EASTERN REGIONAL TECHNICAL ATTACHMENT
NO. 2025-01
MARCH 2025

UTILIZING DUAL-POLARIZATION INSTANTANEOUS PRECIPITATION RATE TO PREDICT FLASH FLOODING

Kirk R. Apffel[1], Aaron Reynolds, David Church[2], and Jacob Escobedo[3]
NOAA/National Weather Service
Buffalo, New York

ABSTRACT

The WSR-88D radar uses a dual polarization quantitative precipitation estimation (QPE) algorithm called Digital (instantaneous) Precipitation Rate (DPR) which can be useful in predicting flash flooding. When re-processed to estimate the duration for which areas meet thresholds of two, three, or four inches per hour respectively, research shows that potential flash flood events may be easier to detect when compared to traditional radar interrogation techniques. This study focused on events from both Buffalo (KBUF) and Cleveland (KCLE) radars during the convective seasons between 2015 and 2017. Radar data were examined to identify cases where DPR exceeded the threshold noted above for 20 minutes or more over the course of an hour. A total of 1710 cases were then compared to observed flash flood events. These cases were categorized further based on a location's vulnerability to flash floods using a local static Flash Flood Potential Index (FFPI) and stratified by rainfall rate and duration. Results show that a DPR of 2"/hr. for 35 minutes or 3"/hr. for 25 minutes are thresholds which correlate with an increased flash flood risk for areas that have at least a moderate FFPI. Rainfall rates over 4 inches per hour, although impressive from a precipitation rate standpoint, usually do not last long at any one location. These rates show less skill since they do not provide much lead time and may be prone to hail contamination. Precipitation rate thresholds of 2 and 3 inches per hour indicate an increased ability to detect and provide lead time for flash floods. These thresholds have been used operationally and have aided meteorologists with detection and lead time for flash floods. Additional research may support the utility of the DPR product in all NWS offices.

---

[1] Corresponding author: Kirk Apffel, National Weather Service, 587 Aero Drive, Cheektowaga, NY 14225. Email: Kirk.Apffel@noaa.gov.
[2] Current Affiliation: NOAA/National Weather Service, Salt Lake City, UT
[3] Current Affiliation: Colorado State University, Fort Collins, CO

1. INTRODUCTION

Flash flooding poses a significant threat to lives and property and is one of the leading causes of weather-related fatalities (Ashley and Ashley 2008). Flash flooding can be challenging to predict since there is a large variability in associated meteorological patterns which can produce heavy rain and flash flooding (Maddox et al. 1979). Radar-estimated precipitation is a common tool used by meteorologists for flash flood decision-making processes.

Between 2011 and 2013, the National Weather Service (NWS) upgraded its network of Weather Surveillance Radars (WSR-88D) to include Dual Polarization (DP) technology. This enhancement provides additional information about precipitation type, intensity, and drop size and shape (WDTB 2011). One of the new DP radar products available is Digital (instantaneous) Precipitation Rate (DPR). Meteorologists at the NWS Buffalo office noticed that the risk of flash flooding increased when heavy rainfall identified by the DPR product persisted at the same location for even a short period of time.

While DP radar has improved Quantitative Precipitation Estimates (QPE; Giangrande and Ryzhkov 2008), there are still problems with both overestimates and underestimates. The Hydrometeor Classification Algorithm (HCA; Park et al. 2009) determines the most likely type of precipitation for a radar bin and uses this to determine the rainfall rate and the resulting QPE. This is distinctly different from the pre-DP legacy precipitation processing system (PPS; Fulton et al. 1998), which uses various reflectivity-rainfall relationships and does not attempt to identify precipitation type. In flash flooding scenarios, today’s DP radar algorithms must successfully distinguish heavy rain from hail, as hail results in greater reflectivity, which can lead to overestimates in QPE. Despite improvements in QPE, polarimetric signatures for hail are not always unique, and HCA algorithms employ a fuzzy logic approach that attempts to determine the most likely hydrometeor (Heinselman and Ryzhkov 2006). Errors in hydrometeor identification can result in inaccuracies in DPR and DP-based QPE (OFCM 2017).

Precipitation that primarily develops beneath the freezing level through the collision-coalescence process can be especially dangerous from a flooding perspective. These warm rain processes have traditionally been challenging and are often underestimated by radar. Polarimetric signatures improve the identification of warm rain events and QPE, but algorithms are still being developed and refined (Carr 2016).

While DP is a big step in the right direction, more work remains to be done. Examining past events may help establish critical thresholds for heavy rainfall detected by the DPR product. These thresholds may aid meteorologists in flash flood detection and improve lead time.

2. DATA AND METHODOLOGY

Cases were gathered over a three-year period from 2015-2017 for two WSR-88D sites located in Buffalo, NY, and Cleveland, OH. Days for further examination were selected from warm season months between April and September using flash flood events reported in NWS Storm Data which occurred between 10 km and 120 km of each respective radar site. Some of these events extended into the forecast area of neighboring offices, including NWS offices in Binghamton, NY, and Pittsburgh, PA. Radar data were used to determine the start and end times for any significant rainfall on that day or extending into adjacent days if the event was ongoing. This “wide net” approach was used to include potential false alarms. After excluding days where radar data was missing, DPR was gathered for 28 days, which included 80 flash flood events identified in Storm Data.

2.1 Identifying Cases

DPR was examined to identify cases within the 80 flash flood events. The criteria were designed to include rainfall rates that would not typically be expected to produce flash flooding, allowing the threat to be stratified by precipitation rate duration. Software was developed to compile the duration for which the DPR met specified criteria during each available scan over the preceding hour. The following criteria were used for precipitation rates of 2, 3, and 4 inches/hour:

1. A minimum of 20 minutes within any one-hour period. This did not have to be continuous.
2. A coherent event originating from the same storm system or cluster of storms, with at least 3 adjacent radar bins.
3. Large events extending approximately more than 5 km were separated into multiple cases.

The precipitation rate and duration were recorded for each case. Central location and start time were determined based on when the criteria were first met. A total of 1710 cases were identified: 1134 from the Buffalo radar and 576 from the Cleveland radar.

The DPR product is available with each complete volume scan. The time between volume scans depends on the Volume Coverage Pattern (VCP) and whether the Automated Volume Scan Evaluation and Termination (AVSET) or Supplemental Adaptive Intra-Volume Low-Level Scan (SAILS) modes are active. Taking these variables into account, DPR is available approximately every 5 minutes. This was used to estimate the precipitation rate for the five-minute period corresponding to the volume scan (OFCM 2017).

2.2 Flash Flood Events

Heavy rain cases were compared to flash flood events reported in NWS Storm Data (NCEI 2015-2017). Flash flood events and their associated verification polygons vary in size. For polygons smaller than 40 km^2, the central location of the event was identified, and cases were verified if they occurred within 8 km of the flood event. For larger polygons, events were reviewed to ensure all cases located within 8 km of the event polygon were verified. Cases were verified if flash flood events occurred between 45 minutes before and up to two hours after the case criteria were first met. This staggered time window was used to account for the time it takes for heavy rain to run-off, which can delay the onset of flash flooding. A verification rate and False Alarm Rate (FAR) were calculated for each case category. In some cases, flash flooding may have occurred but was not reported, which could potentially increase the FAR.

Lead time was calculated as the difference between the start of the flash flood event and the time when the case criteria were first met. When cases were verified by multiple flash flood events, the lead time for each verifying event was used. In some cases, flash flooding occurred before the case criteria were reached, but it was eventually identified. This resulted in negative lead times, which lowered the overall lead time but still counted as a verified event. Flash flood events were also compared to heavy rain cases to establish the Probability of Detection (POD). It should be noted that these verification methods differ slightly from official NWS verification statistics.

2.3 Flash Flood Susceptibility

Flash flood susceptibility varies by location and can be estimated by combining risk factors such as slope, soil type, land cover, and surface impermeability. These factors are combined to develop a Flash Flood Potential Index (FFPI) for areas within 120 km of the Buffalo and Cleveland radars (Smith 2013). The result is a map that estimates flash flooding vulnerability for each stream basin identified in the Flash Flood Monitoring and Prediction (FFMP) map (Figure 1). This index is static and does not account for antecedent conditions. FFPI was chosen over other flash flood guidance methods due to its simplicity as a static index, which allows for a direct comparison to rainfall intensity without introducing more dynamic models that are complex and potentially subjective (Clark 2014).

3. RESULTS

Table 1 illustrates the stratification of identified cases by rainfall duration and rate, along with the percentage of these cases verified as flash flood events. The minimal criteria of rainfall rates of 2 inches per hour and a duration of 20 minutes account for nearly half of the cases. These cases have longer lead time, but false alarm rates are generally too high to provide ample confidence to issue a warning. Longer duration of heavy rainfall increases the flash flood risk but reduces lead time. Determining an optimal threshold using only DPR is challenging because either the false alarm rate is too high or the lead time too short.

Considering flash flood susceptibility as shown by the FFPI provides a much clearer picture of critical thresholds for the DPR product. Table 2 shows that areas with a low FFPI were much less likely to flood, with only 10% of the cases resulting in flash flooding. In contrast, areas with a moderate or high FFPI had a much lower false alarm rate of about 30%. Areas with a low FFPI account for only 18% of all cases but represent a significant portion of the false alarms. Table 3 shows that flood risk increases for at least moderately susceptible locations during longer-duration heavy rain events. This trend is more apparent graphically, as illustrated in Figure 2, which shows a sharp increase in flash flood risk when DPR exceeds 2 inches per hour and lasts 35 minutes or longer. Figure 3 shows a similar increase in flash flood risk when DPR exceeds 3 inches per hour and lasts 25 minutes or longer. The sharp increase in flash flooding at these durations suggests that these may represent critical thresholds for the 2- and 3-inch per hour rates, respectively. Additionally, the shorter duration required for rates exceeding 3 inches per hour compared to 2 inches per hour suggests DP radar has some skill in differentiating between the two rates.

It is rare for DPR rates of 4 inches per hour or more to persist for 20 minutes at a single location. Table 1 shows that only 23 cases met this threshold, accounting for about 1% of all cases. For these cases, the duration ranged from 20 to 30 minutes, and only about half were verified with a flash flood report. While it is difficult to draw conclusions from such a small sample size, these findings suggest that the duration of less extreme rainfall rates may be a more important indicator of flash flooding than DPR rates exceeding 4 inches per hour. It is also possible that hail contamination is a contributing factor, highlighting the importance of identifying when precipitation is generated through warm rain processes.

About two-thirds of the cases were associated with the Buffalo radar. Table 4 shows a comparison between the 1134 cases identified for the Buffalo radar and the 576 cases for the Cleveland radar. The FAR rate was higher for Cleveland than for Buffalo, especially for areas with a moderate FFPI risk. This discrepancy could be due to differences in verification practices, beam blockage, or the smaller sample size for the Cleveland radar. Figures 4 and 5 show the FFPI along with the locations for the cases for the Buffalo and Cleveland radars respectively.

The lead time for flash flood events included negative lead times in the average, which results in shorter lead times compared to standard NWS flash flood verification. Table 5 shows the percentage of cases that were verified with negative lead times, separated by estimated precipitation rate.

Overall, approximately 73% of the 80 flash flood events were identified by at least one case in this study (Table 6). Since cases were identified based on 60-minutes time periods, it is expected that some long-lasting or multi-round heavy rain events may have been missed. Antecedent conditions may have also contributed to missed events.

4. CONCLUSION

Focusing on the longevity of heavy rainfall rather than storm total radar estimates may provide greater utility. While meteorologists commonly use hourly and storm total radar estimates to aid in issuing flash flood warnings, results suggest that heavy rainfall lasting 30 minutes or less can trigger flash flooding in vulnerable locations. The identified critical thresholds can help meteorologists issue timely and accurate flash flood warnings, potentially saving lives and reducing property damage. This approach may also help mitigate the impact of erroneously high rainfall rates caused by hail contamination.

Vulnerable locations can experience flash flooding even in a dry regime. FFPI identifies vulnerable locations, such as urban areas or those with steep terrain, but it does not account for antecedent conditions. If heavy rain exceeds the identified duration thresholds, there is a significant risk of flash flooding at these locations, regardless of antecedent conditions. Meteorologists may be able to improve lead time by considering recent rainfall, but research suggests that persistent heavy rainfall in a dry regime should not be overlooked in areas prone to flooding.

Focusing on DPR rates of 4 inches per hour or more may not be the most effective approach for predicting flash flooding. Such high DPR rates rarely persist for more than 20 minutes at a single location. Waiting for this threshold to be met could result in missed events. Additionally, the high percentage of false alarms suggests that DPR of 4 inches per hour or more may be influenced by hail contamination. Meteorologists can potentially identify hail contamination through radar interrogation and by assessing environmental conditions.

5. FUTURE WORK

The DPR product is available in real-time and can be used to estimate the duration of heavy rainfall at a given location. This approach could complement traditional flash flood forecasting methodologies in operational settings.

Future work could expand to other geographic regions to determine whether results are consistent across all areas or vary by region. The multi-radar/multi-sensor system (MRMS) instantaneous precipitation rate product, which combines data from multiple radars (Zhang et al. 2020), could also be used in a similar study. Results may also support collaboration with FFMP software, which is commonly used at NWS forecast offices for flash flood forecasting.

Further research is needed to refine the FFPI. While general guidelines exist for developing an FFPI, additional research may improve these concepts and enhance the product. Combining the FFPI concept with antecedent conditions could lead to more robust flash flood risk assessment tools.

Acknowledgements

The authors would like to thank Jefferson Wood for his assistance in developing the Flash Flood Potential Index for our area, Sarah Jamison, Service Hydrologist at NWS Gray, for her dual-pol radar expertise and support throughout this project, and David Zaff for his guidance and feedback during this process.

References

Ashley, S. and W. Ashley, 2008: Flood Fatalities in the United States. *J. of Appl. Meteor. Climatol.*, 47, 805-818, https://doi.org/10.1175/2007JAMC1611.1.

Carr, N., P.E. Kirstetter, J.J Gourley, and Y. Hong, 2017: Polarimetric Signatures of Midlatitude Warm-Rain Precipitation Events. *J. Appl. Meteor. and Climatol.,* 56, 697-711, https://doi.org/10.1175/JAMC-D-16-0164.1.

Clark, R.A., J.J. Gourley, Z.L. Flamig, Y. Hong, and E. Clark, 2014: CONUS-Wide Evaluation of National Weather Service Flash Flood Guidance Products. *Wea. Forecasting*, 29, 277-392, https://doi.org/10.1175/WAF-D-12-00124.1.

Fulton, R.A., J.P. Breidenbach, D. Seo, D.A. Miller, and T.O'Bannon, 1998: The WSR-88D Rainfall Algorithm. *Wea. Forecasting*, 13, 377-395, https://doi.org/10.1175/1520-0434(1998)013<0377:TWRA>2.0.CO;2.

Giangrande, S.E., and A.V. Ryzhkov, 2008: Estimation of Rainfall Based on the Results of Polarimetric Echo Classification. *J. Appl. Meteor. Climatol.*, 47, 2445-2462, https://doi.org/10.1175/2008JAMC1753.1.

Heinselman, P. and A. V. Ryzhkov, 2006: Validation of Polarimetric Hail Detection. *Wea. Forecasting*, 21, 839-850. https://doi.org/10.1175/WAF956.1.

Maddox, R.A., C.F. Chappell, and L.R. Hoxit, 1979: Synoptic and Mesoscale Aspects of Flash Flood Events. *Bull. Amer. Meteor. Soc.*, 60, 115-123, https://doi.org/10.1175/1520-0477-60.2.115.

National Centers for Environmental Information, 2015-2017: Storm Events Database. [Available online at http://www.ncdc.noaa.gov/stormevents/.

OFCM, Office of the Federal Coordinator for Meteorological Services and Supporting Research, (2017). FMH Handbook 11, WSR-88D Products and Algorithms. Part C, p. 2-131, https://www.icams-portal.gov/resources/ofcm/fmh/FMH11/fmh11partC.pdf.

Park, H.S., A.V. Ryzhkov, D.S. Zrnic, and K. Kim, 2009: The Hydrometeor Classification Algorithm for the Polarimetric WSR-88D: Description and Application to an MCS. *Wea. Forecasting*, 24, 730-748, https://doi.org/10.1175/2008WAF2222205.1.

Smith, G., 2003: Flash flood potential: Determining the hydrologic response of FFMP basins to heavy rain by analyzing their physiographic characteristics. Report to the NWS Colorado Basin River Forecast Center, 11pp. [Available at: https://training.weather.gov/wdtd/courses/dualpol/documents/DualPolRadarPrinciples.pdf]

Warning Decision Training Branch, 2011: Dual-Polarization Radar Principles and System Operations, 94pp. [Available at: http://training.weather.gov/wdtd/courses/dualpol/doccuments/DualPolRadarPrinceples.pdf]

Zhang, J., L. Tang, S. Cocks, P. Zhang, A. Ryzhkov, K. Howard, C. Langston, and B. Kaney, 2020: A Dual-Polarization Radar Synthetic QPE for Operations. *J. Hydrometeor.*, 21, 2507-2521, https://doi.org/10.1175/JHM-D-19-0194.1.

Table 1. The percentage of cases verified by a flash flood event and average lead time stratified by rainfall rate and duration.

Rainfall Rate (inches/hour)	Duration (minutes)	Total Cases	Verified Cases	Percentage of Cases Verified	Average Lead Time for All Flood Events
2	20	774	118	15%	45
2	25	384	104	27%	46
2	30	176	53	30%	40
2	35	75	33	44%	36
2	40	56	33	59%	26
2	45-55	35	20	57%	14
3	20	103	36	35%	46
3	25	42	24	57%	22
3	30	23	15	65%	21
3	35-45	19	14	73%	15
4	20-30	23	12	52%	15
Total		1710	462	27%	39

Table 2. The percentage of cases verified by a flash flood event compared to the flash flood vulnerability of the case location determined using the FFPI.

FFPI category	Total Cases	Percentage of Cases	Percentage of Cases Verified by Flood Event
Low (<4)	310	18%	10%
Medium (4-5)	585	34%	30%
High (>5)	815	48%	31%

Table 3. The percentage of cases verified by a flash flood event stratified by rainfall rate and duration and flash flood vulnerability using FFPI.

Rainfall Rate (inches/hour)	Duration (minutes)	Percentage of Cases Verified with Low FFPI	Percentage of Cases Verified with Moderate FFPI	Percentage of Cases Verified with High FFPI	Average Lead Time for All Flood Events
2	20	4%	16%	19%	45
2	25	5%	26%	35%	46
2	30	0%	43%	32%	40
2	35	0%	52%	62%	36
2	40	33%	56%	68%	26
2	45-55	40%	83%	46%	14
3	20	24%	32%	42%	46
3	25	31%	77%	63%	22
3	30	25%	67%	80%	21
3	35-45	50%	100%	83%	15
4	20-30	38%	75%	43%	15

Table 4. A comparison between cases verified by a flash flood event between the Buffalo and Cleveland radars and separated by FFPI category.

	Buffalo	Cleveland
Total Cases	1134	576
Percentage of Cases with a Low FFPI Verified	11.6%	7.5%
Percentage of Cases with a Moderate FFPI Verified	35.4%	12.8%
Percentage of Cases with a High FFPI Verified	32.8%	29.2%
Total % Verified	30.2%	20.7%

Table 5. The average lead time for flash flooding and percentage of cases verified with a negative lead time, separated by radar estimated precipitation rate.

DPR	Average Lead Time	Percentage of Cases Verified with a Negative Lead Time
2 in/hr.	40	17.4%
3 in/hr.	33	26.2%
4 in/hr.	15	35.3%

Table 6. The percentage of flash flood events from Storm Data which were identified using DPR rates, shown for both the Buffalo and Cleveland radars.

	Buffalo	Cleveland	Total
Flash Flood Events	64	16	80
Flash Flood Events Identified by DPR rates	47	11	58
Probability of Detection	73%	69%	73%

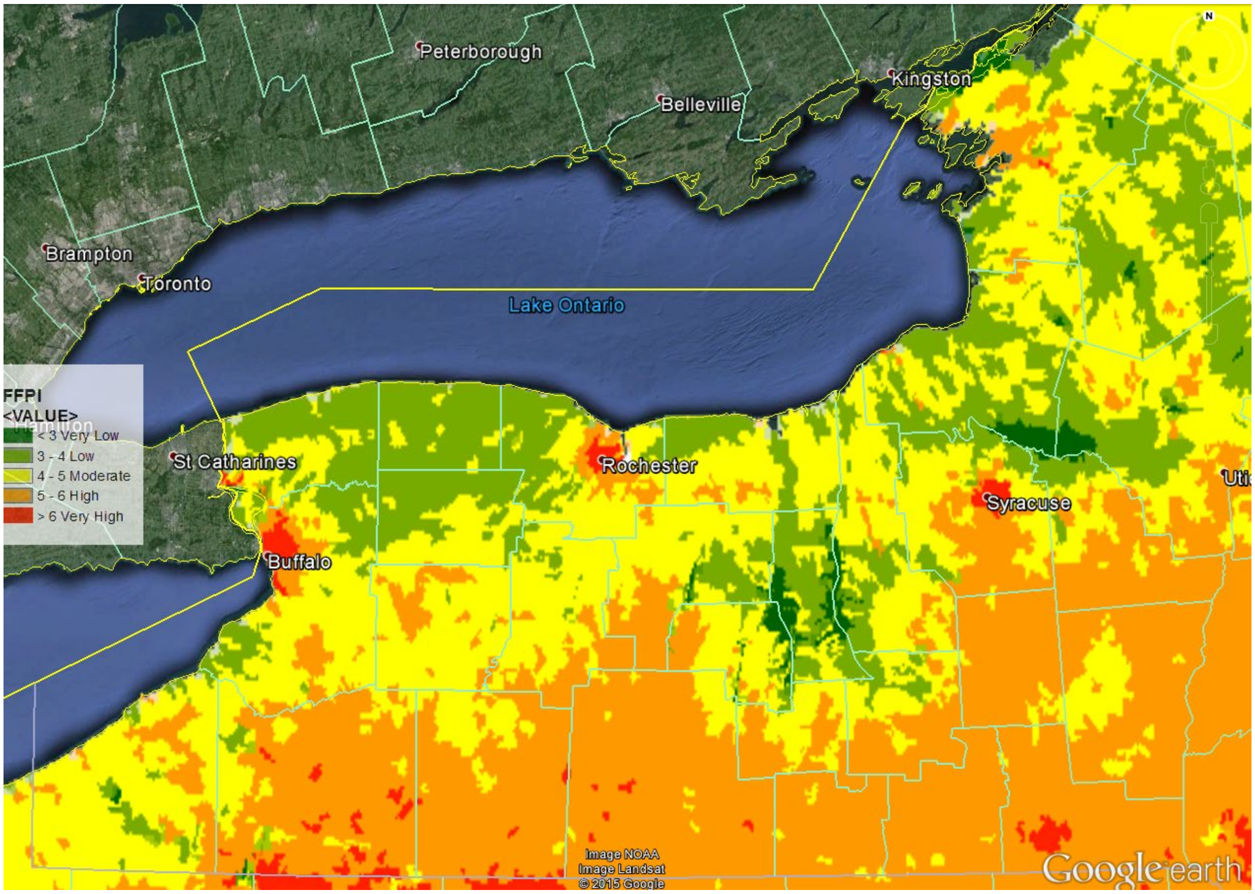

Figure 1. An FFPI map developed for western New York.

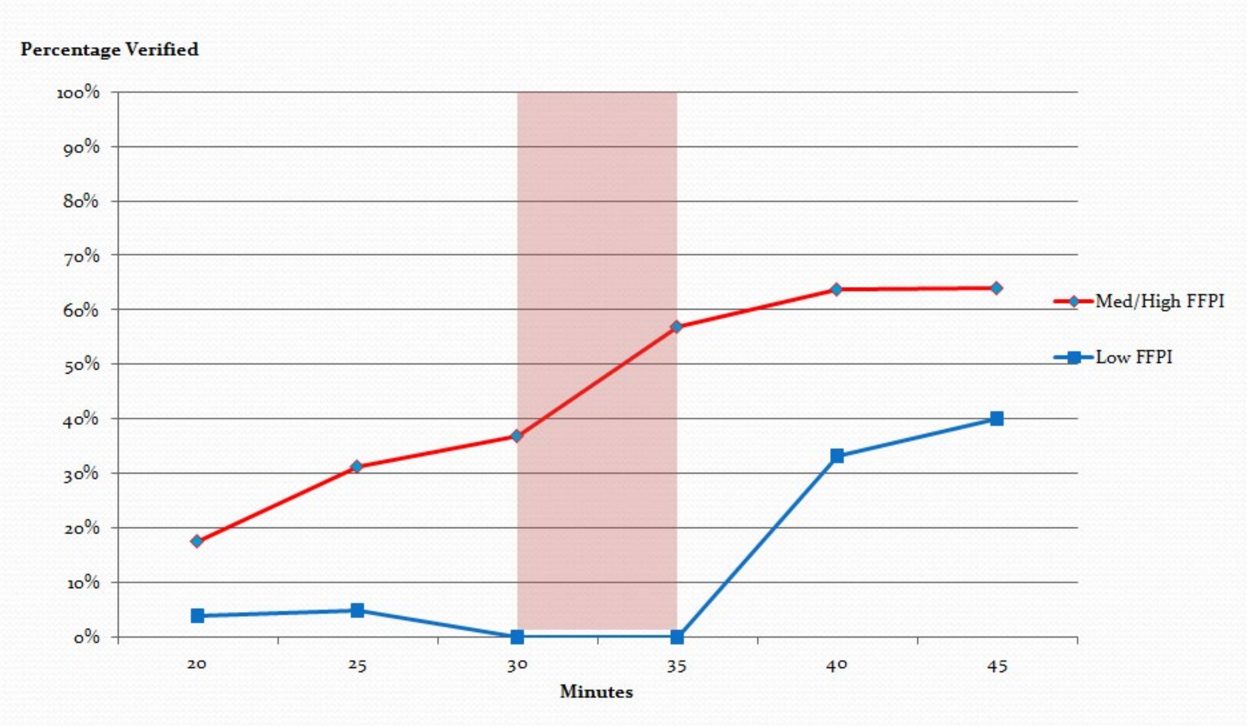

Figure 2. Duration of rainfall rates exceeding 2 inches per hour in a 60-minute time period compared to the percentage of cases verified by a flash flood event stratified by the FFPI flash flood risk.

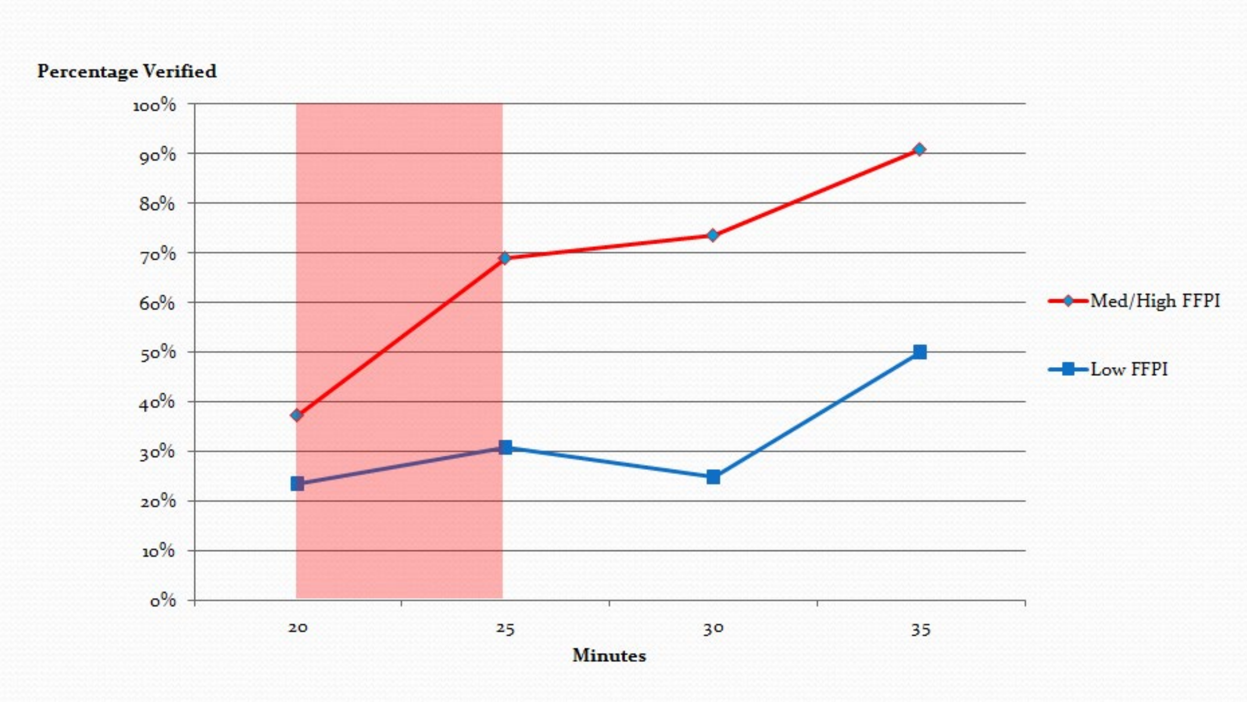

Figure 3. Duration of rainfall rates exceeding 3 inches per hour in a 60-minute time period compared to the percentage of cases verified by a flash flood event stratified by the FFPI flash flood risk.

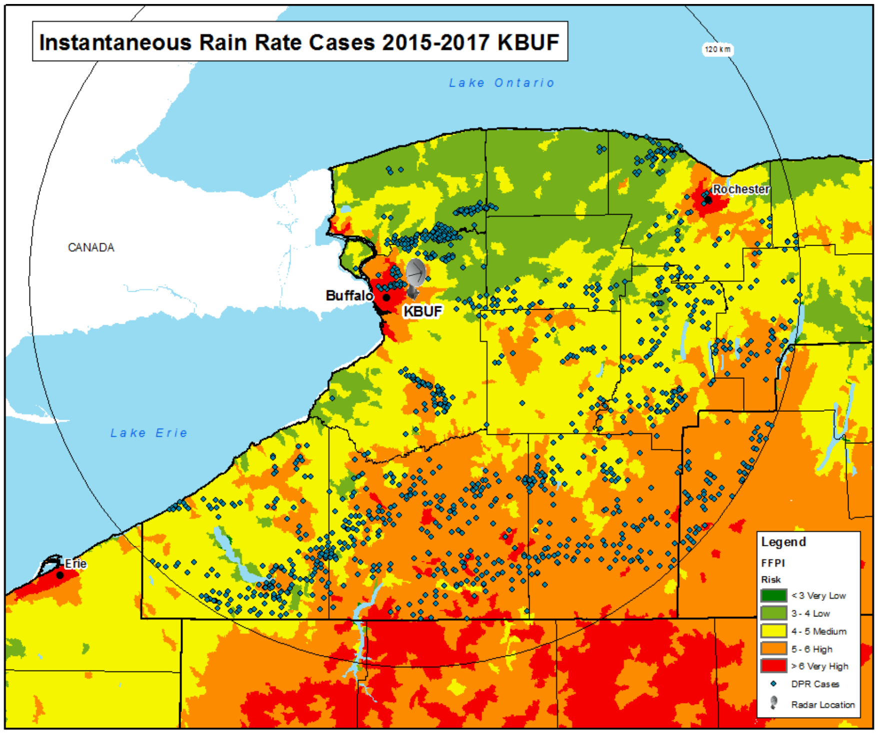

Figure 4. The FFPI map used for western New York with blue dots showing the 1134 heavy rain cases identified by radar from 2015 - 2017.

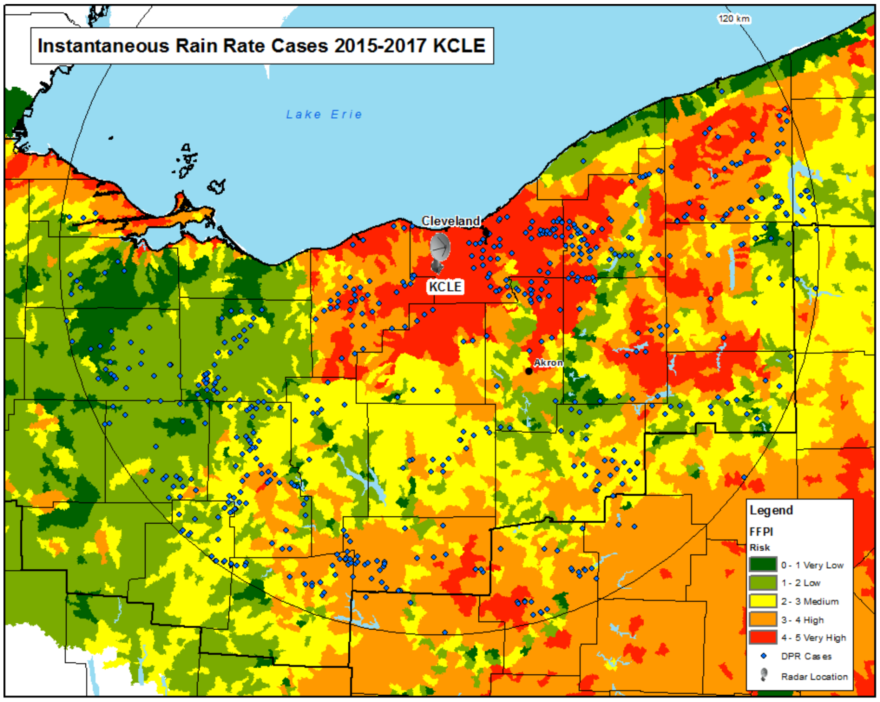

Figure 5. The FFPI map used for northern Ohio with blue dots showing the 576 heavy rain cases