I. Summary

Title of Project: Improving upon flash flooding forecasts for two major Great Lakes cities

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Principal Investigator: *Dr. Beth Hall; Director, Midwestern Regional Climate Center; University of Illinois, 2204 Griffith Dr., Champaign, IL 61822; 217-265-7610; bethhall@illinois.edu*

Co-Principal Investigator: N/A

Abstract*:* Flash flood vulnerability and impacts on large communities such as Chicago and Milwaukee are dependent on the resiliency and preparedness of critical infrastructure, emergency management programs, and the public to flash flood events. The risks and susceptibility of flash flood impacts are dependent on the advanced warning and preparedness time that a community has. Factors that influence the magnitude of an event may include, but is not limited to: antecedent surface conditions such as soil moisture and temperature, time since last precipitation event; land use/land cover; the slope of the land (topography); and the identification of and sufficient forecast lead time of rainfall events likely to produce a flood event. This project developed a more unique approach to flash flood risk potential, flood risk communication, and flood impact mitigation though the development of an operational flash flood potential tool and static flash flood vulnerability map. These resources are intended to be utilized by the National Weather Service (NWS) Weather Forecast Offices of Chicago/Romeoville and Milwaukee/Sullivan as additional risk assessment information when developing their value-added forecasts for the public and key stakeholders such as emergency managers and public safety programs.

Keywords: Flash flood; Risk prediction; Greater Chicago; Greater Milwaukee; precipitation; antecedent conditions

Lay Summary: Flash flood prediction is often a function of how much precipitation is anticipated to fall over the next 24-48 hours in a given location. However, many factors contribute to whether or not flash flooding will actually occur. Examples of other factors to consider include: whether the pervious ground is already saturated from recent rainfall events, if the ground is impervious, or if the location is historically known to experience flash flooding given particular environmental conditions. This project had two objectives: (1) identify areas that are most at risk to flash flooding given their static environment; (2) operationally and statistically assess the risk of flash flooding given recent rainfall compared to historical conditions when flooding occurred. The first objective is achieved with a static map that considered various environmental parameters that rarely change (*e.g.,* land cover; slope; population; type of vegetation) and highlights areas that historically produced flash flood reports versus those areas that rarely (if ever) produced a flash flood report. Commonalities were determined under those two options in order to develop a general guidance map of areas that are more likely to flood than others. The second objective is achieved by running artificial intelligence algorithms on historical precipitation data and the timing and location of when flash flooding was reported. These routines examine how much rain fell within the 6 days prior to when a flash flood report occurred compared to 6 days of precipitation that did not precede a flash flood. These algorithms were developed at individual locations to assess the risk of a flash flood being reported given the most recent precipitation and a selected list of potential forecast rainfall amounts. The end product is a flash flood risk map that forecasters could consider in conjunction with other forecast models and data when deciding whether to issue a flash flood alert.

II. Accomplishments

<u>Introduction</u>

The ultimate goal of this project was to improve the resiliency of the Great Lakes communities and surrounding areas of Chicago and Milwaukee to the inevitable occurrence of heavy rainfall and flash flooding events – particularly for the reduction of vulnerability and risk to critical infrastructure and key resources.

In response to findings from a prior flood risk project that was focused in Chicago and Cook County, this project sought to find a more unique approach to flood risk forecasting, flood vulnerability and risk communication, and flood vulnerability risk mitigation through the development of several flash flood risk potential tools that take into account antecedent ground conditions such as prior rainfall, soil moisture, and soil temperatures in addition to atmospheric signals that are associated with types of flooding events. To do this we hoped to collaborate with the local emergency management programs and the National Weather Service (NWS) to develop communication and awareness resources.

There were four main objectives for this project:

1. Identify critical atmospheric signals that lead to distinguishable flooding events. Building upon a pilot study that developed a forecast tool for heavy rainfall events for the upper Midwest, this project would further investigate atmospheric patterns associated with flooding for the Milwaukee-Chicago expanded regions.
2. Identify and correlate antecedent conditions to the occurrence of flash flooding events. Historical precipitation (*e.g.,* rainfall, snowfall, snow depth), soil moisture, soil temperature, and surface temperature will be statistically analyzed alongside land use/cover and static environmental data to determine correlations to the timing of flooding events at specific sub-regions throughout these two metropolitan areas.
3. Apply storm intensity and duration parameters to the developed operational flash flood risk tool and share with respective National Weather Service (NWS) offices that cover Milwaukee and Chicago for use in triggering threat-based forecasts warnings. The NWS needs information concerning how the meteorology translates to impacts. A series of case studies will be identified from the precipitation analyses and evaluated with the flash flood risk too to maximize statistical confidence to various risk levels. This will allow forecasters to understand what types of events and varying antecedent conditions will be of high impact across the spatial domain of the project. Project PI's will work with the NWS offices in both Milwaukee and Chicago to facilitate the data exchange necessary for impact based forecasts to be issued in each city.

4. Develop an outreach program for city emergency management and safety officials, alongside outreach and education for the public. Using the developed tools and with feedback from the public, gauge the effectiveness of impact-based flood forecasts developed and issued by the NWS from the new flash flood risk tools. From the feedback, communication pathways will be adjusted accordingly and an outreach program developed that can be used by Sea Grant extension specialists throughout the Great Lakes to work with their communities to increase awareness concerning the various conditions of the environment that are conducive to flooding. The flash flood risk tools will be refined and made available online and also used as a teaching tool in outreach presentations. The Midwestern Regional Climate Center will work with Illinois-Indiana and Wisconsin Sea Grant programs to develop communication strategies.

Project Narrative

BACKGROUND

Flash flooding events can impact emergency vehicle access, transportation thoroughfares, and everyday activities. While working on a flooding impact and risk project for the major Chicago / Cook County regions in 2013-2015, communication with the Cook County Department of Homeland Security and Emergency Management (DHSEM) provided insight to the needs of advanced warning of when and where flash flooding may occur. For many public organizations responsible for the safety and protection of communities, advanced flash flood risk communication comes from alerts and advisories issued by the National Weather Service (NWS). The NWS utilizes a variety of forecast models providing the timing, intensity, and amount of precipitation that help identify where high-intensity rainfall is predicted to occur and then conveys that information to emergency management personnel and through public communication platforms. However, DHSEM noted that from their perspective, these alerts are mostly driven by forecasts of precipitation and rarely seem to take into account antecedent conditions that may dampen or magnify the risk of flash flooding.

In an ideal situation, because of the extreme local nature of non-riverine flash flooding, advanced warning of flash floods would provide alert information down to the street or local neighborhood or park level. Unfortunately, the observational and derived precipitation data is not available at every location and applying spatial coverage at the available 4-km (~2.5 mile) precipitation data resources limits the level of specificity the NWS can provide within the alerts. However, local knowledge may be able to fill that gap if forecasted precipitation and inclusion of antecedent conditions improve NWS guidance.

Several resources were proposed in this project that could help increase the awareness of flash flooding risk and preparedness by the public to minimize flash flooding impacts in a timely manner. The first resource would be a static map (*i.e.,* one that is not regularly updated) that provides information about the level of general risk to flash flood occurrence. This may be similar to flood inundation maps, but would be targeted toward flash flood risk rather than all floods (*e.g.,* riverine flooding). Through consideration of factors such as land use, vegetation cover, slope, vegetation type, and population, a map could be developed that would highlight areas most likely to experience a flash flood event under extreme precipitation.

The next resource would be an operational flash flood risk map that would update four times a day to take into consideration how much rainfall has occurred in recent days – a proxy for ground saturation levels -- and the likelihood of a flash flood occurrence under various future rainfall scenarios. This operational map could be utilized by NWS forecasters as they are examining multiple forecast models of varying amounts of predicted precipitation to assess where there is the greatest risk of flash flooding. In other words, forecasters could scenario plan flood risk and incorporate those risks into their flash flood advisories and alerts.

Finally, atmospheric forecast models could be developed that takes into consideration the type of weather event that is entering the region (*e.g.,* frontal, convective, mesoscale storm complex) and derive a variety of forecast scenarios from input data to produce the most likely precipitation and flood probability forecasts for a region. Forecasters would utilize these forecast model scenarios alongside other forecasts models to increase the data and guidance when developing a value-added forecast for the public.

These three resources could be used separately or in conjunction with other flash flood forecast resources to better isolate the locations within a region where flash flooding is most likely. Depending upon the level of certainty, spatial resolution of the guidance data, and historical event knowledge, communities would gain more-informed, advanced warning of a potentially impactful event that could elicit preventative action.

PROJECT OVERVIEW

The Midwestern Regional Climate Center (MRCC), in partnership with the University of Wisconsin-Milwaukee (UWM), through funding support from the Illinois-Indiana Sea Grant and Wisconsin Sea Grant programs, respectively, sought to investigate, design, and deliver these three resources for end users to utilize when making decisions and planning for flash flood events. The MRCC led the activities to produce the static flash flood risk map and the operational flash flood scenario planning map, while UWM led the development of a forecast model that would improve precipitation forecasts. This final report only addresses the work, activities, and deliverables produced by the MRCC.

PHASE ONE – Static flash flood risk map

The primary goal of Phase One was to develop a static map for the Chicago/Romeoville NWS and Milwaukee/Sullivan NWS forecast regions (*Figure 1*) that was based on relatively unchanging environmental conditions. Historical flash flood occurrences would be correlated with environmental factors such as slope, soil type, land use, and land cover to indicate the level of risk to flash flooding across the project domain. This map would only address flooding due to excessive precipitation events as opposed to high-stream level, riverine flooding that can have longer-term development and impacts. In other words, flash flood events tend to be more situational and local due to factors such as impervious surfaces and slope as opposed to proximity within a floodplain.

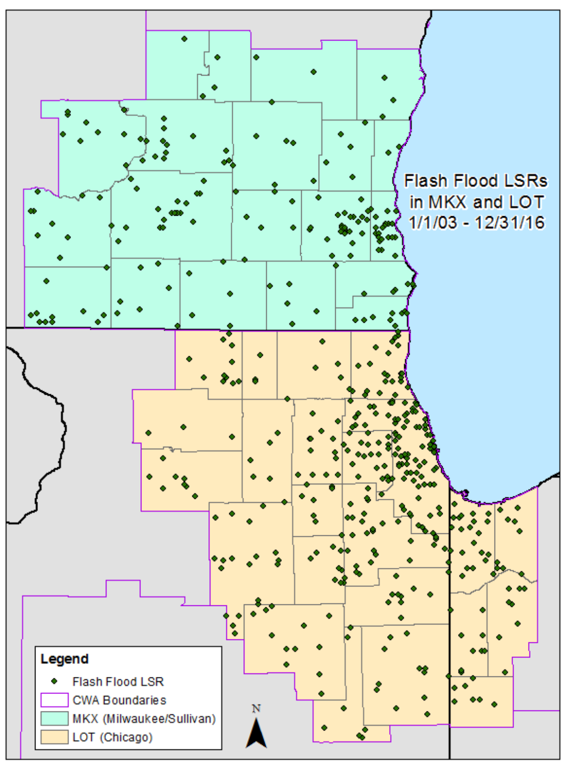

Figure 1. Study domain showing the county regions for the Chicago/Romeoville NWS forecast area (tan) and the Milwaukee/Sullivan NWS forecast area (green). Green diamonds indicate locations of flash flood LSRs from 2003-2016.

One of the greatest challenges of this project was collecting flash flood event data that was not socioeconomically biased and could capture the localized spatial detail often associated with flash flooding. Basement flooding reports tend to be highly localized and dominated within lower-income, older housing neighborhoods. Department of Transportation and emergency personnel reports of road closures tend to focus on roadways and exclude more open areas such as community spaces, parking lots, and critical facilities. Local Storm Reports (LSRs) are official reports of storm events submitted for public record that often fail to capture the more localized events and is driven by someone (a) serving as witness to the event and (b) reporting the event through official channels. Therefore, none of these sources of historical flash flood events is unbiased and can consistently capture the complete, historical reality of flash flood locations and timing. It was ultimately decided to only use flash flood events from the LSRs since these tended to be more "official" at the federal level and less biased toward socioeconomic classes or roadway-only flooding.

Flash flood LSRs were collected from 2003-2016 across the two NWS regions (*Figure 1*). While the historical LSRs are spread across the domain, they still show spatial clustering where there are greater populations.

Next, data layers of slope, aspect, land curvature, vegetation canopy, land use, and soil type/permeabiity were collected and correlated with the LSR locations. The hypothesis was there would be a combination of the various layers that would correlate strongly with LSRs. For example, LSRs would be located where there is the greatest slope, least amount of vegetation, and compacted soil types. However, through much analysis, none of these data layers had a stronger correlation to the location of LSRs than the land use type – particularly when land use was divided into either an impervious or pervious classification. Further, population was assumed to be a driving factor of where LSRs occurred, however, when population (census data) was combined with land use (impervious vs pervious surface), the land use classification was the dominating factor.

The final map product is shown in *Figure 2* and is essentially a map showing land use classifications (National Land Cover Database 2011 (NLCD 2011); https://www.mrlc.gov/nlcd2011.php) at a 30-m resolution where the original variables were reclassified into three categories (*Table 1*) and then reclassified further to a 1-km spatial resolution. The reclassification to the coarse grid was to accommodate varying location precision of the LSRs. Analysis of the LSR location details indicated that a 1-km grid would maximize information detail and minimize any location error associated with the LSR. The LSRs are displayed as dots in *Figure 2* to highlight their relationship to the binary land use classification.

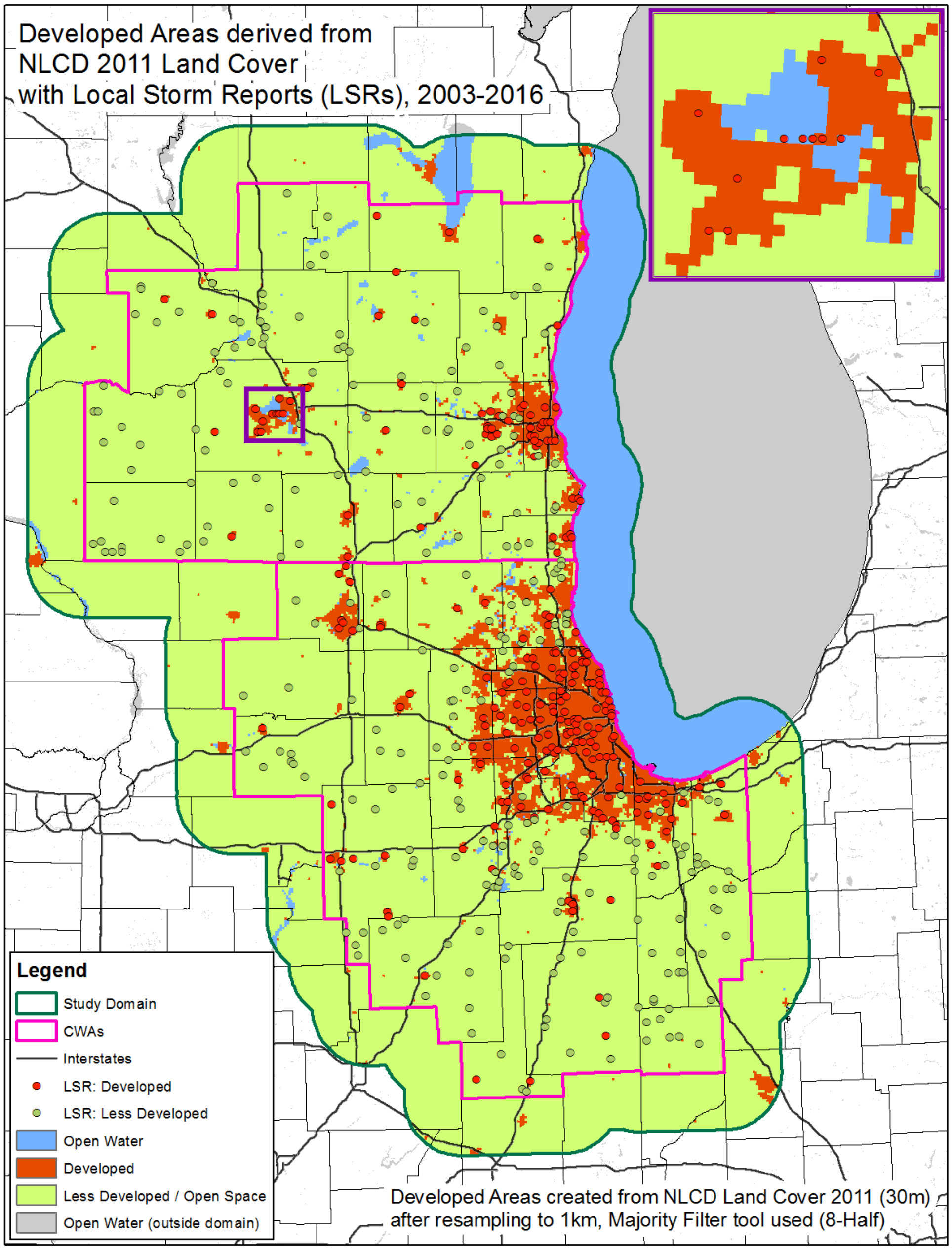

Figure 2. Final static flash flood risk map using land use classifications reduced down to open water, developed, or undeveloped / open space conditions. Red and grey dots indicate locations of historical LSRs. This figure shows a zoomed in inset box for a high-population area (purple bos on map with zoomed in detail as an inset at upper-right). Several of the high-population areas have this zoomed in feature on the online version of these maps.

Table 1. Reclassification of original layers of the NLCD 2011 into three classification to highlight areas of high or low flash flood risk.

Original Land Cover Name	Reclassified Name
Open Water	Open Water
Developed, Low Intensity Developed, Medium Intensity Developed, High Intensity	Developed *(low, medium or high density developed)*
Developed, Open Space Barren Land Deciduous Forest Evergreen Forest Mixed Forest Shrub/Scrub Herbaceous Cultivated Crops Woody Wetlands Emergent Herbaceous Wetlands	Less developed / open space *(all other values)*

PHASE TWO – OPERATIONAL FLASH FLOOD SCENARIO RISKS

For this phase, antecedent (recent, historical) environmental conditions within 6 days of a forecasted precipitation event was gathered and analyzed to quantitatively determine how those conditions might contribute to the risk of a flash flood event occurring. For example, if a lot of rain fell over the past few days, then very little additional rainfall may be necessary to cause flash flooding due to ground saturation. Contrarily, if it has been very dry the last few days, more rain may be needed to fall for flash flooding to occur. In other words, simply knowing that 0.5” of rain is expected over the next 12 hours may not be enough information to know the risk of a flash flood event. Therefore, a variety of parameters were identified that may contribute to the likelihood of near-future precipitation causing a flash flood (*i.e.,* antecedent rainfall; terrain slope, aspect, and curvature; vegetation canopy; land cover type;

soil type/permeability). Several of these variables were spatially too coarse to offer enough scientific integrity (*e.g.,* soil moisture data, evapotranspiration rates) to the project, so it was ultimately determined that recent precipitation was sufficient to use for near-future flash flood risk.

Using the same LSRs from Phase One and 4-km gridded precipitation data from the Multi-Sensor Precipitation Estimates database (https://www.weather.gov/marfc/multisensor_precipitation), random forest artificial intelligence (AI) algorithms were developed that looked at each 4-km grid cell that ever had an LSR within the period of record. By examining randomly sampled dates between April and October (to remove the complications of winter precipitation and frozen ground to any algorithms) for the period of record of the Multi-Sensor Precipitation Estimate (2002-2017) for each of these grid cells, the AI determined the combination of antecedent rainfall, actual rainfall on the date of interest, and various environmental parameters (previous listed) that led to either the existence or absence of LSRs. Once the AI was trained for each grid cell that ever had an LSR, statistical random testing was applied for other, previously unanalyzed dates to assess how well the AI performed. The AI output was a probability of the existence of a LSR 0%-100%. These probabilities were plotted to identify reasonable risk threshold categories for the user (*Figure 3*). While the actual probabilities could have been presented as the final product output, it was deemed more meaningful to report a classification such as "high risk" or "low risk" versus 95% probability or 45% probability.

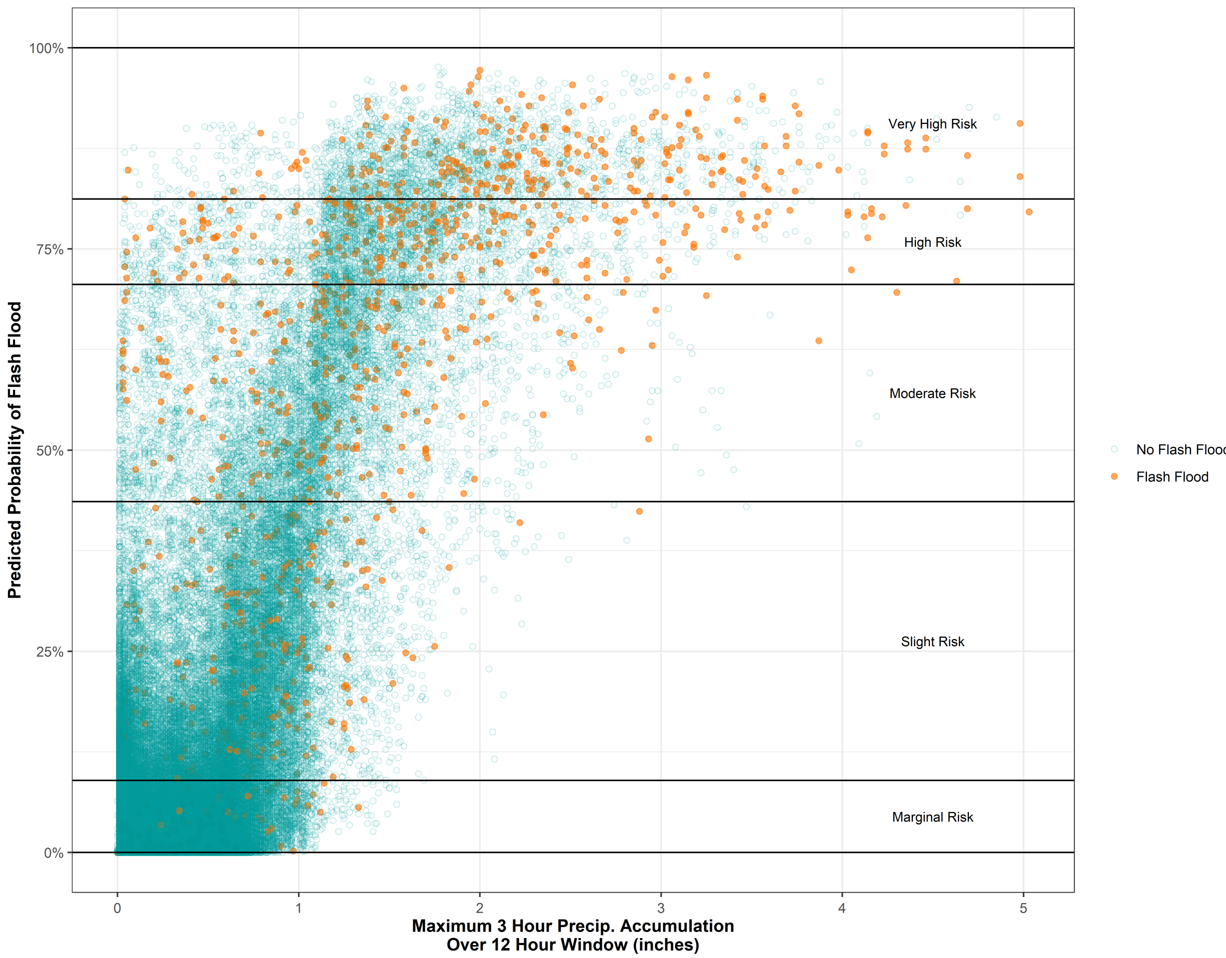

Figure 3. Scatterplot showing AI output of findings relating the maximum 3-hour precipitation over a 12-hour window (inches) with the predicted probability of a flash flood. Note the threshold probability cutoff values that determined the qualitative risk categories based upon the scatterplot.

With thousands of random-sample testing performed at each grid cell, there was enough statistical data to develop risk scenarios for different amounts of forecasted precipitation amounts over the next 12-hour period. *Figure 4* shows a case study example of the scenario risk illustrating where actual precipitation fell and where flash flooding was reported as an LSR. This means a user could examine the current risk map (default forecast 3-hour maximum precipitation amount of 0.25”) and then select alternate forecast precipitation amounts (*i.e.,* 0.25”, 0.50”, 0.75”, 1.0”, 1.5”, 2.0”, 3.0”) to best understand the ranges of flash flood risks in areas with a range of precipitation forecast amounts. The forecasted 3-hour maximum precipitation amount was considered to (1) make the precipitation value easier to comprehend and (2) make the precipitation time-period used more representative of the timeframes associated with flash flooding events.

RESULTS

Products from Phases One and Two are available from the MRCC website at https://mrcc.illinois.edu/research/flashFloodRisk/index.jsp. The static map does not change and can be used as a general reference for flash flood risk between April and October, inclusive. The operational map is updated four times a day between April and October (inclusive). The LSRs and AI outputted algorithms are anticipated to be updated annually to increase the amount of data and historical events that drive the algorithms. A caveat to the operational scenario risk tool is that it is not necessarily providing scenarios of where flash flooding is likely to occur, but scenarios of where flash flood *reports* are likely to occur. This is because the AI methodology is only as strong as the data provided and only LSRs were provided.

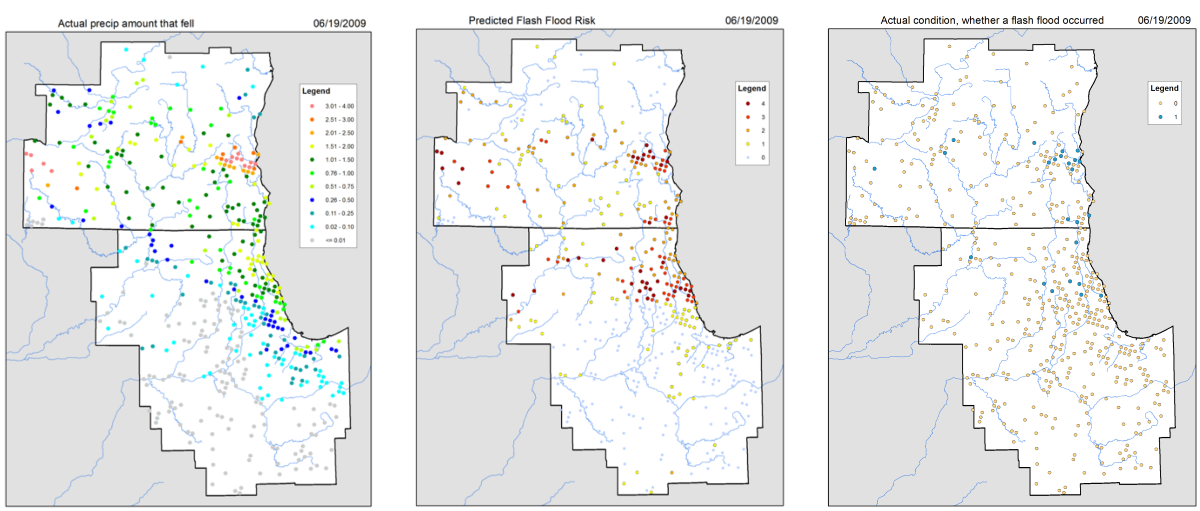

Figure 5. Comparison maps of where precipitation fell (far left) compared to what the scenario risk map predicted for where there was likely to be a flash flood report (center) and where there were actual flash flood reports (far right, blue dots)

CHALLENGES

Data limitations: As previously mentioned, the quality of the data used in the analysis is a driving factor to the deliverables. There were no "high quality" data sets for when and where historical flash flooding occurred across the domain to be able to thoroughly capture all scenarios. While there were multiple options of data sources for historical flash flood events, only those from the LSRs were used in the analysis. This limited the number of cases, but minimized biases that were deemed too significant to satisfy the scientific integrity of the project.

Additionally, the spatial resolution of the data limited being able to provide flash flood risk scenarios at street or park-level detail that was originally desired. Phase One initially utilized data layers having a 30-meter spatial resolution. Unfortunately, the potential location error of the LSRs was much greater than 30 meters, so the analysis was restricted to the coarser resolution of 1 square km.

Outreach accomplishments. The original proposal included a strong outreach component that would have involved partnering closely with Illinois-Indiana Sea Grant's (IISGs) climate outreach specialist. At the time of the proposal, Molly Woloszyn was that person. However, Ms. Woloszyn left that position prior to the project progressing to the point of outreach engagement. The replacement of Ms. Woloszyn took approximately 11 months and by the time the new climate outreach specialist (Veronica Fall) was aware of the project and in a position to start establishing an outreach engagement plan, the project ended. However, about halfway through the project, the MRCC met with the NWS offices involved and they said that the Phase Two deliverable was detailed enough in data, scientific methodology, and data analysis caveats that it would likely not be of direct benefit to the general public or emergency management programs. The NWS offices did feel they had a clear understanding of the science and data caveats that the end product had significant value to them and they would utilize the tool on a regular basis when assessing the issuance of flash flood alerts and advisories. Additionally, the NWS has direct communication with emergency management programs facilitating the dissemination of this project's deliverables into the public and community hands to better prepare for flash flood situations.

FUTURE RECOMMENDATIONS

1. Explore additional antecedent environmental factors: While there were several additional parameters examined for the Phase Two AI analysis, there would be value in further exploring these and other parameters to assess if the final results could be improved. For example, soil moisture, type, and evapotransporation may show a stronger signal if the data for these parameters were more details both spatially and temporally.
2. Continue to update flash flood event database to improve algorithms: Since the quality of the operational tool is dependent upon the input data, each year the algorithms should be updated with the previous year's LSR data. This will continually improve the quality of the risk scenario tool.

Potential Applications, Benefits and Impacts
There were several meetings between the MRCC and the NWS offices to discuss and polish the final deliverables. They told us on multiple occasions that the flash flood potential risk tool is very unique and they seemed excited to start working with it this coming spring. They plan to use it in conjunction with their other forecast models when determining whether to issue a flash flood alert or advisory and how the tool could help them tailor the text to benefit the public. They said they also communicate with emergency management personnel when there is risk for a flash flood event, and the ability to see flash flood risk under varying precipitation forecast amounts will help in those conversations.

International Implications
If and when the operational tool gets promoted, it is possible that other forecast areas/regions/offices will want the tool updated for their domain. This may include locations in Canada since it has a similar 4-km forecast model that could be incorporated into the programs and methodology.

Data Management Plan
All deliverables are now available on the MRCC website at https://mrcc.illinois.edu/research/flashFloodRisk/index.jsp. The LSRs are publicly available from the NWS Storm Prediction Center (https://www.spc.noaa.gov/exper/reports/), and the gridded precipitation data is available online at (https://www.weather.gov/marfc/multisensor_precipitation).

III. Outputs
Media Coverage: None
Publications, Theses, Dissertations: None
Undergraduate/Graduate Names and Degrees: None
Other Outputs: https://mrcc.illinois.edu/research/flashFloodRisk/index.jsp
Patents/Licenses: N/A
Project Partnerships: University of Wisconsin-Milwaukee
Related Projects: 2013 IISG funded "Reducing Flooding Vulnerability of Chicago Critical Facilities"
Awards and Honors: None