An Overview of the Performance and Operational Applications of the MRMS and FLASH Systems in Recent Significant Urban Flash Flood Events

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ABSTRACT: The Multi-Radar Multi-Sensor (MRMS) system is an operational, state-of-the-science hydrometeorological data analysis and nowcasting framework that combines data from multiple radar networks, satellites, surface observational systems, and numerical weather prediction models to produce a suite of real-time, decision-support products every 2 min over the contiguous United States and southern Canada. The Flooded Locations and Simulated Hydrograph (FLASH) component of the MRMS system was designed for the monitoring and prediction of flash floods across small time and spatial scales required for urban areas given their rapid hydrologic response to precipitation. Developed at the National Severe Storms Laboratory in collaboration with the Cooperative Institute for Mesoscale Meteorological Studies (CIMMS) and other research entities, the objective for MRMS and FLASH is to be the world's most advanced system for severe weather and storm-scale hydrometeorology, leveraging the latest science and observation systems to produce the most accurate and reliable hydrometeorological and severe weather analyses. NWS forecasters, the public, and the private sector utilize a variety of products from the MRMS and FLASH systems for hydrometeorological situational awareness and to provide warnings to the public and other users about potential impacts from flash flooding. This article will examine the performance of hydrometeorological products from MRMS and FLASH and provide perspectives on how NWS forecasters use these products in the prediction of flash flood events with an emphasis on the urban environment.

KEYWORDS: Hydrometeorology; Remote sensing; Nowcasting; Operational forecasting; Flood events; Societal impacts

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Flash flooding is defined as the rapid inundation of an area by rising water within a short duration of time, generally less than 6 h (NOAA 2019). Flash floods typically result from rainfall rates that exceed the surface infiltration rate. The flash flood potential in urbanized areas is elevated due to large areas of impervious surfaces coupled with drainage systems that inadequately handle runoff from excessive rainfall rates. Precipitation rates can be enhanced within and downstream of urban influences due to urban heat islands (e.g., Shepherd et al. 2002; Mote et al. 2007; Debbage and Shepherd 2019; Liu and Niyogi 2019) while changes in planetary climate have increased the water-holding capacity of the atmosphere, resulting in more frequent, significant precipitation events (Huntington 2006; Min et al. 2011; Trenberth 2011). Combining more frequent excessive rainfall rates with urbanization has heightened the risk of high-impact flash floods in densely populated regions.

The summer of 2019 produced a series of notable flash flood events in areas of significant urbanization. This study examines six urban flash floods (Table 1) from the perspective of the Multi-Radar Multi-Sensor (MRMS; Zhang et al. 2016) and Flooded Locations and Simulated Hydrographs (FLASH; Gourley et al. 2017) systems. The MRMS system employs state-of-the-art science for the quality control and generation of hydrometeorological products derived from multiple networks at a high spatial (1-km) and temporal (2-min) resolution. The FLASH system provides hydrologic modeling capabilities and QPE comparison tools designed to aid in the monitoring and prediction of flash flooding at the 0–6-h time scale. The overall performance of various MRMS and FLASH products are analyzed for each urban flash flood event. Detailed case analyses are presented to describe the evolution of three events (given some similarities between the urban flash floods documented in this manuscript). The applications of these products are also presented, including the perspectives of operational NWS personnel who worked these events.

Table 1. List of notable urban flash flood events during the summer of 2019 that were evaluated in this study. Included are the dates, start times (UTC), and end times (UTC) of each event along with a description of the flash flood impacts of each event from NOAA Storm Data and local media.

Location	Date	Start time (UTC)	End time (UTC)	Flash flood impacts
Richmond, VA	1 Jun 2019	0100	0300	Multiple stranded vehicles and water rescues performed in and around metropolitan area; water covering Interstates 95 and 64
Washington, DC	8 Jul 2019	1242	1700	Numerous vehicles were stranded with multiple water rescues during morning rush hour; water entered multiple basements and businesses and underground Metro system; sinkholes reported in Potomac and Carderock regions
Minneapolis, MN	16 Jul 2019	2052	2300	Localized area of roads covered with 2–3 ft (~0.6–0.9 m) of water, including Interstate 394, during afternoon rush hour
Newark, NJ	22 Jul 2019	2310	2345	Multiple road closures due to high water in the city with approximately 30 water rescues; event later impacted New York City area (notably Queens and western Long Island)
Baltimore, MD	6 Aug 2019	2237	0100	Numerous neighborhoods with roads closed due to high water and stranded vehicles; one known water rescue and reports of water entering basements
Saint Louis, MO	12 Aug 2019	0820	1530	Multiround event resulting in numerous road closures and water rescues; areas in Illinois had widespread damage to approximately 1,000 homes, numerous businesses, and one high school

MRMS radar-derived QPE

Two radar-based QPEs were analyzed from the MRMS system. The operational MRMS build as of summer 2019 (v11.6.1) utilized a single-polarization (SP) reflectivity-based approach to generate instantaneous precipitation rates and accumulated QPE values (Zhang et al. 2016). Reflectivity–rain-rate relationships were unique to each grid cell based on different precipitation-type classifications. Grid cells that were classified with the precipitation-type of hail were capped at 53.85 mm h^{-1} (2.12 in. h^{-1}) when reflectivity values were $\geq 49 \text{ dBZ}$. MRMS v12.0 (operational as of October 2020) provided a significant QPE upgrade through a dual-polarimetric (DP) synthetic QPE technique (Wang et al. 2019; Cocks et al. 2019; Zhang et al. 2020) with an evaporation correction scheme (Martinaitis et al. 2018). Advantages of the DP technique include using specific attenuation in rain below the melting layer, which is immune to radar miscalibrations and partial beam blockage, and specific differential phase in hail-producing regions that reduced the need for a precipitation rate cap.

Instantaneous rainfall rates for each event were calculated at a representative NWS flash flood local storm report (LSR) using a 3×3 gridcell average. Evaluations for the six flash flood events were synchronized ($T = 0 \text{ min}$) by the onset of excessive instantaneous precipitation rates from the causative rain event. An excessive rainfall rate was defined in this study as $\geq 12.7 \text{ mm h}^{-1}$ (0.50 in. h^{-1}). Excessive rates in the SP QPE product were generally observed for the period $T = 4\text{--}52 \text{ min}$, while the Baltimore, Maryland, and Saint Louis, Missouri, events had prolonged greater rate durations through $T = 110 \text{ min}$ (Fig. 1a). Zhang et al. (2020) demonstrated that SP QPE tends to underestimate the intensity of warm season heavy rainfall events; moreover, numerous instances existed of instantaneous rain rates capped due to hail precipitation type classifications. Prominent examples of the hail cap influence were observed in the Richmond, Virginia ($T = 4\text{--}18 \text{ min}$), and Baltimore ($T = 52\text{--}76 \text{ min}$) events.

The DP QPE rates were generally characterized by higher values than the SP-derived rates during the period of excessive rainfall rates (Fig. 1b). Rate increases were higher in four of the six cases, most notably the Washington, D.C., event where the average rate increased by $50\text{--}120 \text{ mm h}^{-1}$ (Fig. 1c). The DP QPE technique resulted in precipitation rates that were on average 17 mm h^{-1} greater than the SP rates for the period $T = 4\text{--}52 \text{ min}$. The average total accumulation to $T = 120 \text{ min}$ for the SP QPE was 56.24 mm (Fig. 2a), and the average for the DP QPE was 73.45 mm (Fig. 2b). Four cases saw notable precipitation accumulation increases with the DP technique, while the Minneapolis, Minnesota, and Baltimore events had essentially equivalent 120-min accumulation totals for both techniques (Fig. 2c).

Fig. 1. Analysis of the (a) MRMS single-polarization QPE instantaneous rain rate, (b) MRMS dual-polarization synthetic radar QPE with evaporation correction instantaneous rain rate, and (c) the difference between the two MRMS radar-derived schemes for all six urban flash flood events utilized in this study (thin colored lines) and the average value across the six events (thick black line) from time $T = -60$ to 120 min .

FLASH product analysis

The FLASH system provided hydrologic model outputs and rainfall comparison products at the same spatial resolution of 1 km (Gourley et al. 2017). This study utilized the MRMS DP QPEs as forcing into the various FLASH products. Analyses from the Hydrometeorology Testbed—MRMS Hydro (HMT-Hydro; Martinaitis et al. 2017) experiment and feedback from local NWS offices identified three FLASH products that were most useful for the prediction and warning of flash floods:

- 1) Unit streamflow from the Coupled Routing and Excess Storage Model (CREST; Wang et al. 2011) depicts the discharge of surface water normalized by the upstream basin area (Gourley et al. 2017). A maximum unit streamflow value of $2.00 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ was utilized as a reference point in this study as a guidance for warning issuance.
- 2) Maximum QPE to flash flood guidance (FFG) ratios determine when precipitation exceeds estimated values that would produce bankfull conditions on small creeks and streams over a given temporal period (Sweeney 1992). FFG values utilized in FLASH were generated at NWS River Forecast Centers and do not consider locally adjusted values for urbanization and urban-based alterations to the original natural stream networks. Maximum QPE-to-FFG ratios were calculated from 1-, 3-, and 6-h accumulations. A ratio of 1.00 was considered as guidance for warning issuance.
- 3) Maximum QPE average recurrence intervals (ARIs) compare QPEs to NOAA Atlas 14 precipitation frequency estimates (Perica et al. 2013) to evaluate precipitation rarity. Maximum QPE ARI values were calculated from various accumulations ranging from 30 min to 24 h. There is a lack of consensus on ARI guidance that could be applicable for flash flooding. Martinaitis et al. (2020) observed that QPE ARIs began influencing warning decisions when values were approximately 10–20 years and lacked influence when <6 years. Gourley and Vergara (2021) examined QPE ARIs associated with NWS flash flood reports. ARIs of 75–100 years for 3-h accumulations and 50–75 years for 6-h accumulations best corresponded to flash floods reports; however, Lincoln and Thomason (2018) found that the 2-yr ARI for 3-h accumulations corresponded to 90% of LSRs, while 3-h ARI values around 25 years were more correlated with significant flash flooding. Note that there were no discriminations between urban and non-urban events in the aforementioned research.

FLASH products in this study were generated using the MRMS DP synthetic QPE and were analyzed at the same representative LSR locations and time periods used in the MRMS QPE evaluations with the same 3×3 gridcell averaging.

CREST maximum unit streamflow values surpassed $2.00 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ by $T = 30$ min for five of the six events based on values at the representative flash flood reports (Fig. 3a). The Baltimore event had a CREST maximum

Fig. 2. As in Fig. 1, but for the accumulation of rainfall from time $T = -60$ to 120 min.

unit streamflow value of $1.76 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ at $T = 30 \text{ min}$ with a value of $3.80 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ at $T = 40 \text{ min}$. Most events recorded peak maximum unit streamflow values between $T = 50\text{--}70 \text{ min}$ with an average maximum unit streamflow value of $8.03 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ at $T = 70 \text{ min}$, which has been shown to be indicative of a potentially significant flash flood event (e.g., Gourley et al. 2017; Martinaitis et al. 2020; Gourley and Vergara 2021).

The time to exceed the CREST maximum unit streamflow guidance was notably different compared to the time needed to exceed a maximum QPE-to-FFG ratio of 1.00 (Fig. 3b). Only one event (Washington) had QPE-to-FFG ratio values ≥ 1.00 within 30 min of the causative rainfall event and four events within 50 min. The Baltimore event had QPE equaling FFG by $T = 100 \text{ min}$, while a FFG ratio of 1.00 was never achieved for the representative Richmond flash flood report. The average QPE-to-FFG ratio across all six events exceeded the ratio of 1.00 by $T = 40 \text{ min}$, yet the average CREST maximum unit streamflow value at $T = 40 \text{ min}$ was $5.85 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$; thus, the CREST hydrologic model was depicting the potential for a significant urban flash flood events while FFG comparisons were representing an initial exceedance of bankfull conditions.

The combination of various rainfall accumulations and local climatologies resulted in a wide array of maximum QPE ARIs (Fig. 3c). Three urban flash flood events had QPE ARI values < 20 years, including the Minneapolis and Newark, New Jersey, events with maximum ARI values at approximately 2 years. These values do meet the criteria found in Lincoln and Thomason (2018). Contrasting this was the Washington event with an average ARI value reaching 162.8 years. Differences were also noted for when the greatest ARI values were achieved. Four events achieved peak QPE ARI values at $T = 60 \text{ min}$. The Baltimore and Saint Louis cases recorded their greatest ARI values at the end of the analysis period, suggesting longer accumulation durations influenced the flash flooding versus the shorter durations of excessive rainfall rates.

Differences in the magnitudes of the various FLASH products were also noted at the time of the representative flash flood LSRs. All CREST maximum unit streamflow values above the given criteria ($\geq 2.00 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$) at the LSR time, while the QPE-to-FFG ratio did not exceed 1.00 for three of the events (Table 2). Variability in the ARI values also existed at the time of the LSRs. Three events had QPE ARI values around 2 years, while the other three events had ARI values ranging from 13.9 to 77.1 years (Table 2).

Select detailed case analyses

The Richmond event of 1 June 2019 was an example of maximum unit streamflow values providing a greater flash flood predictive value versus traditional QPE comparison to FFG and ARIs. Localized convection formed ahead of a remnant outflow boundary in

Fig. 3. Analysis of the (a) CREST maximum unit streamflow, (b) maximum QPE-to-FFG ratio, and (c) maximum QPE ARI value for all six urban flash flood events utilized in this study (thin colored lines) and the average value across the six events (thick black line) from time $T = -60$ to 120 min . The recommended guidance value (dashed gray line) is provided for the CREST maximum unit streamflow and maximum QPE-to-FFG ratio analyses. Maximum QPE-to-FFG ratios were calculated from 1-, 3-, and 6-h accumulations. Maximum QPE ARI values were calculated from various accumulations ranging from 30 min to 24 h.

Table 2. Analysis of the representative flash flood LSRs selected for each of the six urban flash flood events. Listed are the times for the onset of excessive instantaneous rainfall rates, the time from the onset of excessive instantaneous rainfall rates to the initial time of the representative LSR (min), and the values of the three FLASH system products at the time of the LSR: the QPE-to-FFG ratio, the QPE ARI value (yr), and the CREST maximum unit streamflow value ($\text{m}^3 \text{s}^{-1} \text{km}^{-2}$).

Event	Onset time of excessive rates (UTC)	Initial time to representative LSR (min)	QPE-to-FFG ratio at LSR time	QPE ARI (yr) at LSR time	CREST maximum unit streamflow ($\text{m}^3 \text{s}^{-1} \text{km}^{-2}$) at LSR time
Richmond, VA	0040	50	0.89	13.9	3.09
Washington, DC	1224	34	1.83	77.1	9.77
Minneapolis, MN	2058	54	1.21	2.1	5.40
Newark, NJ	2206	69	1.54	1.9	8.03
Baltimore, MD	2112	85	0.94	24.8	11.16
Saint Louis, MO	0746	34	0.65	2.2	2.16

central Virginia and north of a surface low pressure center over North Carolina (Fig. 4a). The localized convection produced instantaneous rain rates of $40\text{--}100 \text{ mm h}^{-1}$ with additional rainfall from the outflow boundary generating lesser rain rates (Fig. 5). Numerous roads were flooded in Richmond, including portions of Interstates 95 and 64, resulting in stranded vehicles and water rescues (e.g., Fig. 4b). Initial flash flood reports between 0050 and 0110 UTC 1 June were at the edge of a consistent area of unit streamflow values $\geq 2.0 \text{ m}^3 \text{s}^{-1} \text{km}^{-2}$. While a signal was present in the CREST hydrologic model from urbanization influences, typical QPE comparisons for predicting flash flooding were not representative of the evolving threat. Average QPE-to-FFG ratios < 0.90 and QPE ARI values < 20 years were observed during the initial flash flood reports. Most flash flood reports by 0130 UTC still had corresponding QPE-to-FFG ratios < 1.00 .

The Saint Louis event of 12 August 2019 stemmed from training convection along a zonally oriented warm front at the nose of a 850-hPa jet (Fig. 6a). The presented analysis focused on the initial flash flooding that started around 0820 UTC, which resulted in road closures due to high water with associated water rescues from submerged vehicles (e.g., Fig. 6b). Precipitation rates at 0750 UTC ranged from 40 to 90 mm h^{-1} and later increased to $>125 \text{ mm h}^{-1}$ (Fig. 7). This created an initially slow rise in CREST maximum unit streamflow values that later escalated in intensity by 0820 UTC in association with the first flash flood reports (Fig. 7). A pronounced signal was shown in the CREST model output, while QPE-to-FFG ratios were just starting to exceed 1.00 by 0840 UTC along with ARI values in

Fig. 4. (a) Surface analysis of the Richmond event at 0000 UTC 1 Jun 2019 overlaid with MRMS seamless hybrid scan reflectivity (SHSR) at 0040 UTC 1 Jun 2019. The purple box represents the area of interest. (b) Abandoned car in flood waters near Shockoe Creek in Richmond (image courtesy of CBS 6 News—WTVR).

Fig. 5. Analysis of (first column) MRMS dual-polarization synthetic QPE with evaporation correction instantaneous rain rates, (second column) CREST maximum unit streamflow, (third column) QPE-to-FFG ratio, and (fourth column) QPE ARI for the Richmond flash flood event from 0040 to 0130 UTC 1 Jun 2019. Flash flood and flood local storm reports are represented by black circles. Urbanized areas (gray shading) along with interstates/highways (red lines) and state/district boundaries (black lines) are also plotted.

the 10–30-yr range (Fig. 7). Flash flood signals in the CREST maximum unit streamflow values were 20 min earlier than QPE ARIs and 30 min earlier than QPE-to-FFG ratios reaching warning guidance values.

The Washington event of 8 July 2019 represented an extreme flash flood over a metropolitan area. This case was defined by a slow-moving thunderstorm cluster located near a surface low pressure center that progressed southward along a weak quasi-stationary frontal boundary (Fig. 8a). Flash flood impacts ranged from widespread road closures, stranded vehicles and multiple water rescues, water entering Metro system structures, and sinkholes (e.g., Fig. 8b). Enhanced rainfall rates $> 125 \text{ mm h}^{-1}$ (Fig. 9) led to rapid increases in CREST maximum unit streamflow values and QPE-to-FFG ratios, yet areas initially exceeding FFG already had

Fig. 6. (a) Surface analysis of the Saint Louis event at 0600 UTC 12 Aug 2019 overlaid with MRMS SHSR at 0750 UTC 12 Aug 2019. The purple box represents the area of interest. (b) Stranded vehicles in flooded roadways in Granite City, Illinois (image courtesy of NBC 5—KSDK).

Fig. 7. As in Fig. 5, but for the Saint Louis flash flood event from 0750 to 0840 UTC 12 Aug 2019.

Fig. 8. (a) Surface analysis of the Washington event at 1200 UTC 8 Jul 2019 overlaid with MRMS SHSR at 1220 UTC 8 Jul 2019. The purple box represents the area of interest. (b) Motorists stranded on top of their vehicles on Canal Road in Washington (image courtesy of Dave Dildine—WTOP).

Fig. 9. As in Fig. 5, but for the Washington flash flood event from 1220 to 1310 UTC 8 Jul 2019.

unit streamflow values $\geq 6.0 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$. There were coherent areas of CREST maximum unit streamflow values $> 10.0 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ with localized values of $20.0\text{--}30.0 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$, signifying a likely high-impact flash flood (e.g., Gourley et al. 2017; Martinaitis et al. 2020; Gourley and Vergara 2021). The QPE ARI values reached the maximum calculated value (200 years), reinforcing the severity and rarity of the event (Fig. 9).

Operational implications

Warning statistics from the NWS (Table 3) were characterized by no unverified warnings with 71 of the 76 flash flood reports being fully or partially warned. Four of the unverified reports were from the Richmond event and were located just outside of the warning polygon. This resulted in the Richmond event having the only CSI value below 0.85. The area-weighted average lead time ranged from 15.3 min with the Richmond event (value was influenced by the unwarned events) to 106.3 min with the Washington event. The average lead time for only the warned flash flood events with the Richmond event was 35.7 min.

Table 3. Operational warning statistics for each urban flash flood event based on statistics from the NWS Performance Management System (<https://verification.nws.noaa.gov/>). Statistics include the number of verified and unverified FFWs, the number of warned (fully and partially) and unwarned flash flood LSRs, the probability of detection (POD), false alarm rate (FAR), critical success index (CSI), and area-weighted average lead time (LT; min).

Event	FFWs		Flash flood LSRs		FFW statistics			
	Verified	Unverified	Warned	Unwarned	POD	FAR	CSI	LT (min)
Richmond, VA	1	0	3	4	0.43	0.00	0.43	15.3
Washington D.C.	6	0	41	0	1.00	0.00	1.00	106.3
Minneapolis, MN	1	0	4	0	1.00	0.00	1.00	31.5
Newark, NJ	4	0	12	1	0.85	0.00	0.85	70.0
Baltimore, MD	1	0	3	0	1.00	0.00	1.00	68.0
Saint Louis, MO	5	0	8	0	0.98	0.00	0.98	68.4

NWS weather forecast offices (WFOs) with responsibility for the flash flood events described here subjectively evaluated how MRMS and FLASH products impacted warning operations for these events. Select operational summaries are presented here. Feedback from WFO Wakefield, Virginia, indicated that the office uses a unit streamflow threshold of $2.00 \text{ m}^3 \text{ s}^{-1} \text{ km}^{-2}$ for urban flooding in warning operations, and forecasters stated that unit streamflow values were more useful than reliance upon QPE and FFG. WFO Wakefield issued a flash flood warning (FFW) for the Richmond area at 0053 UTC 1 June 2019, shortly after their unit streamflow warning threshold was reached, providing an initial 7 min of lead time to the first flash flood report. As noted earlier, the QPE-to-FFG ratio did not exceed the traditional ratio of 1.00, reinforcing the importance of the CREST unit streamflow product in predicting flash flooding within urbanized areas.

WFO Minneapolis indicated that they use FLASH almost exclusively for their warning decision guidance, and have found CREST unit streamflow based on the hydrophobic hydrologic model (i.e., all rainfall becomes runoff) to be useful for urban flash flooding. WFO Minneapolis for the 16 July 2019 event issued an FFW at 2129 UTC, a lead time of 23 min before the first report. WFO Saint Louis indicated that forecasters find the FLASH products to be intuitive and reliable for flash flood operations. The 12 August 2019 event around Saint Louis had FFWs for the reported LSRs in NWS Storm Data with an area-weighted average lead time of 68 min.

Conclusions

Urban flash flooding is often a significant operational challenge during the warm season due to its rapid onset resulting from extensive areas of impervious surfaces combined with high rainfall rates. This study described six events from the summer of 2019 and how the MRMS and FLASH systems combined provided products which enable meteorologists to quickly analyze situations supportive of urban flash flooding. NSSL continues to work with the NWS to evaluate and enhance the MRMS and FLASH systems through research-to-operations efforts. Future MRMS operational builds will provide improvements to the accuracy of the QPEs. Future research is centered on assessing high-resolution nested domains over major metro areas as well as incorporating sub-hourly observational platforms to be combined with radar.

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