Flash flood forecasting for ungauged locations with NEXRAD precipitation data, threshold frequencies, and a distributed hydrologic model

Brian A. Cosgrove[1], Seann Reed[1], Feng Ding[1,2], Yu Zhang[1], Zhengtao Cui[1,3], Ziya Zhang[1,4]

[1]NOAA, National Weather Service, Office of Hydrologic Development, 1325 East-West Highway, Silver Spring, MD 20910; phone: 301-713-0640 x 226; email: Brian.Cosgrove@noaa.gov
[2]Wyle Information Systems, [3]Lentech Incorporated, [4]UCAR

ABSTRACT

A flash flood forecasting system has been developed which combines distributed modeling and statistical analyses to produce gridded forecasts of return periods. A distributed hydrologic model (DHM) coupled to a threshold frequency (TF) post-processor, DHM-TF, is currently being tested over a Maryland-centered domain, and has verified well against National Weather Service (NWS) flash flood warning areas and verification points. The prototype system is currently running in real-time at the NWS Office of Hydrologic Development (OHD), and efforts are underway to test DHM-TF at several NWS field offices.

INTRODUCTION

Flash floods are a devastating natural disaster, causing millions of dollars of damage each year and putting many lives in danger. With the exception of excessive heat, flooding leads to more weather-related fatalities than any other cause. In 2007, the last year for which statistics were available, flash flooding caused 70 fatalities, 51 injuries, and 1.2 billion dollars in damage (NWS, 2009a). Half of flood-related deaths were caused when victims were caught in vehicles and swept away. Given these statistics, accurate predictions of flash floods are essential for the protection of life and property. Unfortunately, the nature of these events makes them quite difficult to monitor and predict. Flash floods feature a fast onset—less than 6 hours from the causative event (NWS, 2002)—are local in scope, and depend greatly on fine scale weather and land surface conditions.

Monitoring efforts are valuable but do not provide enough lead time for affected parties to take the action needed to prevent loss of life and property. Forecasts, which have the potential to increase warning lead time, can be produced by standard lumped hydrological modeling. However, these models are handicapped by the fact that they only provide information at basin outlets and cannot accurately represent the highly variable land surface and meteorological conditions that impact flash flooding. A promising alternative to lumped modeling is distributed modeling. Gridded distributed models more effectively represent the variable nature of meteorological forcing and land surface parameters and provide flood information at any grid point within the model domain. With this in mind, a method to use a distributed hydrologic model (DHM) in conjunction with a threshold frequency (TF) post processor (Reed et al., 2007) and NEXRAD precipitation data has been developed at NOAA's Office of Hydrologic Development (OHD). Forced by

Multisensor Precipitation Estimator (MPE) and High Resolution Precipitation Estimator (HPE) precipitation observations, and High Resolution Precipitation Nowcaster (HPN) precipitation forecasts, this modeling approach is focused on improving flash flood prediction capabilities by increasing forecast accuracy and usability (Kitzmiller et al., 2008). It also seeks to improve upon the current NWS flash flood warning lead time goal of 49 minutes through leveraging the two available hours of HPN precipitation forecasts (NWS, 2009b). Flash flood warning lead times have improved over the past several years (Figure 1), and DHM-TF forced by HPN output has the potential to lengthen lead times even more.

DHM-TF OVERVIEW

Operating on the Hydrologic Rainfall Analysis Project (HRAP) grid at a 4km resolution and hourly time step, DHM-TF produces gridded flow forecasts, from which gridded frequency forecasts are derived using historical simulations. These frequency forecasts are then compared against threshold frequency grids derived from local information for flash flood determination. DHM-TF relies on several hydrological modeling components to generate the required flow forecasts. These components, which include a gridded Sacramento hydrologic model, overland and channel routing algorithms, and a statistical post processor, are part of the research version of OHD's distributed model (Koren et al., 2004).

Hydrologic Modeling Components

The Sacramento hydrologic model (Burnash et al., 1973) represents spatially heterogeneous runoff processes over river basins ranging from tens to a few thousand square kilometers. It accounts for processes in which the freeze and thaw of soil moisture can have significant effects on water balance and soil moisture dynamics (Koren et al., 1999). Runoff from Sacramento is routed via a kinematic wave channel router (Koren et al., 2004). Routing is a key component of the DHM-TF flash flood forecast approach. Flash floods may occur near the causative rain event, or may occur downstream from the rainfall. The latter case is especially dangerous, as the lack of heavy rain in a particular area may provide residents or forecasters with a false sense of security. With routing enabled, DHM-TF is able to transport water from channels in areas of heavy rainfall to downstream points, providing an accurate simulation of the potential for flash floods along an entire river network.

Statistical Processing

Distributed hydrologic models have the potential to provide valuable gridded flow information, and yet, as with other models, may be subject to biases which limit their applicability without calibration or post processing. To solve this problem, DHM-TF utilizes a threshold frequency post processing approach. Rather than assuming that the exact magnitudes of the simulated flows are correct, DHM-TF relies on the concept that the relative ranking of the flows are accurate. That is, even if the flows are persistently biased, they will be internally consistent and thus can be correctly ranked against each other. It is this assumption which allows for the reliable conversion of flow values to return period values without need for accompanying observations. Reed et al. (2007) demonstrated the effectiveness of this inherent bias

correction for a simulation in the Dutch Mills basin of Arkansas. In particular, they showed that although raw model flow values may be biased, the probabilities of these model flows are accurate and able to support the calculation of return periods.

The statistical package which accomplishes this task depends on a high-quality long-term simulation of flow, which in turn requires high-quality hourly precipitation data as input. Flow values from this long term simulation are first passed through a routine which generates a grid of annual maximum peak flow values. A second routine fits the peaks to a log Pearson Type III distribution, and calculates a corresponding set of summary statistics which describe the distribution. Once the historical baseline simulation and associated computation of summary log Pearson Type III statistics are complete, real-time hourly simulations of discharge can then be ingested into a final DHM-TF routine. This routine utilizes the summary statistics to convert discharge into frequency and then return period for final display. Forecasters can compare these grids to locally derived threshold frequencies (and associated return periods) to aid in warning decisions. Local threshold frequencies may be derived from several sources of information such as known flood frequencies at selected river locations or frequencies associated with culvert designs. An in-depth discussion on this process can be found in Reed et al. (2007)

Taken together, the various components of the DHM-TF modeling approach produce flash flood forecasts which feature many advantages over traditional flash flood guidance. These include the ability to predict flash flooding at ungauged locations, a high resolution 4 km product (versus basin scale for standard flash flood guidance), a rapid update ability (every 15 minutes), and the production of verifiable small basin flow estimates.

NEXRAD PRECIPITATION DATA

Three NEXRAD-based precipitation products are used as input to DHM-TF: MPE, HPE, and HPN. The MPE uses a combination of radar and gauge input data and is produced hourly within the AWIPS environment by each RFC on a 4 km grid (Kitzmiller et al., 2007). Rainfall estimates from Doppler radar, gauges, and satellites are automatically ingested, and bias correction factors are developed from a comparison of radar and gauge data. After automatic derivation of a gauge-only field, and a bias-corrected radar field, a blended radar/gauge product is produced through an automatic merging of the two fields. Since manual adjustments of input fields may occur repeatedly over several hours as additional gauge reports are received, the final MPE field may not be available for several hours (Kitzmiller et al., 2008). Thus, although the high quality of the MPE product makes it ideal for the long term baseline DHM-TF runs, the long lag times and slow updating characteristics of the product makes real-time use in flash flood forecasting impractical.

Although not offering the rigorous manual quality control that defines MPE, HPE features a lower latency time (less than 1 hour), a more rapid update (every 15 minutes), and a higher resolution (1 km), and is thus better suited than MPE for real-time, flash flood operations. HPE leverages recent MPE gauge/radar bias information to automatically generate rainfall and rainrate products statistically corrected for bias. The process also ingests a user-defined radar mask which determines how

overlapping radars will be blended for each pixel within the domain of interest. HPE is slated for implementation within AWIPS during 2009 (Kitzmiller et al., 2008).

While MPE and HPE can be used by DHM-TF to bring model states up to the present, the most important aspect of the DHM-TF approach is its forecast capability which is powered by HPN data. Based on an updated extension of the Flash Flood Potential algorithm (Walton et al., 1985), the HPN process begins with the calculation of local motion vectors. These vectors are derived through a comparison of radar rain rates spaced 15 minutes apart, and are used to project current radar echoes forward in time out to two hours. Rain rates are then variably smoothed by a method based on the observed changes in echo structure over the past 15 minutes, as well as the current observed rain rate field (Walton et al., 1985; Kitzmiller et al., 2008).

CASE STUDY

Both the NWS Mid Atlantic River Forecast Center (MARFC) and the NWS Sterling Weather Forecast Office (WFO) have expressed interest in implementing DHM-TF. As such, DHM-TF developmental work and case study research is currently occurring over a 14,000 km^2 Maryland-centered domain which lies within both the MARFC and Sterling WFO areas of responsibility (Figure 2). Uncalibrated parameters for the gridded Sacramento model were taken from an *a priori* set of land surface parameters derived by Koren et al. (2000) using the National Resource Conservation Service State Soil Geographic Database. These parameters were complemented by a percent impervious area data set derived by Elvidge et al. (2004). Flow measurement data (cross sectional area and flow) at downstream gauges within the test domain were used to derive channel routing parameters. Values at upstream cells were derived using geomorphological relationships (Koren et al., 2004).

Even with automatic and manual error correction procedures in place, a time-changing bias was found in the MPE fields used to force DHM-TF over the Maryland domain prior to 2004. This bias stemmed from a truncation error within the NEXRAD precipitation processing scheme. Given the need for an accurate and internally consistent long-term flow simulation, a bias correction procedure was developed to account for this issue (Figure 3). In this procedure, monthly accumulations of Parameter-elevation Regressions on Independent Slopes Model (Daly et al., 1994) observation-based precipitation data are divided by monthly sums of MARFC MPE data. The resulting monthly ratios form monthly correction factors that are applied to all hourly MPE data within each particular month. Application of this procedure to the MPE fields greatly reduces the inconsistency in the bias of resulting distributed model flow fields (Zhang et al., 2009).

Simulations conducted over the Maryland test area with MPE, HPE, and HPN data fall into two categories: 1) retrospective, and 2) real-time.

Retrospective Simulations

A long-term retrospective flow simulation serves as the baseline for conducting both specific retrospective case studies as well as real-time operations. This simulation provides the annual maximum peak data which is used to construct the Log Pearson Type III distribution needed to convert flow values to return periods, and allows forecasted flows to be put into proper historical context. Currently 10

years in length, this simulation is forced by bias-corrected MPE data, and only needs to be updated once per year to generate new annual maximum peak data.

Leveraging the long-term Sacramento simulation, a case study was performed centering on Tropical Storm Hanna, which brought heavy rain to the Maryland region September 6th-7th, 2008 (Figure 4). The intensity and duration of the rain gave rise to eight flash flood warnings issued by the Sterling WFO for areas within Maryland and Virginia. Several local roads and large parkways were shut down due to flash flooding and several rescues and evacuations were necessary. Five of the warnings were outside the Maryland DHM-TF domain, and were not included in the case study. The remaining three were issued at 16:20Z, 17:58Z, and 19:12Z on September 6th, and collectively covered the period of time from 16:20Z on September 6th through 01:15Z on September 7th.

Flow return periods calculated by DHM-TF were plotted in Google Earth and are displayed in Figure 5 alongside the warning polygons defining the three flash flood warning areas mentioned above. In order to match the multi-hour time period covered by these flash flood warnings, the DHM-TF data displayed is the maximum return period generated by the model during the valid time of the three warnings. As can be seen, DHM-TF generates gridded return values above 2 years (approximately bankfull) in each of the three warning areas. In particular, where available, the DHM-TF output matches the coverage of the southernmost warning polygon over Washington DC very well. As DHM-TF is implemented in field offices, its use may allow forecasters to draw smaller warning polygons and reduce false alarms.

Further focusing on this warning area, Figure 6 depicts a large grouping of 4 km grid boxes where DHM-TF generates flash flood conditions. Two verification points where flash flooding was observed by ground spotters are also depicted, and align well with the DHM-TF output. One of the challenges of flash flood forecasting is verification. In many instances, no ground truth is available to corroborate a flash flood warning. Multiple factors can contribute to the lack of observations including population density, adverse weather conditions, and a lack of verification spotters. Recognizing the importance of ground truth, NOAA NWS is currently in the process of upgrading the warning and verification process. This effort, combined with focused, intense validation efforts such as the Severe Hazards Analysis and Verification Experiment (SHAVE, Ortega et al., 2009), will greatly improve the flash flood forecasting process, and will allow for improved validation of DHM-TF output.

Real-time Simulations

Although a valuable tool for research exploration, DHM-TF is ultimately aimed at expanding the operational flash flood forecasting abilities of NWS WFO and RFC offices. As such, much emphasis has been placed on the development of a robust real-time system of data archiving, model execution, and output visualization scripts. Figure 7 shows that two hydrologic model runs are required each time real-time execution is initiated: a state update phase, and a forecast phase.

In Phase 1, which begins 16 hours before present, Sacramento model states and river channel states are updated using MPE and HPE forcing data. The model makes use of a restart file which is saved by the previous state update run, and which contains soil as well as channel state information. MPE data is used for the first 12

hours, while HPE data is used for the remaining 4 hours. Once the model reaches the present time, HPN data is used to force the model 2 hours into the future. To allow water to flow through the channel system and further highlight downstream impacts, the model is run for an additional 4 hours, albeit without any precipitation data.

Once model execution is complete, the statistical processing routines convert flow output into gridded return periods. Automated scripts then produce plots of these return periods using the freely available GRASS GIS and Google Earth programs (no NWS product endorsement implied). Each program has its own strengths and weaknesses and the use of both ensures that the data will be accessible by a broad range of operational and research stakeholders. Google Earth excels at intuitive visualization, while GRASS is able to perform sophisticated geospatial analyses. Both still image and movie-type views of the data are produced each hour.

Currently, the real-time production cycle is executed once per hour. However, given the 15 minute updating of HPE data, the system could be configured to update as often as every 15 minutes by using more HPE data and less HPN data. In addition, as future upgrades to the HPN product extend forecast length past 2 hours, the DHM-TF system will be reconfigured to use all available forecast data.

FUTURE PLANS

The portability of DHM-TF will be increased through inclusion of the Snow17 snow model (Anderson, 1973) and through the derivation of a nationwide routing parameter dataset. The impact of increasing model resolution to 2km will be examined, and a study of the length of flow record needed to support DHM-TF operations will also be undertaken. Concurrent with the research outlined above, collaborative efforts with several National Weather Service WFOs and RFCs will seek to bring DHM-TF into operational forecasting environments. It is in these locations where DHM-TF will have the largest impact, providing increased flash flood warning time and forecast accuracy, potentially saving lives and property.

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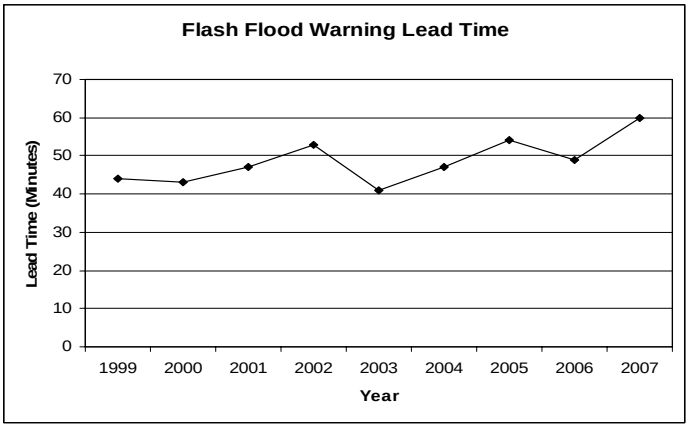

Figure 1. Average yearly National Weather Service flash flood warning lead time from 1999 through 2007.

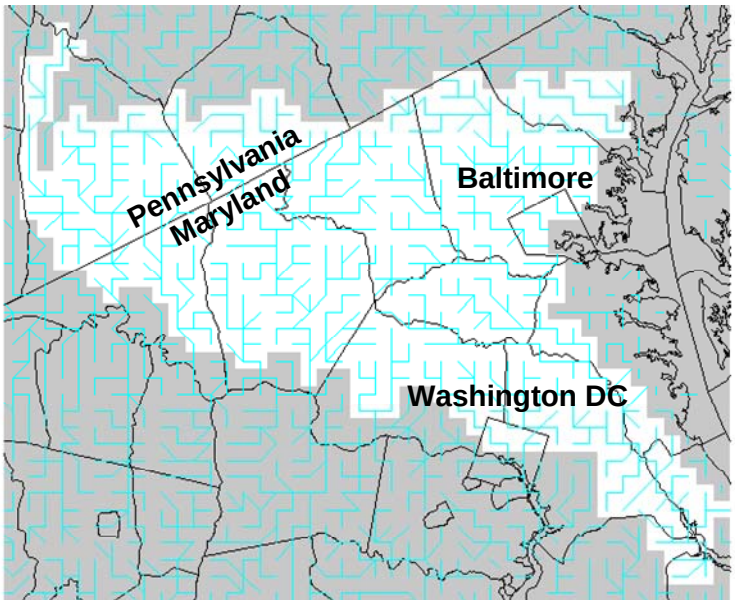

Figure 2. DHM-TF Case study domain centered on Maryland, and featuring a 4km^2 grid resolution.

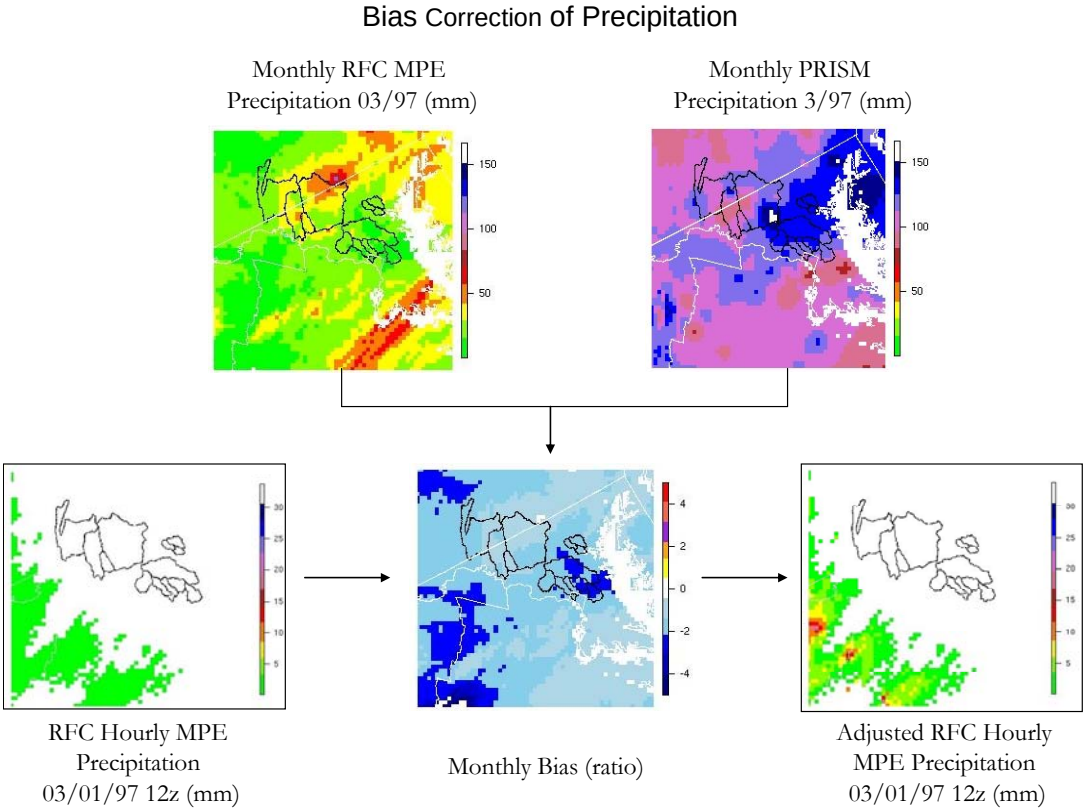

Figure 3. Overview of the bias correction procedure used to reduce the bias present in the MARFC MPE precipitation record prior to 2004.

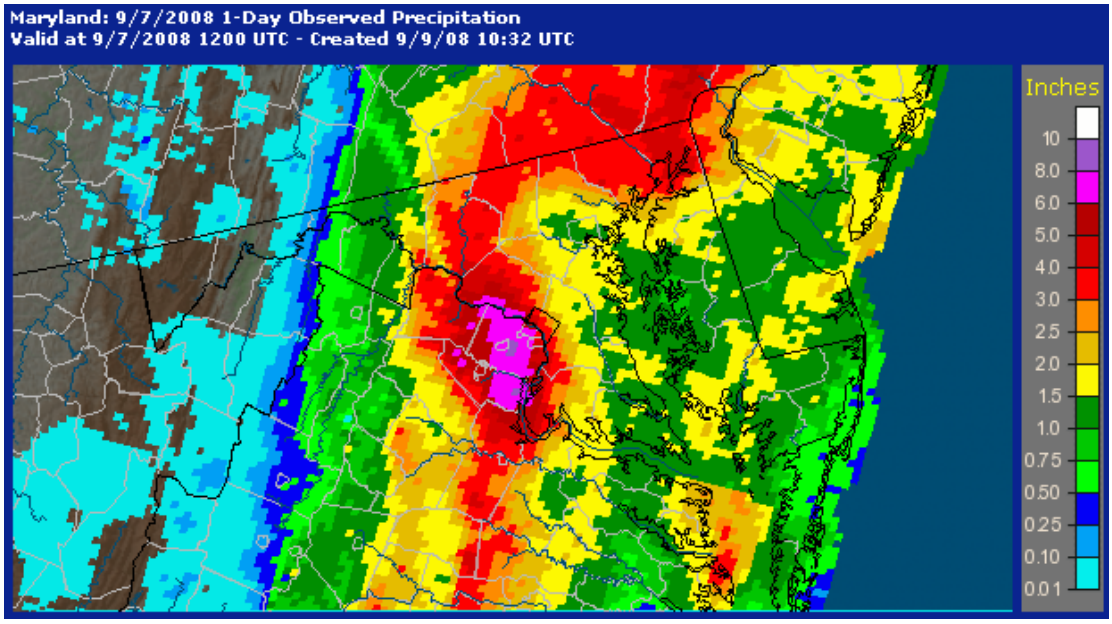

Figure 4. Precipitation (inches) associated with Tropical Storm Hanna from 12Z September 6th, 2008 through 12Z September 7th, 2008.

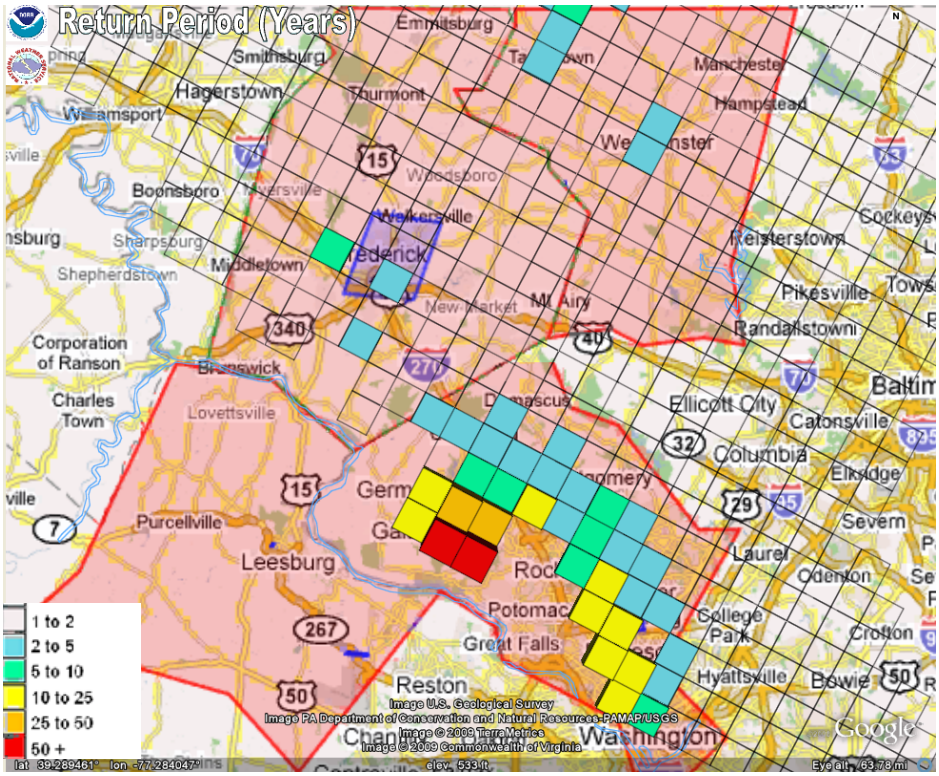

Figure 5. Depiction of the areas covered by the three Tropical Storm Hanna flash flood warnings (outlined in Red) issued by the Sterling WFO that lie within the Maryland DHM-TF case study domain. Figure also depicts maximum return period values from DHM-TF covering a similar time period.

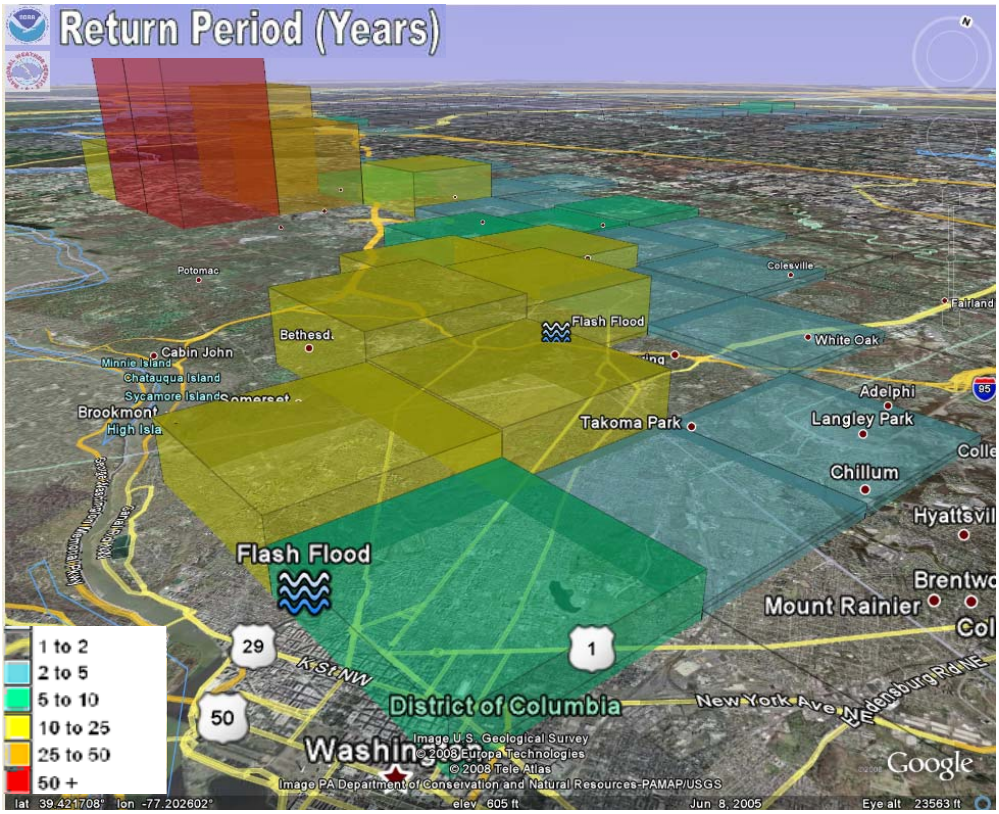

Figure 6. Maximum return period values from DHM-TF simulated during the period of time from 16Z on September 6th through 02Z on September 7th 2008. Spotter-confirmed flash flood events are indicated by the Blue wave symbols.

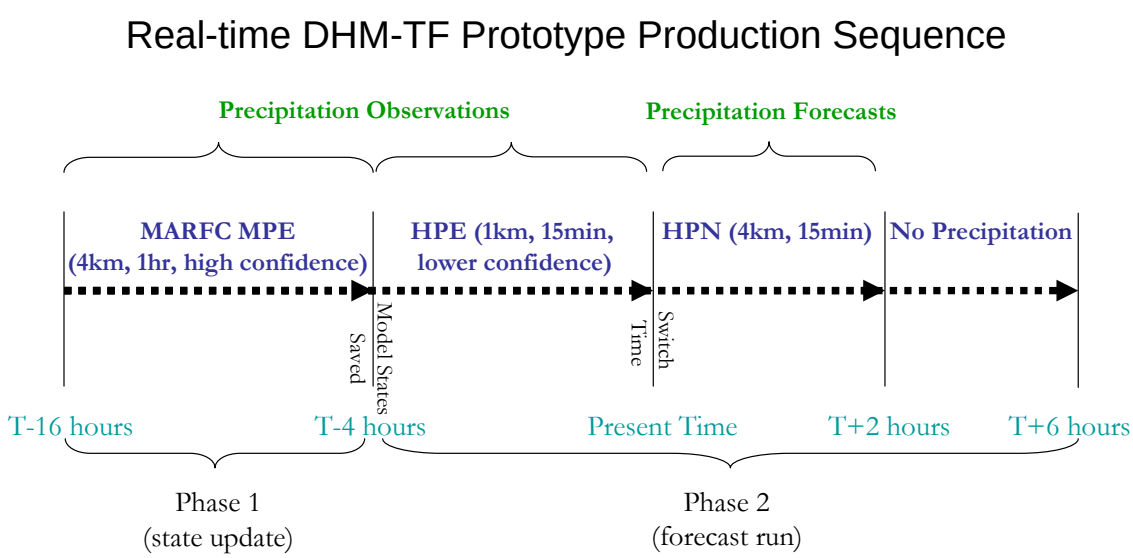

Figure 7. Illustration of the production sequence used in ongoing prototype DHM-TF forecasting prototype.