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Correspondence: Ayantika R. Bose (ayantika.bose@utsa.edu)

Revisiting Discharge Envelope Curves: Hydrometeorological Analysis and Lessons from the 4 July 2025 Kerr County Flash Flood

Ayantika R. Bose[1], Hatim O. Sharif[1], Marcio Giacomoni[1], and Jose Brasil[1]

[1]School of Civil and Environmental Engineering and Construction Management, University of Texas at San Antonio, San Antonio, TX 78249, USA

Abstract.

Flash floods are a primary driver of flood mortality in semi-arid regions where compound risk factors amplify convective extremes. The 4 July 2025 Kerr County flash flood in the Texas Hill Country-a region colloquially designated "Flash Flood Alley"-represents a benchmark hydrometeorological event. Triggered by a quasi-stationary mesoscale convective system derived from Tropical Storm Barry remnants, the event delivered more than 508 mm of rainfall over 72 hours, with peak 3-hour intensities exceeding the local 1,000-year recurrence threshold. Using National Oceanic and Atmospheric Administration (NOAA) Stage IV rainfall estimates, United States Geological Survey (USGS) streamflow records, and mass-balance modeling, we reconstruct the hydrometeorological response of the South Fork and mainstem Guadalupe River. Estimated peak discharge on the South Fork ranged from $7{,}221$ to $7{,}505\ \mathrm{m^3\ s^{-1}}$, while the USGS gauge at Hunt, downstream of the confluence, recorded an estimated $8{,}892\ \mathrm{m^3\ s^{-1}}$ based on high-water marks, approaching or exceeding the regional discharge envelope curve and surpassing the historical record set in July 1932. Antecedent drought may have contributed to runoff through hydrophobic soil behavior, while overnight timing and critical communication gaps compounded human impacts (137 fatalities). This total refers to the broader multi-county flood event; within Kerr County, officials confirmed 119 deaths and 2 individuals missing, with the remaining confirmed fatalities occurring downstream or in other affected counties. Numerous affected structures lay outside Federal Emergency Management Agency (FEMA) designated Special Flood Hazard Areas, exposing the limitations of historically calibrated static hazard maps. The findings support a transition toward impact-based warning protocols, expanded monitoring networks, and climate-aware hazard mapping for topographically complex, data-sparse regions.

1 Introduction

Flash floods are rapid-onset hydrological phenomena characterized by abrupt rises in the stream stage, triggered by the intersection of hydrometeorological extremes at fine spatial and temporal scales (Terti et al., 2015; Furl et al., 2017). Although secondary contributors, including dam breaches, levee failures, and rainfall-triggered geomorphic slope failures such as debris flows and landslides, can exacerbate impacts, the primary driver is high-intensity, short-duration rainfall, generally lasting less than six hours and frequently less than three hours (National Weather Service, 2026). These events occur predominantly in small catchments (<1,000 km^2), generating high-velocity flows with high destructive potential. Because they offer limited predictability and minimal lead time, they are disproportionately associated with flood-related mortality worldwide.

Topographic and pedologic factors can further exacerbate flash flood susceptibility. In the United States, the Texas Hill Country exemplifies a high-risk physiographic setting, colloquially termed "Flash Flood Alley" (Sharif, 2025; Simmerman, 2025; NASA Earthdata, 2025; Han and Sharif, 2021), characterized by steep slopes, thin soils, and terrain carved by a dense network of small streams. These streams rapidly collect rainfall excess from the limestone bedrock and funnel it into larger channels and rivers. The Balcones Escarpment also plays a key role in enhancing rainfall across Central Texas: as moist air from the Gulf of Mexico moves inland, it is forced upward over the escarpment's steep rise, which cools the air, promotes condensation, and increases the likelihood of heavy precipitation. Combined with storm systems that can stall along the escarpment, this topography helps explain why the region is so prone to intense downpours and flash flooding.

Figure 1 illustrates the location of "Flash Flood Alley" along the eastern edge of the Balcones Escarpment, extending from near Dallas–Fort Worth through the urban corridor encompassing Austin and San Antonio and continuing southeastward. This paper presents a hydrometeorological and impact analysis of the 4 July 2025 Kerr County flash flood, linking mesoscale forcing, basin response, and emergency response dynamics in a semi-arid, flash-flood-prone region. The results examine envelope-curve-scale discharges in the Texas Hill Country and highlight actionable pathways for improving impact-based warnings and regional disaster resilience frameworks.

The 4 July 2025 Kerr County flash flood occurred under antecedent drought conditions across Texas. On 3 July, 37.8 % of Texas was affected by drought, with 5.75 % classified as "exceptional drought" and a Drought Severity and Coverage Index (DSCI) of 109 (National Drought Mitigation Center, University of Nebraska–Lincoln, 2025). Prolonged soil desiccation can harden the surface, increase hydrophobicity, and promote pavement-like runoff behavior during subsequent rainfall (CIMA Research Foundation, 2025).

The event was initiated by a mesoscale convective system derived from the remnants of Tropical Storm Barry, which interacted with an upper-level trough and a stalled low-level jet over the Hill Country (Gray, 2025), producing localized totals exceeding 20 inches in three days and peak intensities near 4 in h^{-1} (102 mm h^{-1}). The Guadalupe River rose 26 ft (7.9 m) in 45 min at Comfort and 2 ft (0.6 m) in 5 min at Hunt, ultimately cresting at 37.5 ft (11.4 m), well beyond major flood thresholds (NOAA National Water Prediction Service, n.d.). The estimated discharge volumes reached more than 5,300 times the typical non-flood baseflow discharge of the Guadalupe River near Kerrville.

The flood's impact was exacerbated by high seasonal occupancy in recreational camps and the timing of the intense rainfall and river surge during the night and early morning hours. Camp Mystic, located at the confluence of the South Fork Guadalupe River and Cypress Creek, was severely impacted. The site experienced flow reversal, bank erosion, and cabin inundation, resulting in 27 confirmed fatalities. Facilities within FEMA-designated high-risk zones were overtopped, and floodwater extended beyond hazard boundaries, submerging structures in more than 4 ft (1.22 m) of water (Muyskens et al., 2025). Survivors reported clinging to trees, rooftops, and debris during peak inundation.

The timing, overnight during a national holiday, combined with extreme rainfall, rapid hydrologic response, and communication challenges, contributed to the high casualty count and widespread damage (Fig. 2). As of this writing, 137 fatalities

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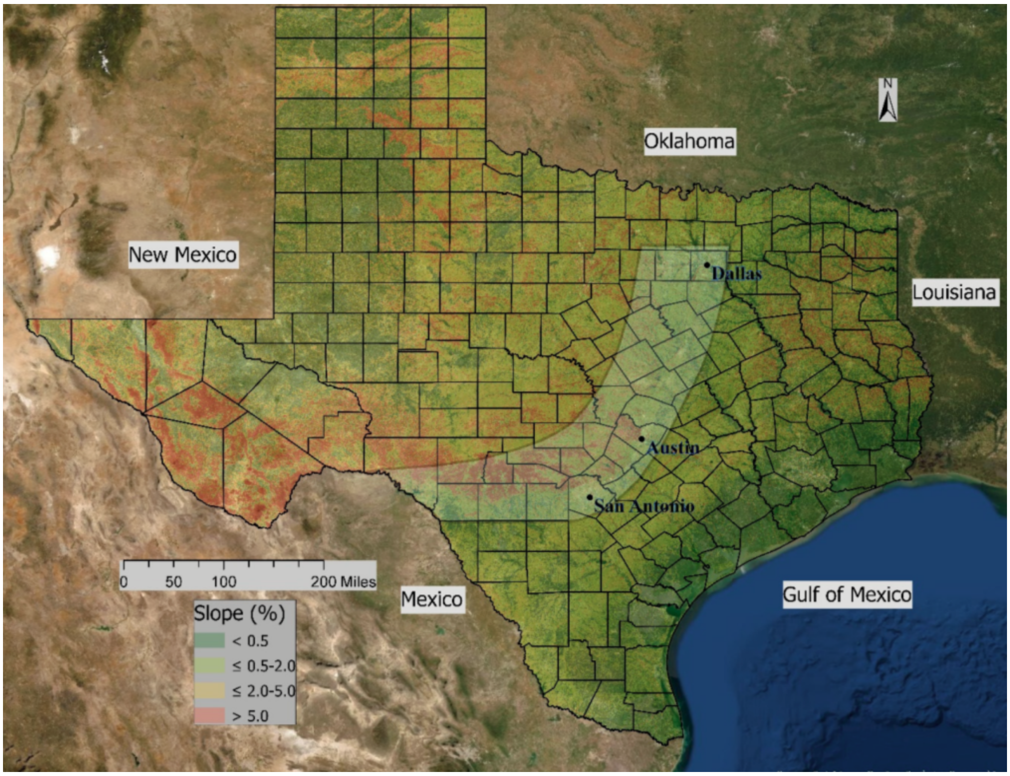

Figure 1. Location of Flash Flood Alley along the Balcones Escarpment in Central Texas, extending from the Dallas–Fort Worth area through Austin and San Antonio. Adapted from Han and Sharif (2021).

have been confirmed, with two individuals still missing (Brooks, 2025). The 137 fatality total reported for the overall event includes fatalities across the broader affected Guadalupe River corridor and associated downstream counties; the Kerr County specific total was 119 confirmed deaths, with two individuals still listed as missing. This event has catalyzed renewed discourse on flash flood forecasting, risk communication, and evacuation protocols in vulnerable regions. Figure 3 provides a geographic overview of the Upper Guadalupe River Basin in Kerr County. As shown, the North and South Forks converge at Hunt, with the river flowing southeast through Kerrville and Center Point toward Comfort. Camp Mystic, located along the South Fork, lies within the area most heavily impacted during the 4 July flood.

The 4 July Kerr County flood highlights growing concerns about intensifying hydroclimatic extremes under anthropogenic climate change, particularly in semi-arid regions recognized for their vulnerability to flash flooding. Climate scientists and meteorological briefings on the 2025 Texas Hill Country floods have emphasized that warming atmospheric and ocean conditions drive greater water vapor availability, fueling more frequent and severe precipitation events in these areas (ClimaMeter, 2025; Faranda et al., 2022). Regional and global studies consistently show that extreme precipitation and flood risks are intensifying in semi-arid zones due to the dual effects of higher atmospheric moisture and geomorphological vulnerability, with anthro-

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pogenic warming playing a demonstrable role in making catastrophic events more frequent and severe (IPCC, 2023; Tabari, 2020).

The Kerr County flood event exemplifies the compound nature of flash flood risk, wherein antecedent hydrologic deficits, mesoscale convective forcing, and infrastructural vulnerability coalesce to produce extreme outcomes. This study integrates high-resolution hydrometeorological diagnostics with spatial impact assessment to improve our operational understanding of flash flood dynamics in data-sparse, topographically complex regions. By characterizing the atmospheric precursors, hydrologic response trajectories, and extent of fluvial inundation, the analysis identifies critical amplifiers of disaster severity. These findings inform targeted preparedness frameworks and adaptive resilience strategies for similarly exposed landscapes. The following sections describe the atmospheric drivers, rainfall–runoff dynamics, human impacts, and recovery challenges of the event and discuss implications for flash flood risk management under a warming climate.

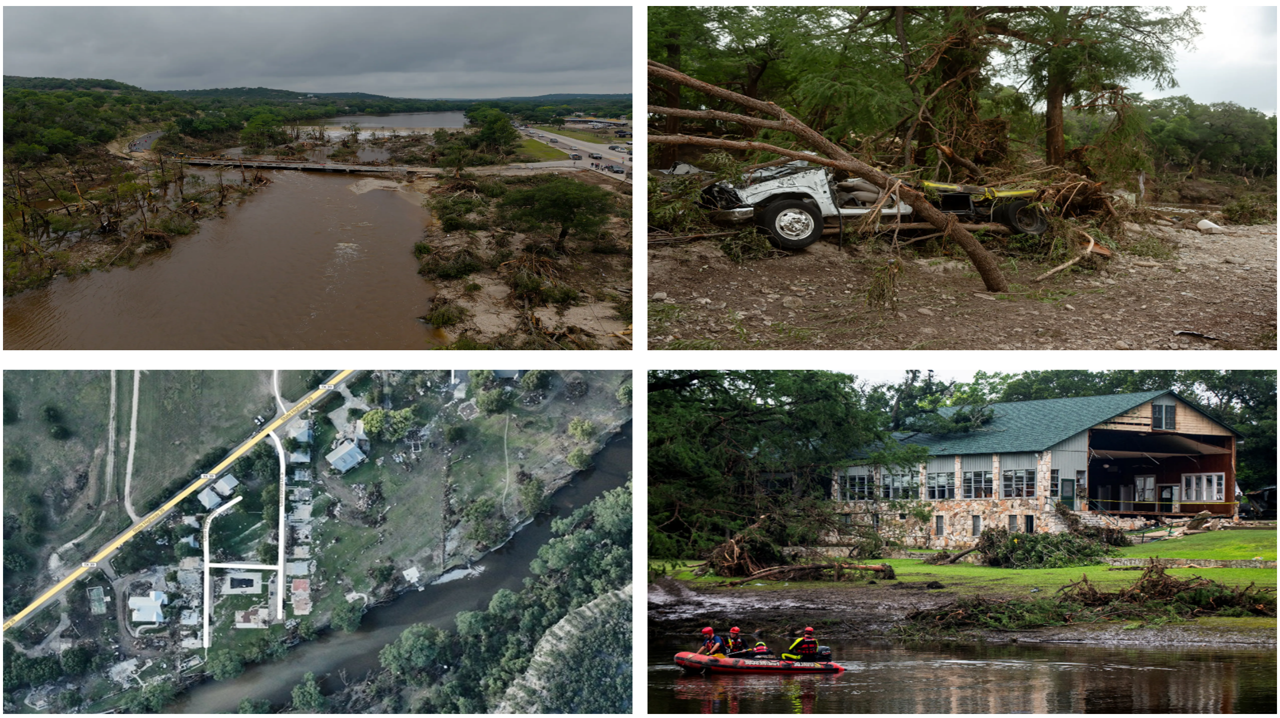

Figure 2. Montage showing (clockwise from top-left) aerial damage along the Guadalupe River in Kerrville (Brenda Bazán for The Texas Tribune), crushed vehicles and uprooted trees in Hunt (Eric Gay for The Associated Press), search-and-rescue operations following the flood (Sergio Flores for REUTERS), and additional flood impacts in Kerr County (NOAA).

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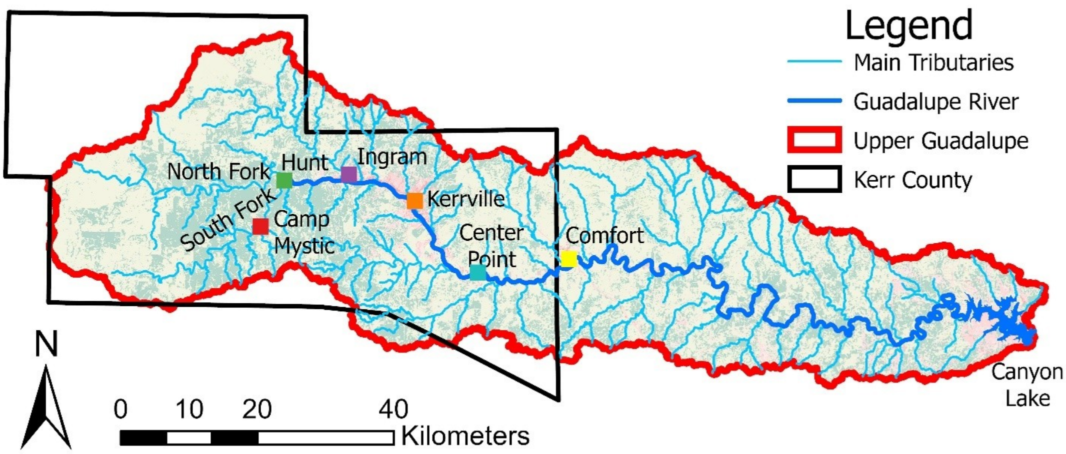

Figure 3. Map of Kerr County showing the Guadalupe River with its North and South Forks, the location of Camp Mystic, and the communities of Hunt, Ingram, Kerrville, Center Point, and Comfort.

2 The Kerr County Flash Flood

2.1 Atmospheric Drivers

The catastrophic flooding in Central Texas on 4 July 2025 was characterized by the synergistic alignment of five key atmospheric drivers (Shepherd, 2025). First, anomalously high precipitable water values were sustained by deep tropical moisture advection from the remnants of Tropical Storm Barry and eastern Pacific moisture sources. Second, synoptic-scale ascent and mesoscale convergence were facilitated by a tilted upper-level trough and an embedded mesoscale convective vortex (MCV), enhancing vertical motion and convective organization. Third, the quasi-stationary nature of the convective system over the Texas Hill Country produced prolonged rainfall accumulation over a confined spatial domain. Fourth, elevated sea surface temperatures in the Gulf of Mexico amplified latent heat fluxes, increasing atmospheric instability and precipitation efficiency. Fifth, a persistent large-scale circulation pattern maintained favorable thermodynamic and kinematic conditions, enabling sustained convective regeneration and extreme rainfall rates (Shepherd, 2025).

2.2 Emergency Communication

The release of public records following the 4 July 2025 floods has highlighted a critical disconnect between regional disaster protocols and the operational reality of the flash flood surge. Dispatch recordings reflect a surge in emergency communication volume that substantially exceeded the design capacity of the county's communications infrastructure: two telecommunicators fielded more than 400–600 calls over several hours, including urgent requests from riverside youth camps, while the Guadalupe River rose 6–9 m (20–30 ft) in approximately one hour in parts of the basin.

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The existing emergency management framework, based on a 2020 template, had not been updated to incorporate full-scale evacuation protocols for high-intensity flash flood scenarios. Legislative hearings and post-event testimony from camp operators further indicate that state and local oversight mechanisms faced challenges in addressing the distinct vulnerabilities of riverside camps, particularly their reliance on radio communications in areas where terrain limits signal reliability. These records suggest that sparse monitoring networks and communication delays hindered coordination during the event, indicating that disaster severity was compounded by operational and technological limitations rather than the hydrological forcing alone.

3 Rainfall–Runoff Dynamics

3.1 Spatial and Temporal Rainfall Distribution

During the early morning hours of 4 July 2025, the South Fork of the Guadalupe River watershed experienced a rapid and spatially concentrated rainfall event that played a decisive role in the catastrophic flooding at Camp Mystic. Conditions were calm at local midnight, with no measurable precipitation recorded at the watershed headwaters. By 01:00 CDT, heavy rainfall had commenced in the headwater zone, with rates exceeding 25 mm h^{-1} (1 in h^{-1}). Within the subsequent hour, rainfall intensified sharply across the southeastern watershed, reaching rates as high as 81 mm h^{-1} (3.2 in h^{-1}). By 03:00 CDT, the storm had expanded to cover the entire watershed, delivering maximum intensities of approximately 102 mm h^{-1} (4 in h^{-1}), saturating thin soils and driving rapid runoff into the South Fork. Rainfall of 89 mm h^{-1} (3.5 in h^{-1}) persisted across the main river corridor at 04:00 CDT. By 05:00 CDT, direct rainfall into the basin began to subside, and by 06:00 CDT no additional precipitation was recorded. Over the course of the event, radar-estimated accumulations of up to 271 mm (10.7 in) were recorded between midnight and 13:00 CDT.

The concentration of maximum rainfall within approximately three hours yields a return-period estimate of approximately 250 years (annual exceedance probability 0.4 %), with individual radar pixels exceeding the local 3-hour, 1,000-year threshold of 238 mm (9.4 in). Fig. 4 presents NOAA Stage IV radar-derived rainfall estimates over the Guadalupe River at Hunt during the high-intensity period in early July 2025, illustrating the spatial concentration of rainfall near Camp Mystic, particularly between 01:00 and 04:00 CDT on 4 July.

3.2 Streamflow Response

The 4 July 2025 flood at Camp Mystic exemplifies the characteristically flashy hydrologic response of the Texas Hill Country, where steep terrain, shallow soils, and underlying limestone severely restrict infiltration. Intense rainfall rapidly becomes surface runoff that accelerates through narrow, confined stream channels, producing extremely short lag times between peak rainfall and peak discharge. The South Fork of the Guadalupe River rose more than 6.1 m (20 ft) in just over two hours, leaving minimal time for warnings or safe evacuation.

At the USGS streamflow gauge at Hunt (station 08165500), the peak discharge is estimated at 8,892 $m^3\ s^{-1}$ (314,000 $ft^3\ s^{-1}$) based on surveyed high-water marks (U.S. Geological Survey, 2025), far exceeding the July 1932 historical peak of 5,833 $m^3\ s^{-1}$

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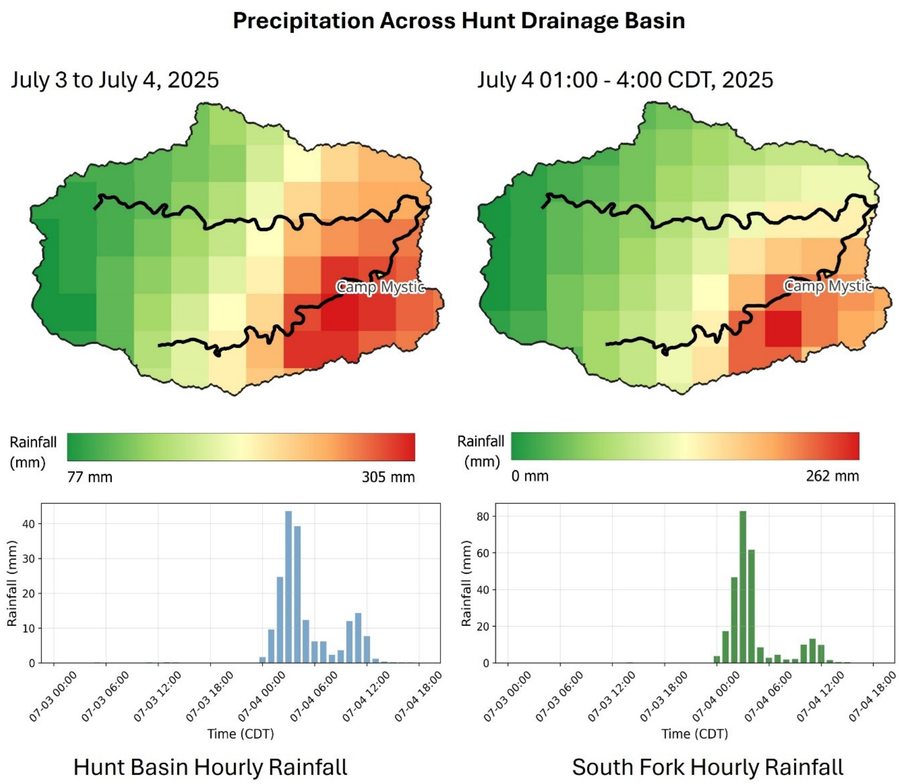

Figure 4. Spatial and temporal distribution of rainfall over the Guadalupe River basin at Hunt, Texas. Top panels show Stage IV radar-estimated rainfall for (left) 3–4 July 2025 and (right) 4 July, 01:00–04:00 CDT; color intensity indicates rainfall accumulation, with red denoting the highest values. Camp Mystic lies within the high-intensity zone during the peak rainfall period. Bottom panels display hourly rainfall totals for the Hunt Basin and South Fork subregion, both showing pronounced peaks between 01:00 and 04:00 CDT on 4 July.

(206,000 $ft^3\ s^{-1}$) at a stage of 11.2 m (36.60 ft), and nearly three times the July 1987 peak of 3,058 $m^3\ s^{-1}$ (108,000 $ft^3\ s^{-1}$) at a stage of 8.7 m (28.38 ft). The gauge failed at 05:10 CDT when the stage was 11.4 m (37.52 ft) and still rising nearly linearly, indicating that this estimate likely represents a lower bound on the true maximum discharge.

Unlike the 1932 flood, which resulted from a broader, longer-duration rainfall event, the 2025 event was remarkable for the short duration and highly localized nature of rainfall extremes over the South Fork, extending toward the confluence with the North Fork at Hunt. San Antonio WSR-88D radar storm totals indicate maximum accumulations centered on the South Fork, with the most intense rainfall almost entirely confined to a three-hour window between 06:00 and 09:00 UTC (01:00–04:00 CDT).

The North Fork hydrograph provides additional context (Fig. 5). Stage at the North Fork gauge (USGS 08165300, 168 mi^2) peaked at 6.46 m (21.2 ft) at 05:30 CDT, approximately 20 minutes after the last stage measurement at the confluence station at Hunt. The maximum discharge recorded on the North Fork was approximately 1,695 $m^3\ s^{-1}$ (58,600 $ft^3\ s^{-1}$), well below

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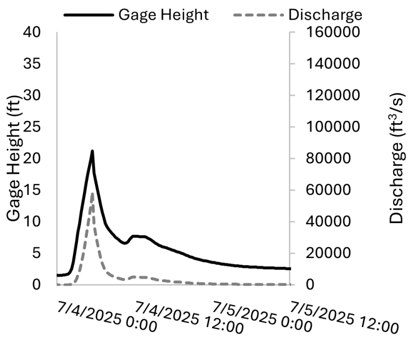
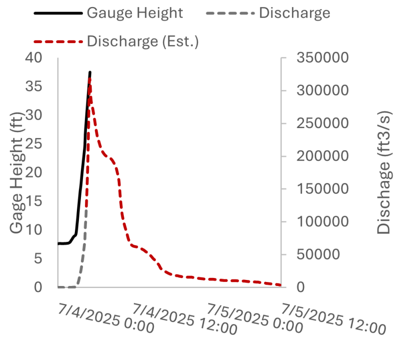
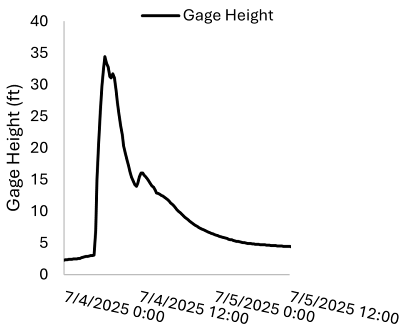
the 1932 North Fork estimate of 3,964 m^3 s^{-1} (140,000 ft^3 s^{-1}), though the stage exceeded the rating curve for over an hour, confirming a substantial flood response. The South Fork in 2025 is where the most extraordinary discharge behavior occurred: the July 1932 flood produced a miscellaneous measurement of 2,377 m^3 s^{-1} (84,000 ft^3 s^{-1}) on the South Fork, whereas the 2025 peak was substantially larger by any available metric.



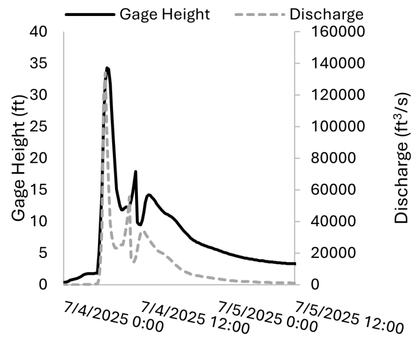
(a) North Fork Guadalupe River (USGS 08165300, 168 mi^2).



(b) Guadalupe River at Hunt (USGS 08165500, 288 mi^2).



(c) Guadalupe River above Bear Creek (USGS 08166140, 494 mi^2).



(d) Guadalupe River at Kerrville (USGS 08166200, 510 mi^2).

Figure 5. Stage hydrographs at (a) North Fork Guadalupe River (USGS 08165300, 168 mi^2), (b) Guadalupe River at Hunt (USGS 08165500, 288 mi^2; red dashed line represents the USGS discharge estimate based on high-water marks), (c) Guadalupe River above Bear Creek (USGS 08166140, 494 mi^2), and (d) Guadalupe River at Kerrville (USGS 08166200, 510 mi^2). The Hunt station ceased reporting at 05:10 CDT; discharge data are unavailable for Guadalupe River above Bear Creek.

3.3 Mass-Balance Discharge Estimation and Envelope Curve Comparison

Applying a first-order mass-balance approach constrained by spatially integrated NOAA Stage IV rainfall estimates and simplified hydrologic routing, the peak discharge at the South Fork gauge immediately downstream of Camp Mystic is inferred to have ranged between 7,221 and 7,505 m^3 s^{-1} (255,000–265,000 ft^3 s^{-1}). Uncertainty in these estimates arises primarily from radar range-dependent bias, spatial rainfall heterogeneity at sub-pixel scales, and simplified routing assumptions. Nevertheless, even under conservative bounds, the peak South Fork discharge is extraordinary in a regional context.

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The 2025 South Fork discharge does not merely represent a new local record; it approaches or exceeds the regional discharge envelope curve for the United States (Asquith and Slade, 1995; Crippen and Bue, 1977), as illustrated in Fig. 6. The South Fork peak of approximately 7,363 $m^3\ s^{-1}$ (260,000 $ft^3\ s^{-1}$) from a 250.5 km^2 (96.7 mi^2) basin yields a unit discharge of 2,689 $ft^3\ s^{-1}\ mi^{-2}$, far exceeding the previously recognized regional extreme defined by the 1935 Seco Creek event at 1,504 $ft^3\ s^{-1}\ mi^{-2}$. By approaching the envelope curve, the South Fork experienced stream power levels capable of fundamentally reorganizing the valley floor. Field observations downstream of Camp Mystic revealed extensive macroturbulent scour and the removal of decades-old bald cypress stands, indicating that hydraulic forces exceeded the shear-stress thresholds of even the most stable Hill Country riparian corridors. This exceedance suggests that the regional discharge envelope, often treated as a static physical bound, may constitute a moving target as atmospheric moisture availability increases under anthropogenic warming. The 2025 event suggests that the "upper bound" of Texas Hill Country flood potential requires upward revision under non-stationary climatic conditions.

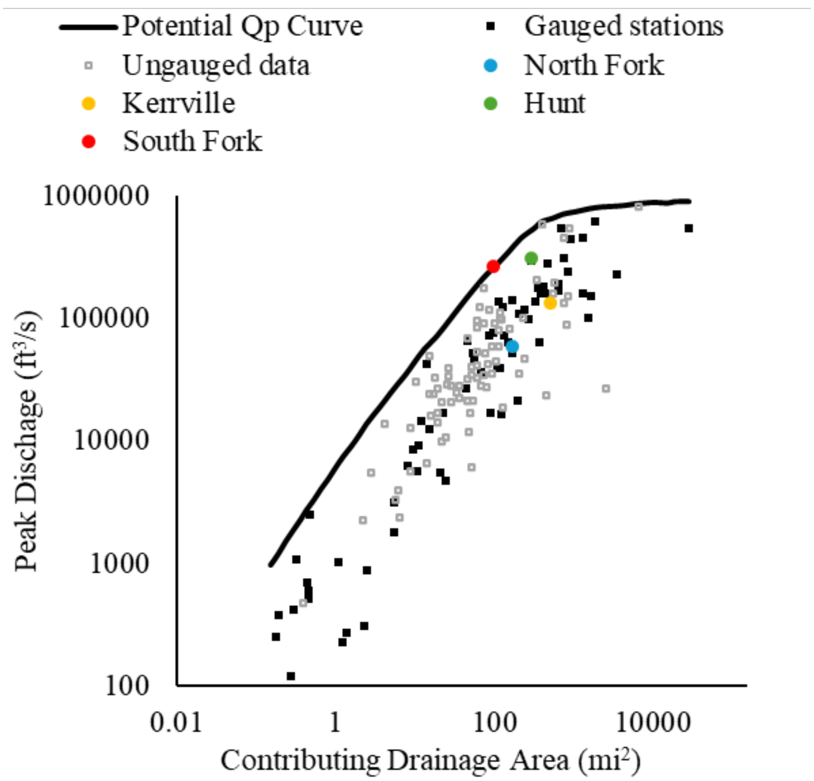

Figure 6. Updated extreme peak discharge measurements and estimates for the Guadalupe River system plotted against the regional discharge envelope curve for the United States (Asquith and Slade, 1995; Crippen and Bue, 1977). Solid circles represent documented peak discharges at USGS streamflow gauging stations; hollow squares indicate sites without permanent gauges. The estimated South Fork peak of approximately 7,363 $m^3\ s^{-1}$ (260,000 $ft^3\ s^{-1}$) from a 250.5 km^2 basin yields a unit discharge of 2,689 $ft^3\ s^{-1}\ mi^{-2}$, substantially exceeding the previously recognized regional extreme.

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4 Human Impact and Emergency Response Limitations

The human toll of the 4 July 2025 flood reflects the intersection of record-setting hydrologic extremes with high seasonal occupancy at riverside camps and critical gaps in emergency communication infrastructure. The gravest losses were concentrated at riverside camps. Camp Mystic, located on the South Fork of the Guadalupe, suffered 27 confirmed fatalities among campers and counselors, with those names formally released by county and state authorities on 8 August (Kumar, 2025). A director who remained on the grounds of Heart O' the Hills, which was between sessions and had no campers on site, was also killed, underscoring how rapidly the river became lethal even in the absence of large civilian populations. At nearby Camp La Junta, dispatch logs recorded a building collapse and urgent rescue calls, yet subsequent reporting and on-camera survivor interviews indicate no fatalities at that camp (KSAT, 2025a). Two other riverfront camps, Waldemar and Mo-Ranch, also avoided loss of life; operators reported rapid, self-initiated evacuations (UPI, 2025). In Kerr County, officials ultimately confirmed 119 deaths, with two individuals still listed as missing; across the broader multi-county flood event, the confirmed fatality total reached 137, indicating that the remaining confirmed deaths occurred outside Kerr County, including downstream portions of the affected Guadalupe River corridor.

In the pre-dawn hours of 4 July, radio traffic and incident timelines depict a crisis accelerating faster than emergency responders could match. Near Hunt and the riverside camps, a corporal called for helicopter evacuations; minutes later, with a swift-water rescue boat still ten minutes away, a deputy warned over the radio that "the kids don't have 10 minutes." A building collapse at Camp La Junta was reported shortly thereafter, and a countywide CodeRED alert was issued at 05:01 CDT, following the initial Flash Flood Warning for Bandera and Kerr counties at 01:14 CDT (Click2Houston, 2025). The rapid onset of the event during overnight hours coincided with non-emergency staffing levels that were not positioned for immediate mesoscale response.

Beyond the camp fatalities near Hunt, the 4 July floods inflicted severe regional damage throughout the Guadalupe corridor. Kerrville issued a disaster declaration as floodwaters submerged Louise Hays Park and destroyed sections of riverside trails (Click2Houston, 2025). Ingram experienced inundation of local businesses and RV parks, with the Old Ingram Loop district sustaining heavy damage (Texas Public Radio, 2025). Transportation infrastructure was substantially disrupted: State Highway 39 was closed between Highway 27 and FM 187, and FM 1340 remained closed pending flood damage repairs (KSAT, 2025b). Downstream at Comfort, the Guadalupe surged to record heights, rising from roughly hip-deep to three stories within hours and inundating riverside neighborhoods (The Texas Tribune, 2025). While this study identifies technical and infrastructural factors that amplified the event's impact, the attribution of specific outcomes to individual or institutional decision-making remains beyond the scope of this analysis.

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5 Recovery Challenges

5.1 Regulatory Gaps, Insurance Deficits, and Recovery Barriers

The Kerr County flash floods not only produced extensive physical damage but also exposed significant challenges within the existing intergovernmental framework for disaster recovery. A substantial proportion of affected households lacked flood insurance coverage, commonly because their properties were situated outside designated Special Flood Hazard Areas (SFHAs) and had no prior inundation history. In the absence of coverage, residents bore the full financial burden of reconstruction, compounding psychosocial stresses associated with displacement, property loss, and, in many cases, community bereavement.

At legislative hearings in Kerrville, testimony highlighted the complexities residents encountered in navigating federal disaster recovery administrative requirements (Manno, 2025). Aid applications encountered procedural obstacles that affected the timeline for urgent repairs and delayed community recovery. In Kerr County, multiple heavily flooded neighborhoods and camp facilities lie outside current SFHA boundaries, illustrating how underestimation of flood exposure in regulatory products suppresses insurance uptake and distorts individual risk perception.

The event catalyzed broader scrutiny of recovery governance in Texas, including alignment, or misalignment, between federal, state, and local recovery responsibilities. Emerging legislative proposals included (1) strengthening vertical coordination among FEMA, state agencies, and municipal governments; (2) expanding affordable flood insurance access in rural and peri-urban areas; (3) pre-positioning recovery resources in recurrent flood zones; and (4) establishing community-based hubs to support long-term reconstruction (Wardwell, 2025). For Kerr County, the disaster underscored that while hydrometeorological forcing and physiographic context render flash flooding an endemic hazard, its societal impacts are substantially magnified when recovery pathways encounter multi-jurisdictional coordination and resource alignment challenges. Legislative inquiry has generated cautious optimism regarding policy reform, yet for many displaced families still navigating the aftermath, such structural changes remain aspirational (Fulce, 2025).

Despite ongoing advances in geospatial technology and hydrologic modeling, federal flood-hazard delineations continue to underrepresent actual flood exposure, a discrepancy made starkly evident by the 2025 Texas Hill Country floods. Current hazard maps omit numerous high-risk locales, particularly under non-stationary climatic regimes characterized by intensifying convective precipitation. The consequences are tangible: property owners may receive false reassurance of minimal risk while their assets remain highly susceptible to recurrent inundation. The national risk-assessment framework would benefit from incorporating dynamic hydrometeorological data, high-resolution terrain modeling, and community-sourced observations to more accurately quantify exposure and vulnerability; otherwise, continued reliance on historically calibrated baseline datasets will limit the effectiveness of risk-mitigation strategies and perpetuate societal susceptibility to flash flood hazards.

5.2 Mortality Demographics and Fatality Circumstances

NOAA's Storm Events Database records for the 4 July 2025 Kerr County flash flood document 106 fatalities with individual-level age, sex, and location-of-death information, providing an unusually detailed basis for characterizing the demographic profile of flood mortality in this event. Across these records, individuals range in age from 1 to 82 years, with the age distribution

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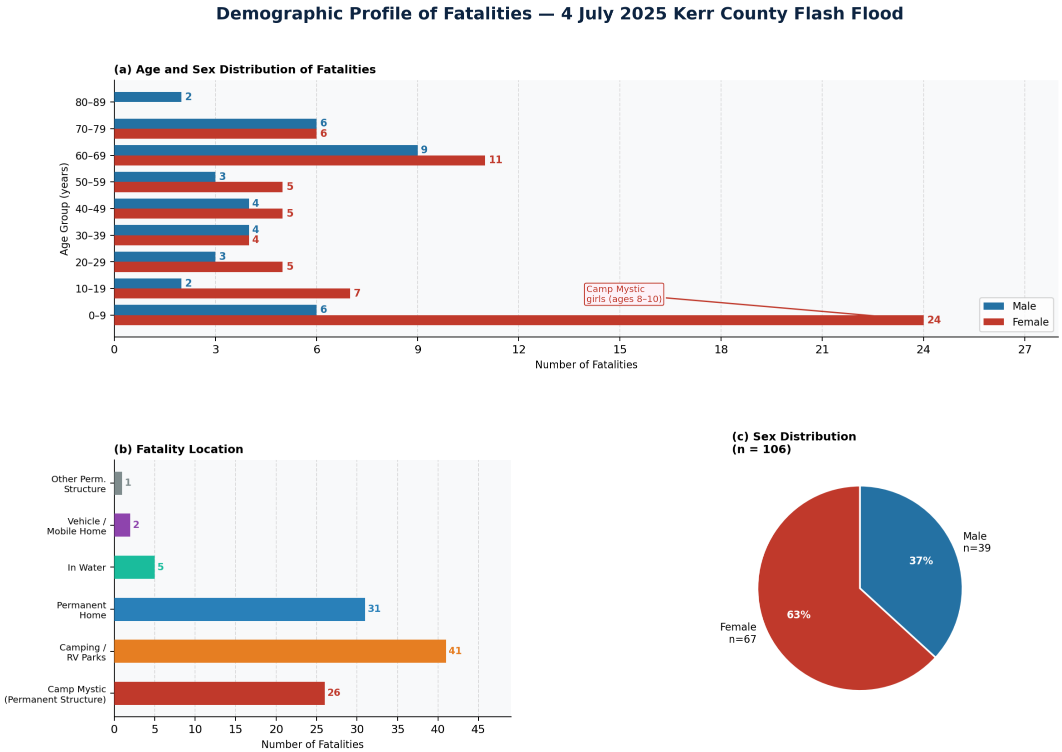

Figure 7. Age–sex distribution (a), fatality location (b), and sex breakdown (c) of the 106 recorded fatalities from NCEI Storm Events Database records (event IDs 1287369 and 1287451). These records do not constitute the full fatality accounting for the event. They exclude 10 additional Center Point fatalities without comparable individual-level demographic/location information, 3 additional Kerr County fatalities needed to reconcile with the county-confirmed total of 119 deaths, and 18 fatalities that occurred outside Kerr County or farther downstream within the broader multi-county flood event.

exhibiting a pronounced bimodal structure (Fig. 7). The demographic analysis is limited to the 106 fatalities with complete individual-level information in the two NCEI Storm Events Database records analyzed here. This subset does not fully reconcile with the 119 county-confirmed Kerr County deaths because it excludes 10 Center Point fatalities lacking comparable individual-level demographic/location records and 3 additional Kerr County fatalities not represented in the analyzed NCEI subset. The remaining 18 fatalities in the 137-fatality event total occurred outside Kerr County or farther downstream in the broader multi-county flood event. A sharp concentration of young victims (ages 0–9) is driven almost entirely by the Camp Mystic fatalities on the South Fork Guadalupe River, while a second, broader cluster spans the 50–79 age range and is associated with permanent-residence fatalities along the river corridor.

The sex distribution is markedly asymmetric: female fatalities account for 63 % of the 106 documented deaths ($n = 67$) compared with 37% male ($n = 39$; Fig. 7). This disparity is principally attributable to the institutional demographics of Camp Mystic, a summer camp exclusively for girls. Of the 61 fatalities in the South Fork sub-event, represented in the NCEI individual-

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level records, 26 were coded as occurring at Camp Mystic, including campers and staff. This source-coded Camp Mystic category is used in (Fig. 7) and is distinct from the broader official Camp Mystic fatality total of 27 reported elsewhere in the manuscript. One additional fatality involved a 76-year-old individual in a vehicle along the South Fork corridor. The remaining 34 fatalities occurred elsewhere in the South Fork/Hunt corridor, including permanent residences in the Hunt corridor and the Casa Bonita neighbourhood, as well as open-water locations.

The second event record documents 45 direct fatalities concentrated at camping and RV park settings near Ingram, which constitute the largest single location category across the combined dataset ($n = 41$; Fig. 7). Unlike the Camp Mystic cluster, this group was more evenly distributed by sex and spanned a broader age range (1–82 years), consistent with the mixed-demographic occupancy of the riverside RV parks that were destroyed. Two additional deaths in this record occurred in open water, one in a permanent home, and one in a permanent structure. One fatality was classified as indirect, involving a 27-year-old male in a mobile or trailer home.

Taken together, the fatality data reveal several compound vulnerability dimensions. First, children aged 0–9 account for 30 of the 106 recorded deaths; the single most affected age group, overwhelmingly concentrated in institutional camp settings and family residences that offered no safe vertical refuge during the rapid pre-dawn inundation. Second, adults aged 60 and above are substantially represented ($n = 34$; 32 %), particularly among those who perished in permanent homes, consistent with established evidence that older adults face elevated flood mortality risk due to reduced mobility and limited self-evacuation capacity. Third, the overnight timing of the event, with peak inundation between approximately 03:00 and 05:30 CDT, meant that most victims were likely asleep or had minimal warning before life-threatening water levels were reached. Fourth, the vehicle and mobile-home fatalities ($n = 2$) were comparatively minor relative to structural inundation, reflecting the dominant mechanism of flood mortality in this event.

The concentration of fatalities at locations situated outside or at the margin of FEMA Special Flood Hazard Area boundaries, including both camp facilities and numerous residential structures, reinforces the argument advanced elsewhere in this paper that regulatory flood-hazard products systematically underrepresent actual exposure. The demographic profile of this event, particularly its disproportionate impact on children and older adults in overnight occupancy settings, should directly inform the design of site-specific impact-based warning thresholds and mandatory evacuation protocols for riverside camps, RV facilities, and rural residential corridors operating during high-risk hydrometeorological periods.

6 Future Directions for Flood Preparedness and Resilience

6.1 From Threshold-Based Alerts to Impact-Based Warning Protocols

The reconstructed lag times, stage rise rates, and peak discharges for the South Fork and mainstem Guadalupe demonstrate that life-threatening conditions can develop within one to two hours of intense rainfall onset in the Texas Hill Country. These dynamics justify a fundamental shift in warning systems: from generic threshold-based alerts toward impact-based, location-specific guidance that translates rainfall and stage forecasts into actionable protective decisions. Rather than issuing meteorological advisories that describe what the atmosphere is doing, effective impact-based warnings communicate what impacts are

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expected, where and when they will occur, and what protective actions are immediately required, specifying which roads will become impassable, which riverside areas face imminent inundation, and whether evacuation or movement to higher ground is necessary.

Embedding upstream rainfall or stage thresholds into automatic, site-specific guidance for camps, low-water crossings, and riverside neighborhoods would better align protective actions with the exceptionally short lead times characteristic of Hill Country flash floods. Effective preparedness also requires strengthening the capacity of local decision-makers to manage rapidly evolving flood scenarios. Emergency managers, camp operators, and first responders would benefit from regular simulation-based training that illustrates how inundation propagates under different rainfall intensities, how road networks fragment, and how cascading impacts constrain rescue operations. The discharge estimates, peak timing, and spatial inundation patterns from the 2025 event provide physically realistic boundary conditions for developing dynamic inundation maps and tabletop or virtual training exercises.

The flood further exposed critical vulnerabilities in emergency communication systems. Redundant, interoperable notification pathways are necessary to ensure warnings reach all populations even during power or cellular outages. Investments in multi-channel alert systems, localized siren networks, and publicly accessible real-time dashboards displaying current rainfall, river stage, and road conditions would substantially enhance situational awareness. Expanded monitoring networks and high-resolution mapping should be treated as equity tools, ensuring that rural and peri-urban communities receive protective infrastructure equivalent to that available in urban centers.

6.2 Dynamic, Climate-Aware Hazard Mapping

The approach of South Fork and mainstem Guadalupe discharges toward and potentially beyond regional envelope-curve values demonstrates that historical flood records are inadequate as sole design standards for the Texas Hill Country. This finding supports a transition toward non-stationary, climate-aware hazard mapping that incorporates evolving precipitation extremes, updated high-resolution topography, and localized runoff dynamics driven by land cover and soil condition variability. Integrating dynamic flood maps into land-use planning, insurance frameworks, and infrastructure design would substantially reduce the gap between perceived and actual flood risk, particularly for seasonal-occupancy facilities and rural river corridors where 2025 impacts extended far beyond the boundaries established by current regulatory hazard models.

Preparedness must be institutionalized within county-level governance rather than treated as a transient post-disaster priority. Regular updates to floodplain maps, automated integration of hydrologic forecasts into alerting systems, coordinated training programs, and pre-positioned recovery resources could be considered as part of standard practice. The exceedance of both the 500-year floodplain and regional envelope curves during the 2025 event makes clear that resilience in Flash Flood Alley requires planning for the probable maximum flood under climate-informed conditions rather than historical averages. Embedding this perspective into zoning ordinances, emergency planning, and public education is essential for reducing future loss of life and accelerating equitable recovery from the inevitable recurrence of extreme flash flooding in this region.

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7 Conclusions

This study presents a hydrometeorological reconstruction and impact assessment of the 4 July 2025 Kerr County flash flood, one of the most severe flash flood events in the recorded history of the Texas Hill Country. The analysis integrates NOAA Stage IV radar-derived rainfall estimates, USGS streamflow gauge records, and first-order mass-balance modeling to characterize the rainfall–runoff response and to place the event in the context of regional discharge extremes.

The key findings of this study are as follows. (1) The event was produced by a quasi-stationary mesoscale convective system derived from Tropical Storm Barry remnants, which delivered more than 508 mm of rainfall over 72 hours, with peak 3-hour intensities exceeding the 1,000-year recurrence threshold over portions of the South Fork Guadalupe watershed. (2) Estimated peak discharges at the South Fork gauge ranged from 7,221 to 7,505 $m^3\ s^{-1}$, approaching or exceeding the regional discharge envelope curve and establishing a new benchmark for unit discharges in the Hill Country. (3) Antecedent exceptional drought conditions substantially increased surface runoff through hydrophobic soil behavior, amplifying the hydrologic response relative to what would be expected from a similar rainfall event under non-drought conditions. (4) The extreme discharge, high seasonal camp occupancy, overnight timing, and critical deficiencies in emergency communication infrastructure combined to produce an exceptional loss of life, with 137 fatalities confirmed and 2 missing as of this writing. (5) Numerous affected structures lay outside current FEMA-designated Special Flood Hazard Areas, exposing the limitations of historically calibrated static hazard maps under intensifying hydroclimatic conditions.

These findings carry important implications for flash flood risk management. A combination of impact-based warning protocols tailored to upstream rainfall and stage thresholds, expanded and redundant emergency communication systems, regular simulation-based emergency training for camp operators and first responders, and non-stationary climate-aware hazard mapping will be necessary to reduce mortality and accelerate recovery in Flash Flood Alley. The 2025 Kerr County flood should serve as a catalyst for reconsidering whether the regional discharge envelope, traditionally treated as a stable physical upper bound, remains a reliable design reference under a warming climate with increasing atmospheric moisture availability. Future research should focus on quantifying the soil moisture–infiltration feedbacks that may have amplified the 2025 response, improving sub-hourly radar rainfall bias corrections for convective extremes in semi-arid terrain, and developing probabilistic non-stationary flood frequency frameworks for the Texas Hill Country that explicitly account for anthropogenic climate forcing.

Data availability. All streamflow data used in this study are publicly available from the U.S. Geological Survey National Water Information System (https://waterdata.usgs.gov). Radar-derived rainfall estimates are available through the NOAA Multi-Radar Multi-Sensor (MRMS) and Stage IV archives at https://water.weather.gov/precip/. U.S. Drought Monitor data are available at https://droughtmonitor.unl.edu.

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