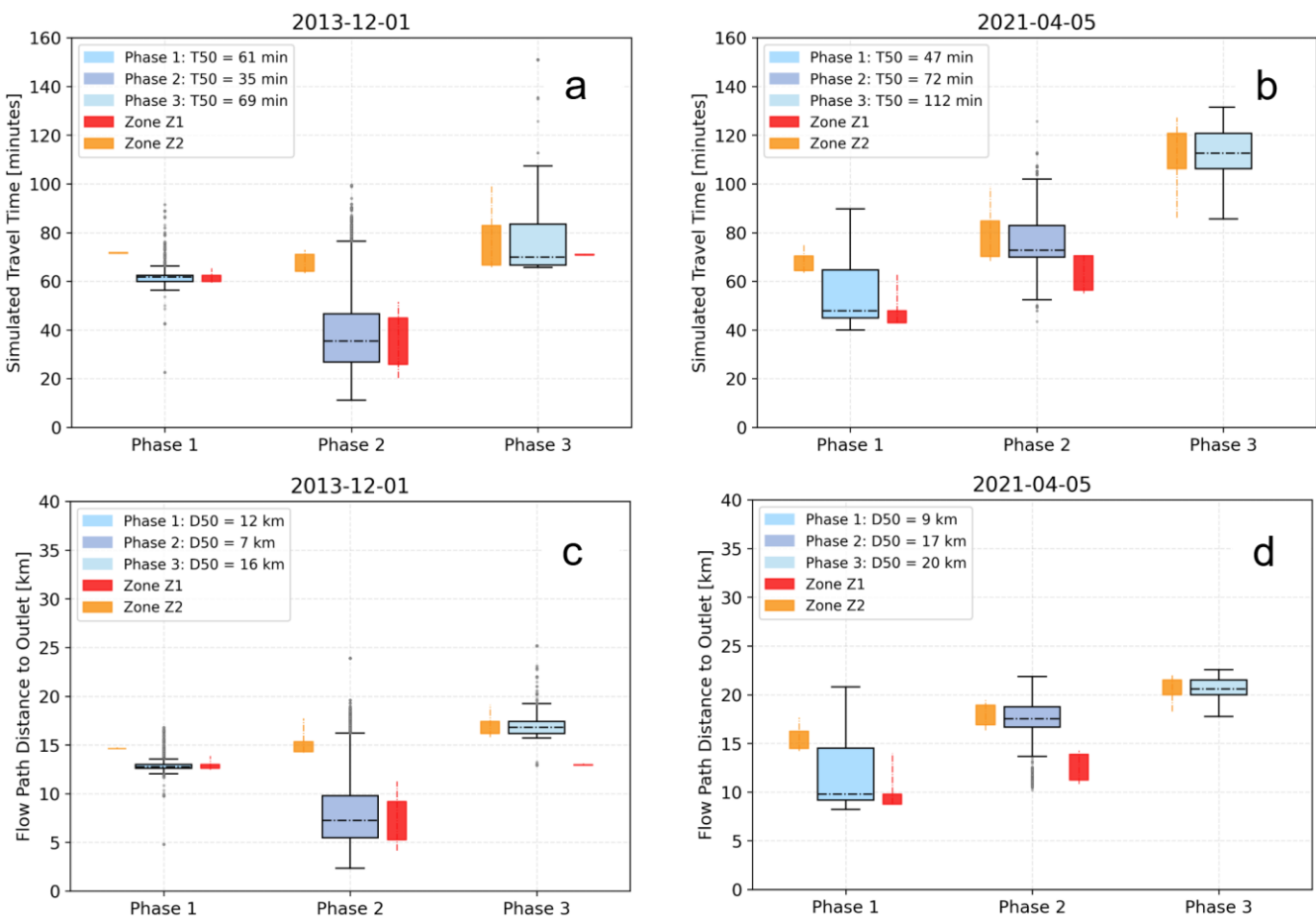


Figure 9. Comparison of travel-time and hydrological flow-path distance distributions associated with the dynamic contributing areas for the two historical flood events. (a–b) Boxplots of simulated travel times corresponding to the three hydrograph phases (Phases 1–3) for the flood events of 1 December 2013 and 5 April 2021, respectively. (c–d) Corresponding distributions of hydrological flow-path distance to the catchment outlet. Boxplots are shown for the complete contributing area (blue) and separately for the zone Z1 (red) and the zone Z2 (orange). The median travel time (T50) and median flow-path distance (D50) for each hydrograph phase are indicated in the legends.

4.4 Transferability and limitations in smaller catchments

To evaluate the transferability of the proposed methodology to smaller catchments, it was applied to the Doña María (W2) and La Presidenta (W3) catchments, both nested within the Medellín River–Aula Ambiental (W1) catchment. The W2 catchment covers an area of 73 km², with a mean channel slope of 5% and an impervious surface fraction of approximately 8%, concentrated primarily in its downstream urban sector. In contrast, W3 covers 15 km², with a mean channel slope of 17% and an impervious surface fraction of approximately 24%, also concentrated in the lower portion of the catchment.



The validation of travel times revealed lower overall model performance than that obtained for W1. For W2, the analysis based on weather radar observations yielded a KGE of -0.18 , an R^2 of 0.12 , and an RMSE of 36 min. Similarly, the evaluation for W3 resulted in a KGE of -0.29 , an R^2 of 0.04 , and an RMSE of 37 min. Nevertheless, both catchments showed improved agreement with the observed response for events in which rainfall was concentrated over the urbanized sectors, where impervious surfaces and the underground stormwater drainage network dominate the runoff response.

For each catchment, a representative flood event was selected based on its magnitude, using peak water level and peak discharge as the selection criteria (see Table 2). In W2, where hydrometric records have been available since September 2017, the most significant event occurred on 25 April 2025 ($L_p = 3.9$ m; $F_p = 314$ m³ s⁻¹). In W3, where records began in December 2013, the selected event occurred on 28 January 2026 ($L_p = 2.6$ m; $F_p = 99$ m³ s⁻¹). These catchments exhibited important differences in hydrological response relative to the larger catchment (W1). The rising limb of the hydrograph was considerably shorter, consistent with the shorter distances to the catchment outlets, while the phase associated with peak discharge (Phase 2) was markedly more prominent than in the events evaluated for W1.

Based on these findings, the rainfall–runoff synchronization analysis focused on the selected events, which exhibited the best agreement between observed and simulated travel times. For W2, the event of 25 April 2025 was selected (Fig. 10a and 10b), yielding an R^2 of 0.47 and an RMSE of 17 min. For W3, the event of 28 January 2026 was analyzed (Fig. 10c and 10d), with an R^2 of 0.58 and an RMSE of 9 min. In both cases, the spatial concentration of rainfall over the urbanized areas enabled the methodology to delineate the dynamic contributing areas associated with the rising limb and peak-flow phases of the hydrograph. In contrast, the contributing areas associated with the recession phase were only partially identified because part of the rainfall occurred outside the domain covered by the travel-time map.

For the W2 event (Fig. 10a), the rainfall centroid trajectory followed the direction of the main drainage axis, promoting synchronization of runoff contributions and resulting in a very short rising limb of approximately 15 min. Although only part of the storm was represented within the travel-time domain, the methodology identified the area contributing to peak discharge. A similar behavior was observed in W3 (Fig. 10c), where rainfall was concentrated over the urbanized portion of the catchment, allowing the contributing area associated with the peak-flow phase to be delineated. However, representation of the recession phase remained incomplete because rainfall also occurred in areas not covered by the hydraulic travel-time model.

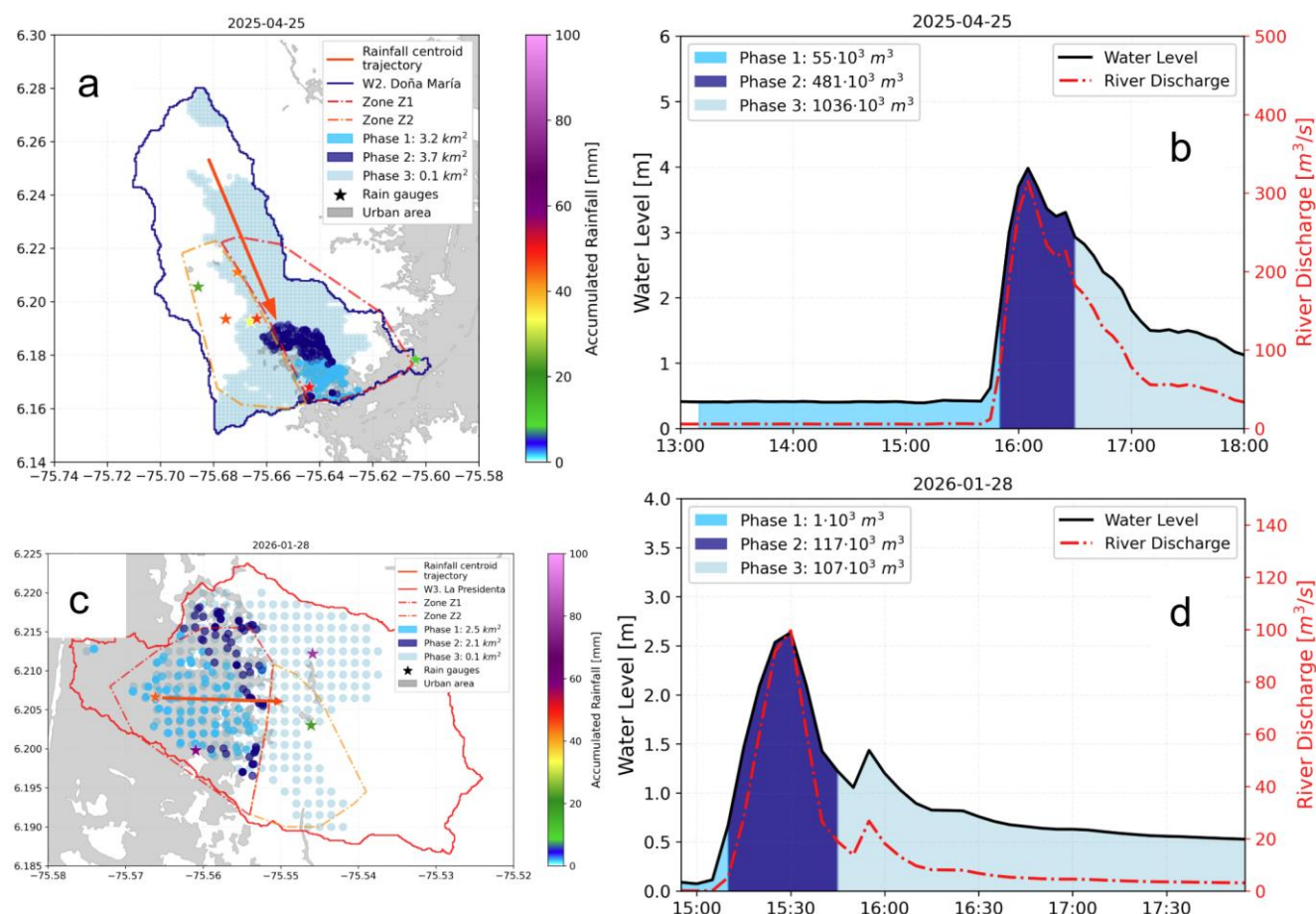


Figure 10. Application of the proposed methodology to the Doña María (W2) and La Presidenta (W3) catchments. (a, c) Spatial distribution of the rainfall centroid trajectory, travel-time-based contributing areas, rain gauges, and rainfall accumulation for the selected extreme events. (b, d) Corresponding water-level and flow hydrographs with runoff volumes estimated for the three hydrograph phases. The identified contributing areas are consistent with the urbanized sectors represented by the artificial drainage network, while the recession phase is only partially captured because part of the rainfall occurred outside the modeled travel-time domain.

The comparison between catchments of different sizes indicates that the performance and transferability of the framework depend strongly on the representativeness of the drainage network used to derive the travel-time field. This limitation becomes particularly relevant when rainfall occurs predominantly over rural or less urbanized areas and runoff is conveyed through natural channels that are not represented in the current travel-time map. Under these conditions, a larger fraction of the observed hydrological response occurs outside the modeled drainage network, reducing the agreement between observed and estimated travel times. Conversely, where artificial drainage networks dominate the hydrological response, the proposed framework can be applied even at relatively small spatial scales. As impervious surface coverage decreases, however, natural channels and surface drainage networks become increasingly important. Extending the travel-time map to include these pathways would therefore provide a more complete representation of hydrological connectivity and improve the identification of dynamic contributing areas. In catchments where the information required to characterize the drainage network is limited or unavailable,



particular attention should be given to developing a sufficiently detailed drainage network from basic topographic information to represent the flow pathways that convey rainfall-generated runoff toward the catchment outlet.

The results also emphasize the complementary roles of rainfall and hydrological information. Weather radar provides the spatial and temporal organization of the rainfall forcing, whereas the travel-time field translates this forcing into its expected propagation through the catchment. Their integration allows rainfall events to be evaluated not only in terms of where and how much precipitation occurred, but also in terms of when the resulting runoff is expected to contribute to the outlet response.

5. Conclusions and implications

5.1 Spatiotemporal synchronization and flood response

The results demonstrate that extreme flood response in the Medellín River–Aula Ambiental catchment (W1) cannot be explained solely by rainfall magnitude or accumulation. Instead, the spatial and temporal organization of precipitation relative to drainage-network travel times plays a critical role in determining both the magnitude and timing of the outlet response. In particular, rainfall trajectory, drainage-network connectivity, imperviousness, and travel times jointly influence the extent to which runoff contributions from different portions of the catchment become temporally synchronized during critical stages of the flood hydrograph. By coupling event-based rainfall fields with the distributed travel-time map, the proposed framework identifies the portions of the catchment whose runoff contributions are synchronized with specific stages of the hydrograph, providing a physically interpretable representation of the dynamic contributing areas during flood development. Thus, the effective contributing area should be regarded as dynamic rather than fixed: different portions of the catchment become synchronized with the outlet at different stages of the hydrograph, depending on rainfall location, movement, and runoff travel times. This perspective extends conventional interpretations based solely on topographic drainage boundaries and frames flood generation as a spatiotemporal synchronization process.

The comparison between the 2013 and 2021 events provides clear evidence of this mechanism. The larger synchronized area during the 2013 event, despite lower rainfall accumulation, indicates that rainfall organization and movement can enhance flood response when they favor the simultaneous arrival of runoff contributions from hydraulically connected areas. Conversely, greater rainfall accumulation may result in a lower peak when rainfall organization and propagation reduce this synchronization.

5.2 Performance, limitations, and transferability

The integration of high-resolution rainfall observations with the distributed travel-time field provides a physically interpretable framework for characterizing dynamic contributing areas during extreme rainfall events. For the Medellín River–Aula Ambiental catchment (W1), the availability of high-resolution radar, rain-gauge, water-level, and drainage-network information allowed the framework to represent the spatial and temporal organization of rainfall together with the propagation of runoff through the catchment. This integration provides a basis for evaluating flood response not only according to rainfall magnitude and location, but also according to the timing and synchronization of runoff contributions reaching the outlet.

The framework also shows potential for application across urban catchments with different spatial scales and drainage configurations. In particular, its application to smaller urban catchments is feasible where the available drainage-network information adequately represents the dominant hydrological pathways. As the degree of urbanization decreases, however, natural channels and surface runoff pathways become increasingly relevant to hydrological connectivity. Incorporating these



pathways into the distributed travel-time field would extend the representation of runoff propagation and allow the framework to be adapted to catchments with contrasting degrees of urbanization and drainage structure.

Future applications can therefore build upon the framework by integrating artificial drainage networks, surface runoff pathways, and natural channels within a unified distributed travel-time field. Combined with high-resolution rainfall observations, this extension would strengthen the representation of hydrological connectivity and support the identification of dynamically evolving contributing areas across a broader range of urban catchments and flood-generating conditions.

Author contribution

EZ contributed to data processing, programming, and statistical analysis. AMC contributed to the identification of the scientific gap and the conceptualization and development of the methodology, and provided supervision and project leadership throughout the study. JB contributed to the identification of the scientific gap and the conceptualization and development of the methodology. AMC and JB contributed to the intermediate and final review of the manuscript. EZ prepared the manuscript, with contributions from all co-authors during the review and editing process. All authors reviewed and approved the final version of the manuscript.

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Data availability

The data that support the findings of this study are openly available in the Early Warning System of Medellín and the Aburrá Valley (SIATA, <https://geoportal.siata.gov.co/>).

Competing interests

The authors declare that they have no conflict of interest

References

- Abedin, S. J. H., & Stephen, H. (2019). GIS framework for spatiotemporal mapping of urban flooding. *Geosciences (Switzerland)*, 9(2). <https://doi.org/10.3390/geosciences9020077>.
- Agonafir, C., Lakhankar, T., Khanbilvardi, R., Krakauer, N., Radell, D., & Devineni, N. (2023). A review of recent advances in urban flood research. In *Water Security* (Vol. 19). Elsevier B.V. <https://doi.org/10.1016/j.wasec.2023.100141>.



- Ali, G. A., & Roy, A. G. (2010). Shopping for hydrologically representative connectivity metrics in a humid temperate forested catchment. *Water Resources Research*, 46(12). <https://doi.org/10.1029/2010WR009442>.
- Alshammari, E., Rahman, A. A., Rainis, R., Seri, N. A., & Fuzi, N. F. A. (2023). The Impacts of Land Use Changes in Urban Hydrology, Runoff and Flooding: A Review. *Current Urban Studies*, 11(01), 120–141. <https://doi.org/10.4236/cus.2023.111007>.
- Amengual, A., Borga, M., Ravazzani, G., & Crema, S. (2021). The Role of Storm Movement in Controlling Flash Flood Response: An Analysis of the 28 September 2012 Extreme Event in Murcia, Southeastern Spain. *Journal of Hydrometeorology*, 22(9), 2379–2392. <https://doi.org/10.1175/JHM-D-21-0001.1>
- AMVA-EAFIT. 2018. *Capacidades de soporte urbano-ambientales para el territorio del Valle de Aburrá*. <https://www.eafit.edu.co/conexion-asuntos-publicos/centros-estudio-incidencia/urbam/proyectos/capacidades-soporte-urbano-ambientales>
- AMVA-SIATA. 2026. Sistema de Alerta Temprana de Medellín y el Valle de Aburrá. https://siata.gov.co/siata_nuevo/index.php/mapa
- Azizian, A. (2018). Uncertainty Analysis of Time of Concentration Equations based on First-Order-Analysis (FOA) Method. *American Journal of Engineering and Applied Sciences*, 11(1), 327–341. <https://doi.org/10.3844/ajeassp.2018.327.341>
- Bedoya-Soto, J. M., Aristizábal, E., Carmona, A. M., and Poveda, G. (2019). Seasonal shift of the diurnal cycle of rainfall over medellin's valley, central andes of colombia (1998–2005). *Frontiers in Earth Science*, 7, 92. <https://doi.org/10.3389/feart.2019.00092>
- Berne, A., & Krajewski, W. F. (2013). Radar for hydrology: Unfulfilled promise or unrecognized potential? *Advances in Water Resources*, 51, 357–366. <https://doi.org/10.1016/j.advwatres.2012.05.005>
- Beven, K. J. . (2012). *Rainfall-runoff modelling : the primer*. Wiley-Blackwell. https://books.google.com.br/books?hl=es&lr=&id=oB5G3ekxpgC&oi=fnd&pg=PR13&dq=Rainfall-Runoff+Modelling+&ots=CSEKUdTzd&sig=szyYxSUB7s-NM8mNe5b9R0HhfZk&redir_esc=y#v=onepage&q=Rainfall-Runoff%20Modelling&f=false
- Bracken, L. J., & Croke, J. (2007). The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*, 21(13), 1749–1763. <https://doi.org/10.1002/hyp.6313>
- Butler, D., & Davies, J. W. (2024). *URBAN DRAINAGE SECOND EDITION*. https://books.google.com.br/books?hl=es&lr=&id=Q3U2EQAAQBAJ&oi=fnd&pg=PP1&dq=URBAN+DRAINAGE+SECOND+EDITION&ots=6syNsp39gv&sig=iTEsafmV1ZBOxerLv7zq9tdSgEw&redir_esc=y#v=onepage&q=URBAN%20DRAINAGE%20SECOND%20EDITION&f=false



- Chow, V. T. (1962). (1962). HYDROLOGIC DETERMINATION OF WATERWAY AREAS FOR THE DESIGN OF DRAINAGE STRUCTURES IN SMALL DRAINAGE BASINS. University of Illinois. Engineering Experiment Station. Bulletin; no. 462. <https://trid.trb.org/View/1131187>
- Cristiano, E., Veldhuis, M. C. Ten, & Van De Giesen, N. (2017). Spatial and temporal variability of rainfall and their effects on hydrological response in urban areas - A review. *Hydrology and Earth System Sciences*, 21(7), 3859–3878. <https://doi.org/10.5194/hess-21-3859-2017>
- Dell'Aira, F., & Meier, C. I. (2025). Beyond total impervious area: a new lumped descriptor of basin-wide hydrologic connectivity for characterizing urban watersheds. *Hydrology and Earth System Sciences*, 29(4), 1001–1032. <https://doi.org/10.5194/hess-29-1001-2025>
- Deng, Z., Villarini, G., & Wang, Z. (2025). Climate change dominates over urbanization in tropical cyclone rainfall patterns. *Communications Earth and Environment*, 6(1). <https://doi.org/10.1038/s43247-025-02048-z>
- Dharmarathne, G., Waduge, A. O., Bogahawaththa, M., Rathnayake, U., & Meddage, D. P. P. (2024). Adapting cities to the surge: A comprehensive review of climate-induced urban flooding. *Results in Engineering*, 22. <https://doi.org/10.1016/j.rineng.2024.102123>
- Douinot, A., Roux, H., Garambois, P. A., Larnier, K., Labat, D., & Dartus, D. (2016). Accounting for rainfall systematic spatial variability in flash flood forecasting. *Journal of Hydrology*, 541, 359–370. <https://doi.org/10.1016/j.jhydrol.2015.08.024>
- Emmanuel, I., Andrieu, H., Leblois, E., Janey, N., & Payraastre, O. (2015). Influence of rainfall spatial variability on rainfall-runoff modelling: Benefit of a simulation approach? *Journal of Hydrology*, 531, 337–348. <https://doi.org/10.1016/j.jhydrol.2015.04.058>
- Farina, A., Di Nardo, A., Gargano, R., van der Werf, J. A., & Greco, R. (2023). A simplified approach for the hydrological simulation of urban drainage systems with SWMM. *Journal of Hydrology*, 623. <https://doi.org/10.1016/j.jhydrol.2023.129757>
- Fletcher, T. D., Andrieu, H., & Hamel, P. (2013). Understanding, management and modelling of urban hydrology and its consequences for receiving waters: A state of the art. *Advances in Water Resources*, 51, 261–279. <https://doi.org/10.1016/j.advwatres.2012.09.001>
- Ghimire, G. R., Jadidoleslam, N., Goska, R., & Krajewski, W. F. (2021). Insights into storm direction effect on flood response. *Journal of Hydrology*, 600. <https://doi.org/10.1016/j.jhydrol.2021.126683>
- Ghomash, S. K. Bin, Bachmann, D., Caviedes-Voullième, D., & Hinz, C. (2022). Impact of Rainfall Movement on Flash Flood Response: A Synthetic Study of a Semi-Arid Mountainous Catchment. *Water (Switzerland)*, 14(12). <https://doi.org/10.3390/w14121844>
- Gleason, C. J., & Smith, L. C. (2014). Toward global mapping of river discharge using satellite images and at-many-stations hydraulic geometry. *Proceedings of the National Academy of Sciences of the United States of America*, 111(13), 4788–4791. <https://doi.org/10.1073/pnas.1317606111>



- Gomez-Rios, S., Zuluaga, M. D., & Hoyos, C. D. (2023). Orographic controls over convection in an inter-Andean valley in northern South America. *Monthly Weather Review*, 151(1), 145–162. <https://doi.org/10.1175/MWR-D-21-0231.1>
- Gupta, H. V., Kling, H., Yilmaz, K. K., & Martinez, G. F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. *Journal of Hydrology*, 377(1–2), 80–91. <https://doi.org/10.1016/j.jhydrol.2009.08.003>
- Herrera-Mejía, L., & Hoyos, C. D. (2019). Characterization of the atmospheric boundary layer in a narrow tropical valley using remote-sensing and radiosonde observations and the WRF model: the Aburrá Valley case-study. *Quarterly Journal of the Royal Meteorological Society*, 145(723), 2641–2665. <https://doi.org/10.1002/qj.3583>
- Hoyos, C. D., Herrera-Mejía, L., Roldán-Henao, N., & Isaza, A. (2020). Effects of fireworks on particulate matter concentration in a narrow valley: the case of the Medellín metropolitan area. *Environmental Monitoring and Assessment*, 192(1). <https://doi.org/10.1007/s10661-019-7838-9>
- Huong, H. T. L., & Pathirana, A. (2013). Urbanization and climate change impacts on future urban flooding in Can Tho city, Vietnam. *Hydrology and Earth System Sciences*, 17(1), 379–394. <https://doi.org/10.5194/hess-17-379-2013>
- Jencso, K. G., McGlynn, B. L., Gooseff, M. N., Wondzell, S. M., Bencala, K. E., & Marshall, L. A. (2009). Hydrologic connectivity between landscapes and streams: Transferring reach- and plot-scale understanding to the catchment scale. *Water Resources Research*, 45(4). <https://doi.org/10.1029/2008WR007225>
- Knoben, W. J. M., Freer, J. E., & Woods, R. A. (2019). Technical note: Inherent benchmark or not? Comparing Nash-Sutcliffe and Kling-Gupta efficiency scores. *Hydrology and Earth System Sciences*, 23(10), 4323–4331. <https://doi.org/10.5194/hess-23-4323-2019>
- Leonard, J. S., & Whipple, K. X. (2021). Influence of Spatial Rainfall Gradients on River Longitudinal Profiles and the Topographic Expression of Spatially and Temporally Variable Climates in Mountain Landscapes. *Journal of Geophysical Research: Earth Surface*, 126(12). <https://doi.org/10.1029/2021JF006183>
- Liu, Y., Huang, Y., Liu, Y., Li, K., & Li, M. (2021). The impact of rainfall movement direction on urban runoff cannot be ignored in urban hydrologic management. *Water (Switzerland)*, 13(20). <https://doi.org/10.3390/w13202923>
- Lu, M., Yu, Z., Hua, J., Kang, C., & Lin, Z. (2023). Spatial dependence of floods shaped by extreme rainfall under the influence of urbanization. *Science of the Total Environment*, 857. <https://doi.org/10.1016/j.scitotenv.2022.159134>
- McCuen, R. H. (2009). *Uncertainty Analyses of Watershed Time Parameters*. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0000011](https://doi.org/10.1061/(ASCE)HE.1943-5584.0000011)
- McCuen, R. H., Wong, S. L. & Rawls, W. J. 1984 Estimating urban time of concentration. *Journal of Hydraulic Engineering* 110 (7), 887–904. Michailidi, E. M., Antoniadis, S., Koukouvinos, A., Bacchi, B. & Efstratiadis, A. 2018 Timing the time of



- concentration: shedding light on a paradox. *Hydrological Sciences Journal* 63 (5), 721–740. doi:10.1080/02626667.2018.1450985.
- McGuire, K. J., & McDonnell, J. J. (2006). A review and evaluation of catchment transit time modeling. *Journal of Hydrology*, 330(3–4), 543–563. <https://doi.org/10.1016/j.jhydrol.2006.04.020>
- Mehta, O., Kansal, M. L., & Bisht, D. S. (2022). A comparative study of the time of concentration methods for designing urban drainage infrastructure. *Aqua Water Infrastructure, Ecosystems and Society*, 71(10), 1197–1218. <https://doi.org/10.2166/aqua.2022.107>
- Michaelides, K., & Chappell, A. (2009). Connectivity as a concept for characterising hydrological behaviour. In *Hydrological Processes* (Vol. 23, Number 3, pp. 517–522). <https://doi.org/10.1002/hyp.7214>
- Michailidi, E. M., Antoniadis, S., Koukouvinos, A., Bacchi, B., & Efstratiadis, A. (2018). Timing the time of concentration: shedding light on a paradox. *Hydrological Sciences Journal*, 63(5), 721–740. <https://doi.org/10.1080/02626667.2018.1450985>
- Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I—A discussion of principles. *Journal of hydrology*, 10(3), 282–290. 10.1016/0022-1694(70)90255-6
- Nikolopoulos, E. I., Anagnostou, E. N., Borga, M., Vivoni, E. R., & Papadopoulos, A. (2011). Sensitivity of a mountain basin flash flood to initial wetness condition and rainfall variability. *Journal of Hydrology*, 402(3–4), 165–178. <https://doi.org/10.1016/j.jhydrol.2010.12.020>
- Oswald, C. J., Kelleher, C., Ledford, S. H., Hopkins, K. G., Sytsma, A., Tetzlaff, D., Toran, L., & Voter, C. (2023). Integrating urban water fluxes and moving beyond impervious surface cover: A review. In *Journal of Hydrology* (Vol. 618). Elsevier B.V. <https://doi.org/10.1016/j.jhydrol.2023.129188>
- Poveda, G., Mejia, J. F., Arias, P. A., Zuluaga, M. D., Salazar, J. F., Carmona, A. M., Builes-Jaramillo, A., Salas, H. D., Yepes, J., Martinez, J. A., & Bedoya-Soto, J. M. (2025). *Climate of Northwestern South America*. Oxford University Press. <https://doi.org/10.1093/acrefore/9780190228620.013.966>
- Dwivedi, D., Poepl, R. E., Wohl, E., Randhir, T. O., Xu, T., Botter, G., & Gov, D. (2025). Hydrological connectivity: a review and emerging strategies for integrating measurement, modeling, and management. *Frontiers in Water*, 7, 1496199. <https://doi.org/10.3389/frwa.2025.1496199>
- Reyes-Silva, J. D., Zischg, J., Klinkhamer, C., Rao, P. S. C., Sitzenfrei, R., & Krebs, P. (2020). Centrality and shortest path length measures for the functional analysis of urban drainage networks. *Applied Network Science*, 5(1). <https://doi.org/10.1007/s41109-019-0247-8>
- McCuen, R. H., Wong, S. L., & Rawls, W. J. (1984). Estimating urban time of concentration. *Journal of hydraulic Engineering*, 110(7), 887–904. [https://doi.org/10.1061/\(ASCE\)0733-9429\(1984\)110:7\(887\)](https://doi.org/10.1061/(ASCE)0733-9429(1984)110:7(887))
- Ruiz-Carrascal, D., Acevedo, A. B., Zuluaga, M. D., Ramirez, G., Ruiz, D. F., Avellaneda-Jiménez, D. S., Carmona, A. M., Guzmán, C., Marulanda-Tobón, A., Puerta-Yepes, M. E., & Mejía-



- 917 Chavarriaga, L. J. (2026). The Early Warning System of the City of Medellín and the Aburrá
 918 Valley – SIATA, Colombia: a + 20-year prolific journey. *Climate Services*, 42.
 919 <https://doi.org/10.1016/j.cliser.2026.100653>
 920
- 921 Saghafian, B., Julien, P. Y., & Rajaie, H. (2002). Runoff hydrograph simulation based on time variable isochrone technique.
 922 *Journal of hydrology*, 261(1-4), 193-203. 10.1016/S0022-1694(02)00007-0
 923
- 924 Semadeni-Davies, A., Hernebring, C., Svensson, G., & Gustafsson, L. G. (2008). The impacts of climate change and
 925 urbanisation on drainage in Helsingborg, Sweden: Combined sewer system. *Journal of Hydrology*, 350(1–2), 100–113.
 926 <https://doi.org/10.1016/j.jhydrol.2007.05.028>
 927
- 928 Sepúlveda Berrío, J. (2015). Estimación cuantitativa de precipitación a partir de la información de Radar Meteorológico del
 929 Área Metropolitana del Valle de Aburrá. PhD thesis. [https://repositorio.unal.edu.co/items/11a60867-e5ac-4b39-9716-](https://repositorio.unal.edu.co/items/11a60867-e5ac-4b39-9716-8a8be15a839e)
 930 [8a8be15a839e](https://repositorio.unal.edu.co/items/11a60867-e5ac-4b39-9716-8a8be15a839e)
 931
- 932 Sigaroodi, S. K., & Chen, Q. (2016). Effects and consideration of storm movement in rainfall-runoff modelling at the basin
 933 scale. *Hydrology and Earth System Sciences*, 20(12), 5063–5071. <https://doi.org/10.5194/hess-20-5063-2016>
 934
- 935 Solano-Rivera, V., Geris, J., Granados-Bolaños, S., Brenes-Cambronero, L., Artavia-Rodríguez, G., Sánchez-Murillo, R., &
 936 Birkel, C. (2019). Exploring extreme rainfall impacts on flow and turbidity dynamics in a steep, pristine and tropical volcanic
 937 catchment. *Catena*, 182. <https://doi.org/10.1016/j.catena.2019.104118>
 938
- 939 Rossman, L. A., & Bernagros, J. T. (2019). National Stormwater Calculator User’s Guide—Version 1.2. 0.1. Office of
 940 Research and Developemnt, USEPA, Ohio, USA. [https://19january2021snapshot.epa.gov/sites/static/files/2019-](https://19january2021snapshot.epa.gov/sites/static/files/2019-04/documents/swc_users_guide_desktop_v1.2.0.3_april_2019.pdf)
 941 [04/documents/swc_users_guide_desktop_v1.2.0.3_april_2019.pdf](https://19january2021snapshot.epa.gov/sites/static/files/2019-04/documents/swc_users_guide_desktop_v1.2.0.3_april_2019.pdf)
 942
- 943 Ten Veldhuis, M. C., Zhou, Z., Yang, L., Liu, S., & Smith, J. (2018). The role of storm scale, position and movement in
 944 controlling urban flood response. *Hydrology and Earth System Sciences*, 22(1), 417–436. [https://doi.org/10.5194/hess-22-417-](https://doi.org/10.5194/hess-22-417-2018)
 945 [2018](https://doi.org/10.5194/hess-22-417-2018)
 946
- 947 Velásquez, N., Hoyos, C. D., Vélez, J. I., & Zapata, E. (2020). Reconstructing the 2015 Salgar flash flood using radar retrievals
 948 and a conceptual modeling framework in an ungauged basin. *Hydrology and Earth System Sciences*, 24(3), 1367–1392.
 949 <https://doi.org/10.5194/hess-24-1367-2020>
 950
- 951 Vrugt, J. A., & de Oliveira, D. Y. (2022). Confidence intervals of the Kling-Gupta efficiency. *Journal of Hydrology*, 612.
 952 <https://doi.org/10.1016/j.jhydrol.2022.127968>
 953
- 954 Walsh, C. J., Roy, A. H., Feminella, J. W., Cottingham, P. D., Groffman, P. M., & Morgan, R. P. (2005). The urban stream
 955 syndrome: Current knowledge and the search for a cure. *Journal of the North American Benthological Society*, 24(3), 706–
 956 723. <https://doi.org/10.1899/04-028.1>
 957



- 958 Yen, B. C. (2002). Open channel flow resistance. *Journal of hydraulic engineering*, 128(1), 20-39.
959 [https://doi.org/10.1061/\(ASCE\)0733-9429\(2002\)128:1\(20\)](https://doi.org/10.1061/(ASCE)0733-9429(2002)128:1(20))
960 Zhou, Z., Smith, J. A., Baeck, M. L., Wright, D. B., Smith, B. K., & Liu, S. (2021). The impact of the spatiotemporal structure
961 of rainfall on flood frequency over a small urban watershed: An approach coupling stochastic storm transposition and
962 hydrologic modeling. *Hydrology and Earth System Sciences*, 25(9), 4701–4717. <https://doi.org/10.5194/hess-25-4701-2021>