Heavy Rainfall Threat Analysis: 2021 Upgrades and Operations
for the Mile High Flood District

Introduction

History of the Tool

The Heavy Rainfall Threat Analysis (hereafter, Tool) was developed for the Mile High Flood District (hereafter, District or MHFD) in 2014 with the main goal of alerting the District about the daily heavy rainfall potential (and by extension, the accompanying threat of excessive runoff). Over the last few years, the Tool has successfully provided a comprehensive look at the heavy rainfall risk across the District over the next 24 hours, including upstream areas where runoff can affect the District. Since its inception, the Tool has undergone several upgrades, which have helped improve Tool performance and engaged more end-users. More details about the yearly updates and the Tool's past performance can be found on the ***F2P2 website***.

Objective for 2021 flood season

For the 2021 season, HydroMet Consulting (hereafter, HMC) proposes both scientific upgrades of the Tool's inner working, as well as upgrades to the Tool's visual output. As for the Tool's inner workings, increased computational power for processing high-resolution models as well as an increase in the number of models available, means that the Tool can now create more localized heavy rainfall forecasts for the District. Additionally, the combination of a larger ensemble of models and a growing archive of rainfall related data implies a more innovative and rigorous bias correction at a smaller scale is likely achievable. Regarding visualization, while the Tool's main objectives will remain the same, upgrades to the user interface include 1) making the site more mobile friendly and 2) consolidating the Tool's output into a single interactive web map. This proposal outlines the aforementioned Tool upgrades and operational support in preparation for the 2021 heavy rainfall season.

Work Plan

Task 1 – Scientific Upgrades

Task 1.1 – Refine Forecast Zones

When the Tool was initially designed in 2014, there was a limited number of reliable high-resolution models readily available for real-time operations as required here. Over the last five years, a combination of an uptick in computational power and ongoing research within the Numerical Weather Prediction (NWP) community, has yielded additional high-resolution models that are publicly available. Moreover, there are more model runs throughout the day, which have increased the potential ensemble size (1) making the Quantitative Precipitation Forecast (QPF) less sensitive to an individual model and (2) allowing for the detection of smaller-scale features that may not be resolved in "normal" model run cycles. It is no surprise that it is precisely these two factors that have traditionally caused the most severe forecast "busts". In addition to the scientific advances above, the ever growing archive of model QPF data provides an opportunity to reassess and improve previous bias correction techniques using the District's data-rich, high-density ALERT rain gauge network.

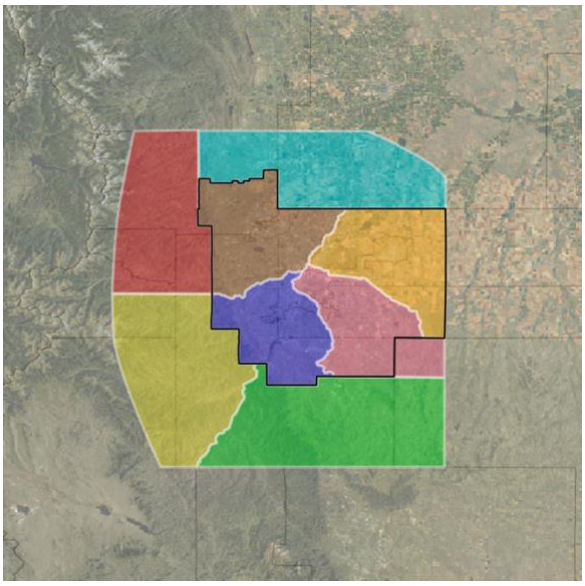
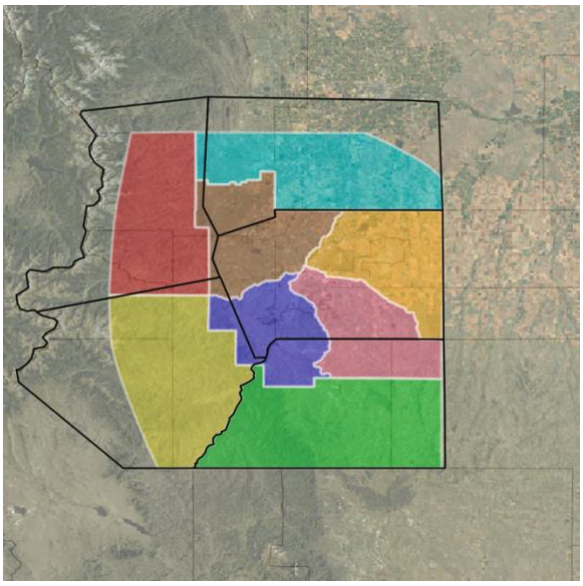
a)  b) 

Figure 1: (a) Heavy Rainfall Threat Analysis domain and zones proposed for 2021 with the MHFD overlaid in black, (b) Proposed 2021 domain and zones with the previous domain and zones (2018-2020) overlaid in black.

Overall, HMC believes the combination of scientific advances and increased QPF archive length has created an opportunity to improve the Tool's resolution of heavy rainfall placement. As shown in Figure 1, HMC proposes (1) slightly modifying the existing zones to better hone in on the District's area, and (2) adding new, higher resolution zones within the actual District domain. Note that from 2015 to the present (Figure 1b), the Tool's forecast zones were roughly 1,000-1,200 square miles in area, and the District itself was almost exclusively contained within Zone D. However, the newly proposed in-District zones (Figure 1a) will be 350-450 square miles, or nearly 1/3 the size of the previous zones. HMC proposes to use MHFD "Service Areas" as the basis for the new zone delineation but will work with the District to determine the most logical solution. HMC thinks that these boundaries will not only expand the Tool's utility for the District, but also for end-users that have voiced interest for these boundaries in the past.

Key Outcomes & Benefits to the District:

- Using the MHFD Service Areas as the basis for the Tool's new zones means that more localized and relevant rainfall forecasts will be possible,
- Upstream zones will still be retained to inform of the risk for downstream runoff,
- The "All Zones" forecast will be retained, serving as the most condensed form of information (i.e. "threat or no threat" and QPF-Max), especially for end-users that are making quick decisions.

Task 1.2 – Update Post-Processing Equations

To continue to refine the Tool's reliability, accuracy and storm resolution, HMC will update the post-processing equations and bias corrections to account not only for new 2020 data but also new methodology. Specifically, HMC will consider the following:

- Explore new predictors based on (1) QPF and QPF-derived fields (e.g. area average versus maximum QPF) including National Weather Service (NWS) precipitation probability and intensity forecast grids, (2) other (non-QPF) atmospheric parameters and (3) non-atmospheric predictors such as seasonality,
- Review the change made in 2019 to the probability of exceedance thresholds, in particular, for days with high threats. HMC will also utilize past season's data to select the appropriate Low threat threshold to simultaneously minimize "Misses" and "False Alarms",
- Evaluate role of diurnal model weighting, and implement, if necessary,
- Evaluate role of using large-scale analog forecasting in combination with historical District rainfall data to supplement ensemble QPF (e.g. Barnett and Preisendorfer, 1978),
- Determine whether a bias correction is needed for the HRRRE models; implement if necessary.

It is important to note that HMC will conduct applied research, emphasis on "applied", on the topics above. The main objective is to select and implement only those methods that will improve forecast accuracy, reliability and resolution, with a particular emphasis on simultaneously minimizing forecast False Alarms and Misses.

Key Outcomes & Benefits to the District:

- Improvement to Tool accuracy, reliability and resolution, which in turn, should continue to encourage increased usage.

Other Direct Costs: Adding Texas Tech Ensemble

The TTU-WRFens was created to compete with other NOAA/NWS operational convective-allowing models, which if trained, will likely help continue to advance and support the best available objective flood warning system to the District. For the 2021 season, HMC proposes adding back in the TTU-WRFens after QPF data has been collected over the last two seasons. While it is still unknown how many years of data are needed to properly train raw QPF, it is likely that two years will be enough data for an effective bias correction across the model's nine ensemble members. In addition, for the rare days where the NOAA models may be unavailable, the TTU-WRFens would provide a backstop enabling the Tool to run smoothly. HMC will work with Group NIRE to negotiate the best price for the data, allowing the TTU-WRFens to become operational for the 2021 season.

Key Outcomes & Benefits to the District:

- An additional, trained multi-member numerical model will continue to improve the probability forecasts by incorporating most all high-resolution models available for the District.

Task 2 – Visualization Upgrades

Task 2.1 – Tool Output Redesign and Development

The first outreach for the Tool was completed during the summer of 2020, and one apparent outcome was that many end-users were accessing the Tool website from their mobile devices. The original website built for the Tool in 2015, albeit functional, was not designed to be mobile friendly partially due to the resource-intensive nature of developing mobile apps at that time. However, due to the "on the go" nature of Emergency Mangers and other end-users, HMC proposes revamping the overall visualization strategy of the Tool by employing an interactive web map. It is important to note that the goal of this is not to change the output data, but merely the visualization of that data. By using interactive layers and hover features available with a standard web map, HMC believes the Tool's output will be significantly more succinct, eliminating the need for mobile unfriendly scrolling. The new map will, at a minimum, contain the Tool's two legacy layers: QPF-Max (intensity) and Threat Level (confidence). Scroll over functions will be developed for data that cannot be displayed graphically, such as the timing of the heavy rainfall threat over a particular Forecast Zone. HMC proposes to work with all relevant MHFD stakeholders to agree on a conceptual design before undertaking actual development. Once the conceptual design has been approved by the District, HMC will develop the new map to be available by the first day of the operational season, May 1.

Key Outcomes & Benefits to the District:

- Consolidation of the Tool's output into a single, interactive web map will make it easier for end-users to check the Tool,
- The new design will be significantly more mobile friendly,
- MHFD will have the option of incorporating the updated web map into an existing map for a more seamless product suite.

Task 2 Deliverables:

1. A daily updated Tool verification web map with and an interactive interface that is more mobile friendly,
2. An archive for all past forecasts.

Task 3 – Daily Operations

Task 3.1 – Daily Verification

The most compelling way for end-users to gain confidence in the Tool's utility is by exploring how the Tool has handled past rainfall events, especially recent ones. HMC proposes making daily verification maps to illustrate the Tool performance. This would include Quantitative Precipitation Estimations (QPE) from a national, gridded dataset as well as ALERT gages that are maintained by the District. While the former has the advantage of full spatial cover, the latter performs better at capturing small, rainfall cores. Paired together, this will make a more robust verification system that will not only help end-users build trust with the Tool, but it will also be a great way to see how the Tool handles multi-day rainfall events. The Tool has typically been evaluated on a 24-hour basis, but it could be used to examine the well-known ramp up and down of heavy rainfall events over a 3-to-7-day period. These multi-day rainfall events are commonplace during the warm season in Colorado. Moreover, the daily verification maps could be rolled into the Tool's daily display map, which is described above.

Key Outcomes & Benefits to the District:

- An archive of daily verification maps would help build user confidence in the Tool's utility and help determine how well the Tool is performing during a multi-day rainfall event.

Task 3.2 – Daily Quality Control/Assurance and Maintenance of Operations

Automation of the Tool allows for multiple, quick updates throughout the day, which incorporate the latest weather model runs. This allows for the best objective forecast for the District. While the Tool is automated, there is still the need for a HMC meteorologist to run quality control. While it has very rarely been an issue in the past, it is possible that the output of weather model(s) may be unavailable for a given run cycle, or the entire day, due to errors outside of HMC's control. In practice, we foresee this only being an issue for the morning (i.e. first) update around 8AM MDT since more models are continuously added throughout the subsequent updates. Similar to years past, in the case that there are days that have four or less contributing models to the Tool, HMC will continue the automation of a "use with caution" message at the top of the Tool. The HMC meteorologist will provide daily quality control and assurance that Tool output makes physical sense and is properly visualized on the website. Occasionally, a broken link or missing automated file can prevent the Tool from updating properly. Finally, on High Threat days, HMC will reach out to the MHFD project manager to provide situational awareness and be prepare a social media post for the District's Twitter account (see Task 3.2 for more details).

Other Direct Costs: Hosting and Computing Platform

HMC will host the Tool using Amazon Web Services (AWS), which ensures maximum uptime of files and Tool output. Archiving of the Tool's daily updates will continue and be available through the Tool's website ("Archives" page) along with the daily verification maps should the District move forward with S2.2. Monthly backups will continue and to ensure the website works properly on all internet platforms, HMC will keep the website SSL certified. The collective cost for hosting and computing will be **$175 per month** during the Tool's warm season operations (May to September).

Key Outcomes & Benefits to the District:

- Quality assurance by a HMC meteorologist would ensure the Tool's functionality and output is accurate

Task 3.3 – Social Media & Outreach

Social media, in particular the Twitter platform (@MHFDFWS), has been proven adept for quickly and simply disseminating succinct, important messages. To encourage a continued increase in Tool usage, a more active communication of the daily flood potential within and in the vicinity of the District's service area began in 2019 for High Threat days. Since then, feedback and usage statistics over the last two seasons has been positive, so HMC proposes updates to the image templates and Twitter protocols for the 2021 season. Updates to the image templates will mimic Tool upgrades from this proposal. To finalize the social media campaign changes, HMC proposes a meeting with the District's project manager as early as possible in the 2021 forecast season.

As mentioned above, training held during the summer of 2020 helped educate end-users on the Tool's methods, features and forecasts. Attendees ranged from local meteorologists to area Emergency Managers. With several upgrades to the Tool occurring in 2021, HMC recommends completing another educational session in coordination with the District's project manager as agreeable by both parties. Outreach would be targeted towards local governments, Emergency Mangers and their public works liaisons. The training would also highlight HMC's proposed work with the National Weather Service (described above) to bring more legitimacy to the Tool.

Key Outcomes & Benefits to the District:

- Early communication about potentially threatening rainfall days to end-users on a widely used, public platform,
- Highlighting the Tool's new features to key end-users.

Task 3 Deliverables:

1. Daily verification maps using combined QPE and District ALERT data,
2. All QC logs and manual messages will continue to be archived and made available upon request,
3. HMC meteorologists will develop image templates for social media use and presentations for outreach,
4. Minutes of all outreach events will be available upon request.

Task 4 – Validation Report

To evaluate the Tool's accuracy and impact, a proper validation of the Tool's performance is necessary at the end of each season. In addition to noting the Tool's progress compared to previous years, the validation reports reveal shortcomings of the Tool, which can often times be corrected to increase the Tool's reliability and accuracy in subsequent seasons. In turn, the compounding effect of yearly validation helps keep the Tool, and the District, on the frontier of the rapidly evolving field of heavy rainfall forecasting. HMC recommends an end-of-season validation for 2021 similar to year's past. This includes using multiple data sources including the District's ALERT data, gridded QPE estimates such as NOAA Stage IV and MRMS, and CoCoRaHS data for quality control. Key aspects of the validation report will investigate the Tool's performance on the metrics for which it was developed:

- Was a flood threat realized (both across the full Tool domain and within each zone)?
- Was the timing reasonably forecasted?
- Was the forecasted QPF-Max consistent with observations?
- Was the probability forecast reliable? For example, if an event was forecasted 20% of the time, did it occur 20% of the time?

The validation report will provide a rigorous assessment of the Tool's 2021 performance in a standalone fashion but also in comparison to other forecasts such as the NWS and the F2P2 HPO. The validation report will be presented in manner appealing to both the District's technical and non-technical stakeholders.

Key Outcomes & Benefits to the District:

- Identifying areas of success and failure by the Tool will help drive improvements for future seasons.

Task 4 Deliverables:

1. A final validation report that will include data and analysis for the early morning run of the 2021 operational season and recommendations for future enhancements.

Daily Logistics

For 2021 Tool operations, HMC recommends 4 updates per day. The proposed update times (MDT) are:

Update	Tool roughly updates at:
Morning	8:15 AM
Early Afternoon	1:15 PM
Mid Afternoon	4:30 PM
Evening	8:00 PM

Since 2015, the operational season has been from May 1 to September 30 and we do not recommend any changes for 2021.

Schedule

The following schedule assumes a notice to proceed date of March 15, 2021. Earlier or later dates will allow us to adjust the schedule accordingly.

Task	Completion Date
1. Scientific Upgrades	May 1, 2021
2. Visualization Upgrades	May 1, 2021
3. Daily Operations: Task 1	June 15, 2021
3. Daily Operations: Task 2 & Task 3	May 1 - September 30, 2021
4. Final Report	November 31, 2021

Staff

Staff	Proposed Role
Dana McGlone *Project Manager & Lead Meteorologist*	Dana will provide project quality assurance and be the administrative and technical point of contact for the client. She will be in charge of the day-to-day quality control of the Tool's output and will also work closely with Dmitry on Tool upgrades.
Dmitry Smirnov *Chief Scientist*	As chief scientist, Dmitry will serve as the architect to develop the scientific upgrades ensuring the project's scientific integrity through quality control. In addition, Dmitry will assistance with the forecast equation development and Tool output. Dmitry will also help with day-to-day quality control of the Tool's output.
Graham Emde *Developer*	Graham will provide application development for the Tool's operation and help build the new visualization features for the Tool.

References

Barnett, T.P, and R.W. Preisendorfer, 1978: Multifield Analog Prediction of Short-Term Climate Fluctuations Using a Climate State Vector. *J. Atmospheric Sciences*, **35**, 1771-1787.

Dewberry, 2019: 2019 MHFD Heavy Rainfall Threat Analysis Tool. Report submitted to Mile High Flood District. 43 p.