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NATIONAL WEATHER SERVICE FLASH FLOOD WARNING SERVICES

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1. INTRODUCTION

Effective warning for flash flooding is extremely difficult given the localized nature and rapid onset of intense rainfall and the fast hydrologic response of small basins. Flash floods can occur within minutes or a few hours of excessive rainfall. All the steps in the warning process need to be effective and completed in the least amount of time possible. These steps include: computing the rainfall, modeling the basin response, analyzing the situation, communicating the warning message, and completing life saving actions such as evacuations. This paper describes some of the tools and techniques being used to improve each step in the National Weather Service's end-to-end flash flood warning process (Office of Hydrologic Development 2010).

With the opportunities presented by both the Community Hydrologic Prediction System (CHPS) (Roe et al 2010) and the resources of an Integrated Water Resources Science and Services (IWRSS) program and the National Water Center facility (Cline et al 2009), flash flood services delivery will most likely evolve significantly in the next 5 to 10 years. Some of the potential changes will be discussed.

Successful implementation of new and improved flash flood warning technologies and best practices will lead to improved warning services and fewer lives lost to these destructive events.

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**Retired from federal service on 12/31/2011

2. COMPUTING THE RAINFALL

The National Weather Service (NWS) relies on a combination of satellites, radars, and gages to provide near real-time rainfall estimates for flash flood forecast and warning. Satellite data are used in some mountainous areas where there are gaps in radar coverage. A national radar network provides updated rainfall estimates (rainfall rates and accumulations) every 4.5 to 6 minutes. Every hour, an updated radar rainfall bias is calculated from radar/gage data pairs. Radar rainfall data are transmitted from the Radar Product Generator computer to Weather Forecast Offices (WFOs) and River Forecast Centers (RFCs) and made available publically in real-time via the internet. Rain gage data, transmitted at fifteen minute and hourly intervals, includes Automated Surface Observing System (ASOS) gages located mainly at airports, U.S. Geological Survey and other agency rain gages reporting via satellite, and state, or locally-operated mesonets that share their data with the NWS.

Substantial resources are dedicated to improving radar rainfall estimates. Over the next 18 months, the radar network is being upgraded to add dual polarization capability. Multi-parameter estimates with polarimetric radar have the potential to substantially improve the accuracy of radar rainfall estimation compared to single polarization radar (Ryzhkov 2005, Giangrande and Ryzhkov 2008, Istok 2009). A system for development and real-time testing of enhancements to single-polarization radar is currently in use in some field offices (see <http://nmq.ou.edu/> and (Zhang et al 2011).

In 1979, the NWS first began development of a prototype Integrated Flood Observing and Warning System (IFLOWS) with the intent to susbstantially reduce annual loss of life, property damage, and disruption of commerce and human activities due to flash flooding. IFLOWS consists of rainfall and stream gages reporting to local base stations every 5 to 15 minutes. The data are collected centrally on NWS servers via a wide area network to compute 15 minute or longer rainfall accumulations and track river stages. Because the all-weather gages are solar powered and report via radio, they can be deployed in remote areas prone to excessive rainfall. Today, numerous communities, state and federal agencies are now linked in a wide area communications network using this technology. This Automated Flood Warning Systems (AFWS) (see <http://afws.erh.noaa.gov/afws/national.php> and <http://www.hydrologicwarning.org>) network connects numerous local flood warning systems and integrates and shares information from 1700 sensors across 12 states.

Forecasters often issue flash flood warnings based solely on the rainfall intensity and rainfall accumulations being reported by radar and mesonets. To enhance lead time, forecasters incorporate short term forecasts of rainfall. To aid local forecasters, the National Centers for Environmental Prediction routinely disseminate quantitative precipitation forecasts (QPF), some specifically for rainfall capable of causing flash flooding (see e.g. <http://www.hpc.ncep.noaa.gov/qpf/excess_rain.shtml> and <http://www.hpc.ncep.noaa.gov/qpf/qpf2.shtml>).

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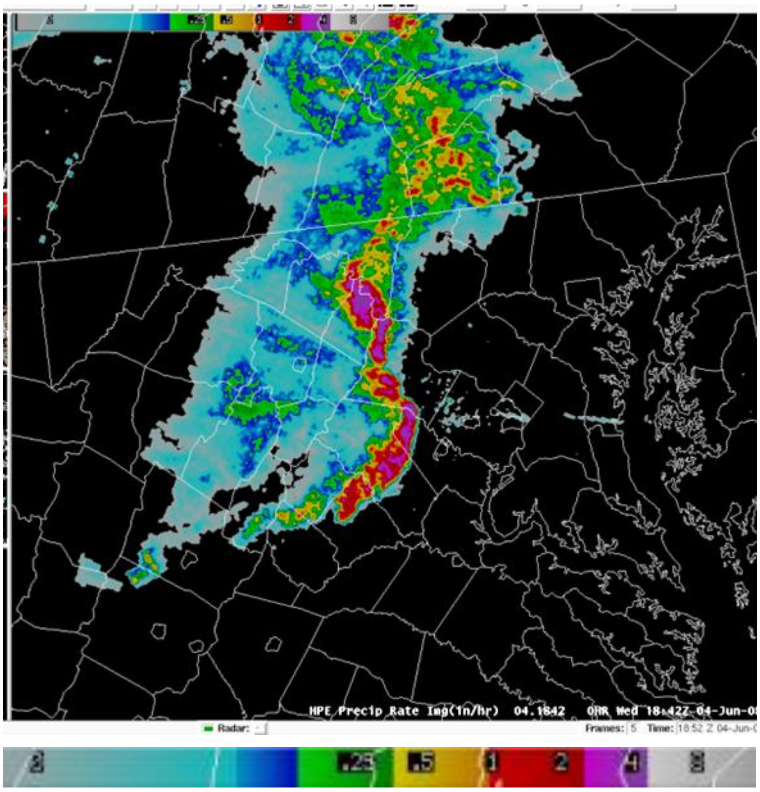
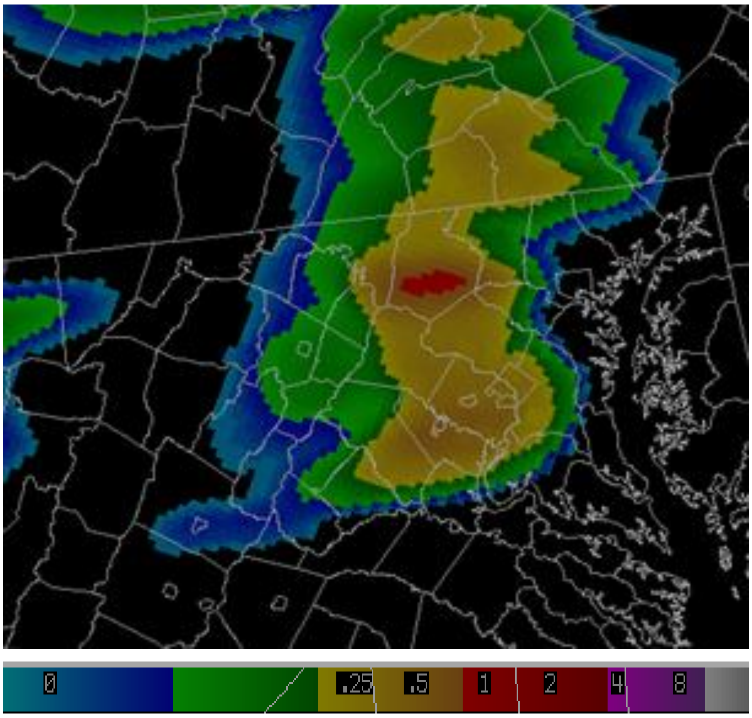
Forecasters can often make short-term 0-3h forecasts of rainfall with a fair degree of accuracy using the projected evolution of the mesoscale forcings, identifying telling trends in the radar patterns, and understanding conceptual models of convective storm archetypes. These forecasts are sometimes issued to affected communities in text form as Special Weather Statements. Also, an automated forecast system based on radar data, is available for 0-1h nowcasts (Fig. 1).

The NWS is also improving quantitative antecedent precipitation estimates (QPE) using multi-sensor approaches focused on integration of high resolution radar, satellite, mesoscale models, surface observations and statistical techniques. An ongoing collaboration among NWS, Institute of Atmospheric Physics ASCR, and Czech Hydrometeorological Institute researchers has resulted in prototype real-time systems for 0-6h multisensor-based QPF (Kitzmiller et al. 2010).

A critical component to the entire warning process is forecaster understanding of the weather patterns and trigger mechanisms causing the heavy rainfall. The NWS calls this 'situational awareness' and provides training through workshops and web-based modules (see e.g. http://www.meted.ucar.edu and http://www.erh.noaa.gov/bgm/research/ERFFW/.



(a)



(b)

Figure. 1. Radar-based rainrate analysis over Maryland, Virginia, and Pennsylvania at 1842 UTC, 4 June 2008 (a); extrapolation nowcast of 1-h rainfall, based on this radar data, valid at 1942 UTC (b). Amounts are in inches.

3. MODELING THE BASIN RESPONSE

How much rainfall is needed to generate a flash flood? The answer is not straightforward. First, one must define what is meant by a flash flood. The NWS defines a flash flood as a rapid and extreme flow of high water into a normally dry area, or a rapid water level rise in a stream or creek above a predetermined flood level, beginning within six hours of the causative event (e.g., intense rainfall, dam failure, ice jam). However, the actual time threshold may vary in different parts of the country. Ongoing flooding can intensify to flash flooding in cases where intense rainfall results in a rapid surge of rising flood waters. Second, the rainfall necessary to produce flash flooding depends on many variables such as previous rainfall (i.e. antecedent soil moisture conditions), basin size, slope, soil type, urbanization (i.e. impervious area), and vegetation. In use for many years at the NWS, forecasters depend heavily on Flash Flood Guidance (FFG) and Headwater Guidance (FFH) issued by the RFCs (Ostrowski 2003). FFG, updated 1 to 4 times a day, gives an estimate of the rainfall required in a 1-, 3-, 6-, or 12- hour period to initiate flash flooding on an un-gaged small stream typical of that area. When a new FFG is issued, forecasters and other users such as local emergency officials can examine the guidance before heavy rain begins and have a good estimate for how much rain is needed to trigger flash flooding in their area. Most flash flood warnings in the U.S. today are issued based on rainfall observations (accumulations and intensity), forecaster's short-term estimate of additional rainfall that may fall in the next 30 minutes or so, and Flash Flood Guidance. A recent enhancement in FFG has been to issue higher resolution guidance on a 4km grid (Figure 2). Headwater Guidance is computed in a similar way, but is derived for a gaged point on a specific headwater stream with known antecedent channel contents and a defined flood level. For selected gaged points on small streams, WFOs with assistance from the RFCs, have calibrated and implemented Site Specific lumped hydrologic models running at one hour time steps.

New tools for modeling the basin response are being developed and tested. These include distributed hydrologic models which not only model the local runoff for small modeling elements over which rainfall occurs, but also route water from modeling element to modeling element to accurately detect and characterize flash flooding occurring at downstream locations. One interesting application of distributed hydrologic models to flash flood detection and

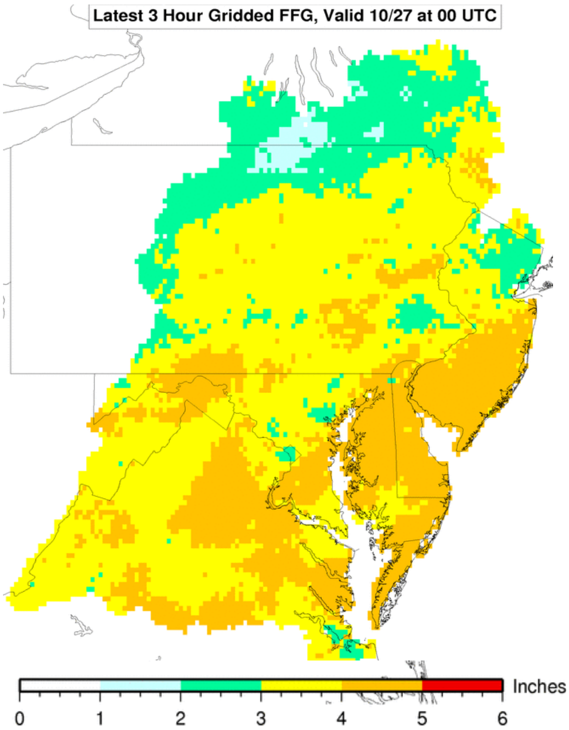


Figure. 2. National Weather Service 3-hour Flash Flood Guidance on a 4km grid for the Mid-Atlantic region.

modeling is the Distributed Hydrologic Model Threshold Frequency (DHM-TF) technique. DHM-TF is a statistical post-processing module within the NWS Office of Hydrologic Development Research Distributed Hydrologic Model (RDHM) (Reed 2007). The distributed model is run in a hind-cast mode using historical high-resolution QPE to generate annual peak discharge for each grid cell. Discharge frequency distributions are developed from the modeled flows at every grid cell in the domain, whether gaged or not. In a forecasting application, DHM-TF is executed every hour using high resolution QPE and QPF. The simulated flow at each grid point is compared to the historical discharge frequency distribution in order to estimate the flow return period. The forecaster views the model output as geospatial grid coverage of maximum return flow periods for the model period (typically the current hour plus 3 hours into the future). Warnings could then be issued based on an established flow return period threshold for that region that has been associated with flash flooding in the past. DHM-TF requires sufficient computer resources to provide frequent model runs and to rapidly generate the output displays for forecaster analysis.

Another new approach originally developed for use in mountainous areas and now being tested in other areas is the Flash Flood Potential Index (FFPI) (Jackson et al 2005). FFPI is a

Geographical Information System (GIS) based approach to map the relative threat of flash flooding based on factors such as terrain slope, land usage, soil type, etc. Such maps (Fig. 3) objectively identify locations of highest potential, and when overlaid with precipitation estimates can help forecasters quickly identify the current threat areas where warnings should be issued. This approach has been primarily adopted in regions of the southwest were antecedent soil moisture conditions are of lower impact to flash flood occurance.

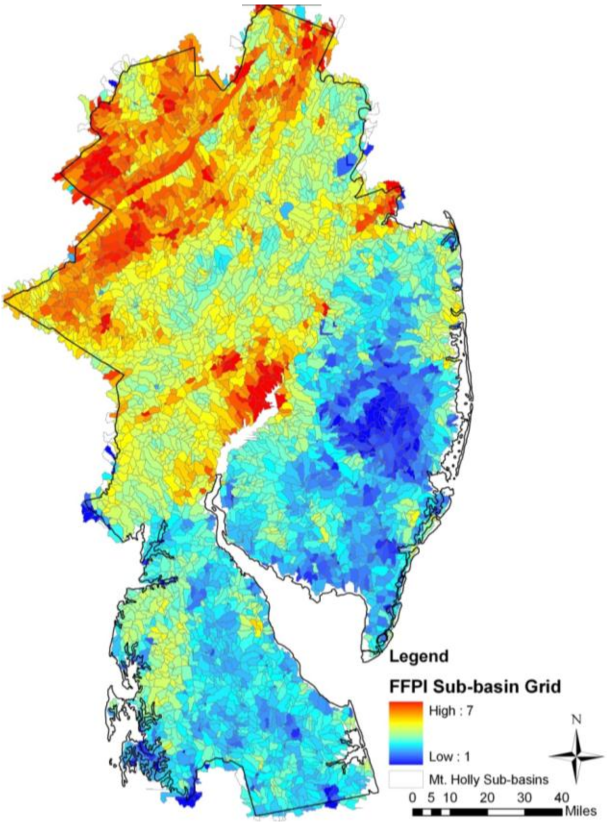


Figure. 3. Flash Flood Potential Index (FFPI) for the area surrounding Delaware Bay and the New Jersey coastline extending northwest to the Pocono/Catskill mountains. Higher values near the center are the result of the urbanized areas in and around the city of Philadelphia, Pennsylvania. Lowest values near the coast are the result of sandy soils and flat terrain. (http://www.erh.noaa.gov/bgm/research/ERFFW/posters/kruzdlo_FlashFloodPotentialIndexforMountHollyHSA.pdf)

A third new approach applied in some areas is the Kinematic Runoff and Erosion Model (KINEROS) (see <http://www.tucson.ars.ag.gov/kineros/> KINEROS is an event-oriented, distributed, physically-based model developed to continuously simulate the runoff response in basins having predominantly overland flow. KINEROS compliments existing modeling tools by providing information beyond the simple issuance of a flash flood warning, such as how high the water will get at the specified outlet or for any channel model element, when worst flooding will take place, and what will be impacted (Schaffner 2010).

4. ANALYZING THE SITUATION

For timely decision making, the forecaster needs an integrated set of tools to perform synoptic and mesoscale analyses, monitor rainfall and stream stages, make short-term forecasts, evaluate the flash flood threat, and issue warnings and statements. A comprehensive training program utilizing a combination of classroom seminars, computer-based learning, and simulation exercises is also essential to develop and maintain heavy rain and flash flood forecasting skills. The NWS uses several tools within the Advanced Weather Interactive Processing System (AWIPS) that are optimized in order to try and provide the needed information without overloading forecasters with too much information. These include: Display Two Dimensions (D2D), a graphical software application used to monitor observational data and perform synoptic and mesoscale analyses of observed hydrometeorological and model forecast data. The WFO Hydrologic Forecast System (WHFS) provides a relational database (IHFS) that provides integrated data storage and access for hydrologic functions. Graphical tools within WHFS include the Multisensor Precipitation Estimator (MPE) to monitor precipitation from rain gages and radar and Hydroview to monitor stages from stream and river gages. Another important WHFS application is Riverpro, a tool for issuing river-based hydrologic products (see <http://www.weather.gov/oh/hrl/whfs.htm>).

The Flash Flood Monitoring and Prediction system (FFMP) is an application specifically designed to help forecasters monitor and evaluate the flash flood threat and decide whether or not to issue flash flood warnings (Smith 2000; Filiaggi 2002)(see <http://www.nws.noaa.gov/mdl/ffmp/index.php?L=5>). FFMP provides displays, similar to the one shown in Figure 4, comparing observed and predicted rainfall to flash flood guidance for each small basin, and provides information on the names of impacted small streams for inclusion in the text warning. Sub-basin rainfall accumulations over a variety of durations and rates of rainfall per radar volume scan are easily displayable in FFMP, both of which are critical variables in the flash flood decision-making process. IFLOWS rain gage data can also be displayed within FFMP for rapid comparisons between gages and radar data.

Another tool, Warning Generation for AWIPS (WARNGEN) enables the rapid generation of a Flash Flood Warning polygon and warning message and allows the forecaster to provide value-added information specific to that warning. Improved forecaster training along with the implementation of FFMP and the use of local flash flood studies have also been credited with improving flash flood warning accuracy and lead time. For instance a local study at WFO Blacksburg, VA (Stonefield and Jackson 2007) was used to better understand the climatology and impact of flash flooding in that area. Similar studies have been completed at numerous WFOs across the U.S.

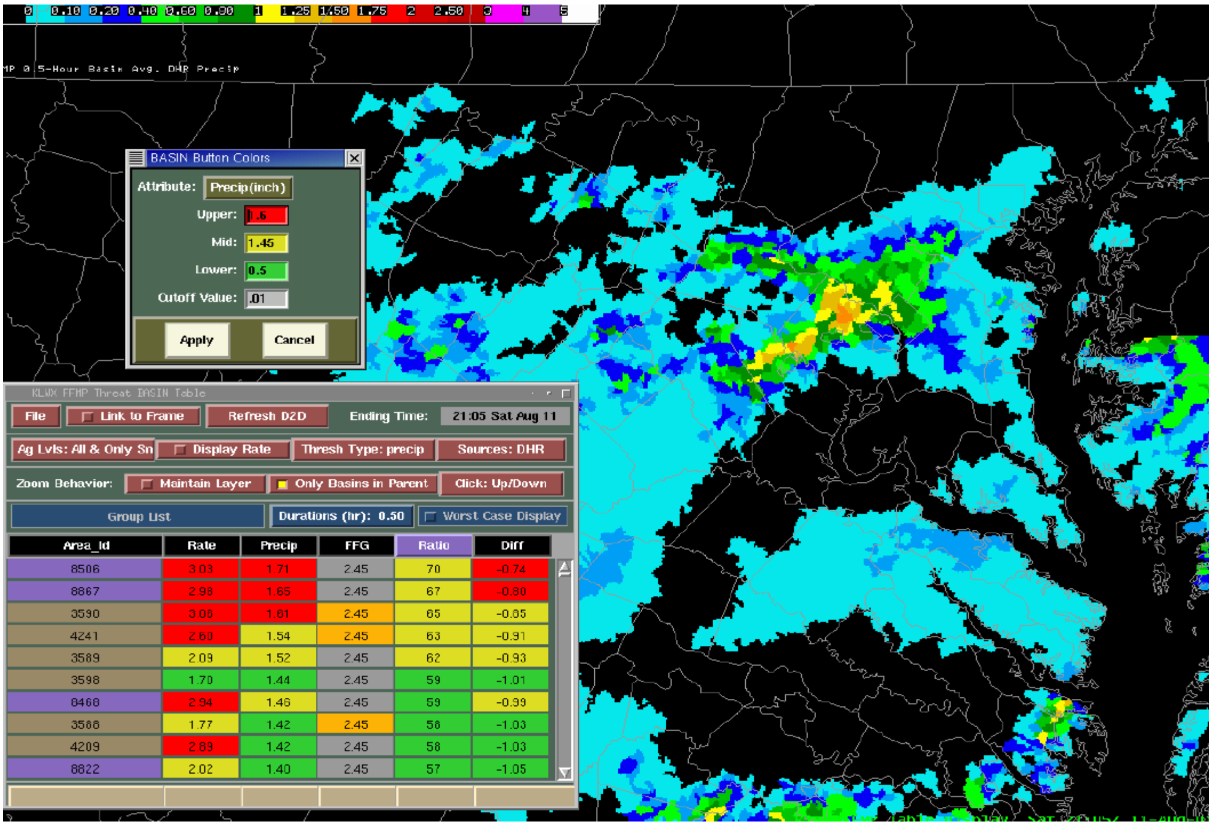


Figure. 4. The Flash Flood Monitoring and Prediction tool used by National Weather Service forecasters to track the precipitation rates and accumulations in small basins (typically 5 to 25 square kilometers) as compared to flash flood guidance. Information is updated every 4.5 to 6 minutes. The stream name and county can also be displayed so

Comparison of national verification statistics from the period 1997-2000 before FFMP implementation and 2006-2009 after FFMP implementation (Tab. 1) shows a significant improvement in both the probability of detection (POD; 0.85 improving to 0.91) and the percentage of warnings with lead times greater than zero minutes (66% improving to 79%). While average lead time improved from 47 minutes to 64 minutes, false alarm rates (FAR) have worsened, increasing from 0.42 to 0.56. One possible explanation for the increase in the false alarm rate is FFMP makes it more likely forecasters will issue warnings for remote areas before any flash flood observations are received. The true false alarm rate is probably lower since some flash floods in remote areas are unlikely to be observed or reported.

Table. 1. Comparison of National Weather Service flash flood warning verification statistics from the 4 year periods 1997-2000 and 2006-2009. Green numbers show improvement between periods. Improvement in POD and average lead time has been attributed in part to the implementation of FFMP across the country between 2001 and 2005.

Years of Study	Probability of Detection (POD)	% of warnings with > 0 min lead time	Average lead time for warnings	False Alarm Ratio (FAR)
1997-2000	0.85	66%	47 min	0.42
2006-2009	0.91	79%	64 min	0.56

Ideally, forecasters should have access to real-time information on flash flooding and flood impacts such as: streams out of their banks, roads and homes flooded, bridges overtopped, status of dams (releases, spills, emergency situations). Obtaining this information as it is happening is often extremely difficult, especially at night and in remote areas. Without this type of feedback, forecasters are often left wondering if anything is happening. This is cited by some NWS forecasters as the biggest weakness in the flash flood program. To improve access to information, WFOs are recruiting volunteer severe weather spotters, exploring the use of the web and social media such as Twitter and Facebook, establishing chat rooms for emergency management and the media, and installing situational awareness displays to monitor local and national media outlets.

Post-analysis of flash flood events and their impacts is another essential ingredient needed to further develop forecaster skills and decision support capabilities. NWS offices continue to educate themselves and the public about the nature and severity of flash flooding through scientific studies and post-event service reviews. Publications such as Storm Data (see <http://www7.ncdc.noaa.gov/IPS/sd/sd.html>) are painstakingly compiled to document the human and societal impacts of all weather phenomena, including flash floods. The sources for Storm Data include the post-event verification efforts undertaken after every event and numerous outside sources such as newspapers and county reports.

5. COMMUNICATING THE WARNING MESSAGE

Warnings have no benefit unless the people that need to protect themselves get the warning in time and understand its meaning so they can act. The end user can be a homeowner, a business operator, a vehicle driver, a local fireman, emergency medical technician, local transportation department, local emergency official, etc. Given the diversity of end users, a fully automated dissemination system with multiple, resilient communication paths and some redundancy is best (see <http://www.weather.gov/om/disemsys.shtml>). Whenever possible, communication systems should incorporate back-up power sources because electric utility power often fails during severe storms.

"It is the policy of the United States to have an effective, reliable, integrated, flexible, and comprehensive system to alert and warn the American people…establish or adopt, as appropriate, common alerting and warning protocols, standards, terminology, and operating procedures for the public alert and warning system to enable interoperability and the secure delivery of coordinated messages to the American people through as many communication pathways as practicable…administer the Emergency Alert System (EAS) as a critical component…ensure that under all conditions the President of the United States can alert and warn the American people."

Excerpted from Executive Order 13407: Public Alert and Warning System

Figure. 5. Key alert and warning distribution system characteristics from Executive Order 13407: Public Alert and Warning System, signed by the President June 26, 2006.(FEMA 2011)

In the U.S., the Federal Emergency Management Agency (FEMA) established the Integrated Public Alert and Warning System (IPAWS) to improve public safety through the rapid dissemination of emergency messages such as flash flood warnings to as many people as possible over as many communications devices as possible (see http://www.fema.gov/emergency/ipaws/aggregator.shtm). To do this, FEMA is coordinating with government authorities and private organizations (see Fig. 6, IPAWS Architecture) to upgrade the country's alert and warning infrastructure and to exploit emerging technologies so that no matter what the crisis, the public will receive life-saving information. In 2011, FEMA began operation of the automated Alert Aggregator/Gateway to validate and authenticate Common Alerting Protocol (CAP) Version 1.2 alert messages for distribution to public alerting systems and the American people (see http://www.fema.gov/emergency/ipaws/projects.shtm>). The Commercial Mobile Alert System (CMAS), or Wireless Emergency Alerts (WEA) as it is being referred to by the cellular carriers, is the first major project to leverage this new alerting technology. CMAS is a radio broadcast from a nearby cell tower to all CMAS-capable phones and devices in the threat area and not subject to network congestion as person-to-person calls and text messages are. CMAS is free and not a subscription.. CMAS alerts, including flash flood warnings, have a distinct vibration cadence to differentiate from other types of notifications produced by mobile devices. All major cell carriers are participating in CMAS on a voluntary basis and are committed to offering CMAS capable phones but must begin deployment by April 2012. CMAS complements the NWS's experimental Mobile Decision Support Services (MDSS) interactive NWS (iNWS) service, a subscription text message based service for NWS partners, community decision leaders, emergency responders and members of the electronic media (see <http://inws.wrh.noaa.gov/>).

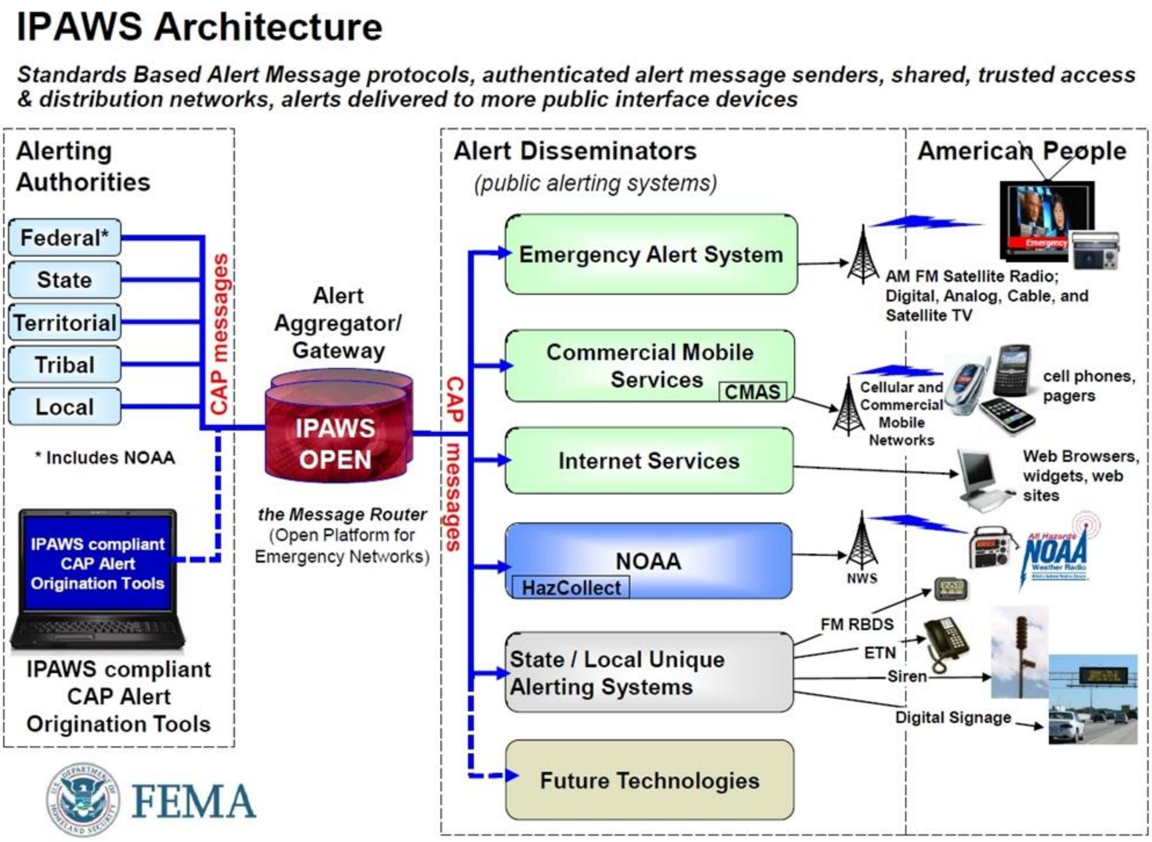


Fig. 6. IPAWS Architecture showing three key components: 1) alert origination by government alerting authorities, 2) alert aggregator/gateway or message router operated by FEMA and, 3) the public alerting systems operated by government agencies and private sector organizations disseminating alerts and warnings to the American people.

FEMA administers the Emergency Alert System (EAS) (see <http://transition.fcc.gov/pshs/services/eas/> and <http://www.weather.gov/os/NWS_EAS.shtml>) as one of the many means used by alerting authorities to send warnings via broadcast, cable, satellite, and wireline communications pathways. FEMA is integrating the EAS into IPAWS and upgrading the EAS to include more broadcast stations and warning distribution methods. A schematic of a state EAS network is shown in Figure 7. Television and radio stations have decoders that automatically, or manually at the discretion of the station staff, interrupt normal programming to broadcast the warnings.

For many years, the NWS has operated NOAA Weather Radio (NWR) (see <http://www.weather.gov/nwr/>) which is a network of over 1000 radio transmitters continuously broadcasting environmental information and timely warnings of weather and non-weather events and emergencies. NWR also serves as the primary NWS path into the EAS system. Weather radio receivers are extensively used in schools, hospitals, nursing homes, and by government agencies and large businesses in their emergency operations centers. However, less than 20% of individual households choose to own weather radios and a survey in one state revealed that fewer than 7% of individual households would get an emergency notification via weather radios (Redmond 1995).

In addition to relying on NWS warnings, some communities with their own AFWS networks of rain and stream gages have employees or volunteers monitor conditions and warn flood-prone neighborhoods and initiate evacuations (see <http://www.highwater.org/Brittany/temp%20site/temp_fws.html>). Since people have access to different communications linkages at different times, the number of people who hear a warning message can be maximized by disseminating warning messages over the full range of public communications networks (Mileti 1990).

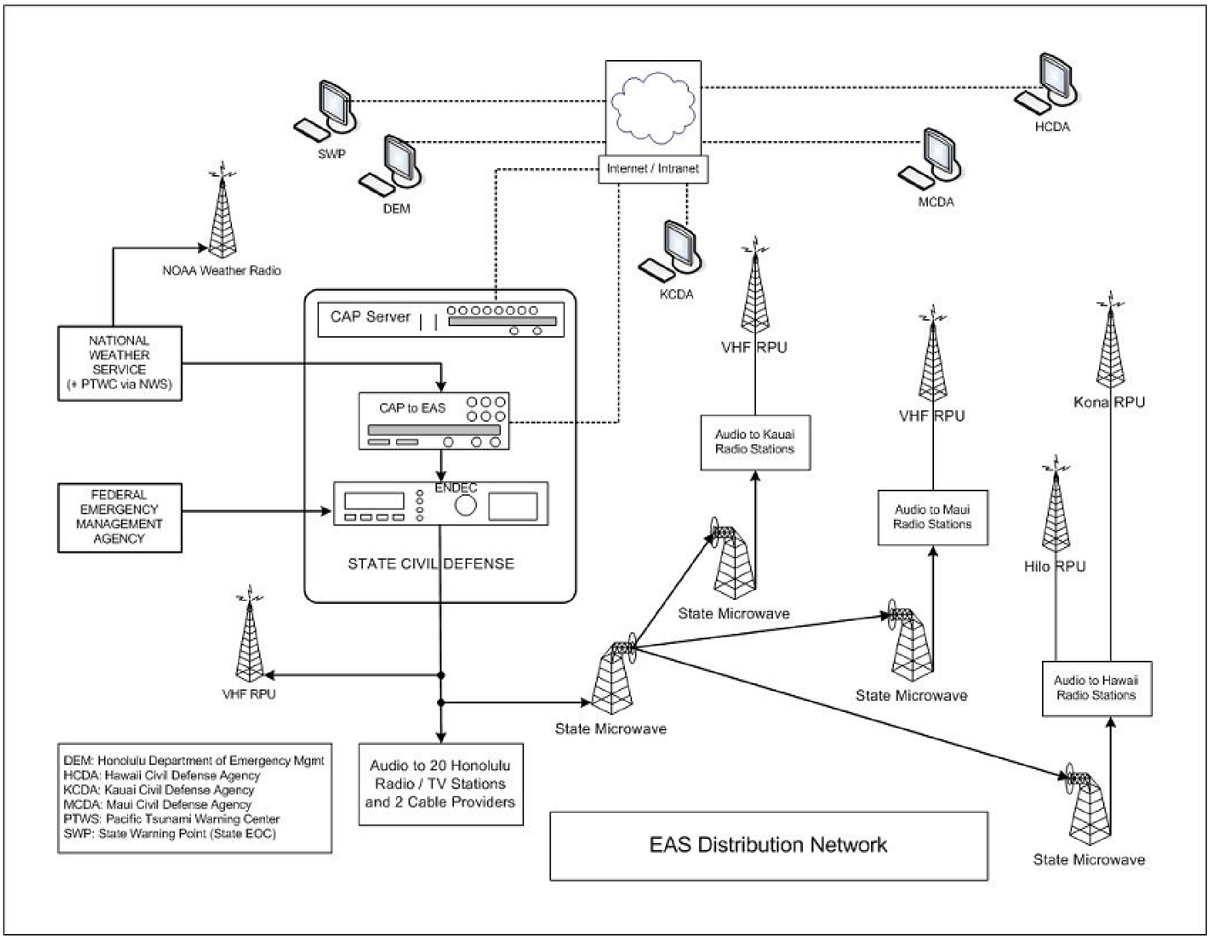


Fig. 7. Hawaii Emergency Alert System (EAS) for communicating warnings to response officials and the general public. Note the multiple redundant channels of communications to the public including State Civil Defense network, NOAA Weather Radio, Cable and Broadcast Television, and Commercial FM and AM radio stations.

6. COMPLETING LIFE SAVING ACTIONS

For various reasons, people don't always make good decisions to protect themselves and others from harm even when they have received a warning or they see a developing flash flood situation. Social scientists and hazard response planners have identified multiple factors that influence how people respond (Mileti 1975). These include their past experience, their understanding and assessment of the immediate threat to themselves and their loved ones, and their evaluation of (and trust in) the sources of information. Very often, after getting a warning, people will look for additional clues or confirming information to help them assess their immediate risk (Leik 1981). For example, what are neighbors doing in response and what are local police and fire departments saying about the situation? Many people will drive across a flooding roadway if the person driving in front of them makes it across. More than half of flash flood deaths occur in automobiles so education on this aspect of the hazard is particularly important.

People are less likely to act in response to a warning if they have never discussed the dangers of flash flooding in their local area or have never seen educational videos on the dangers of flash flooding. For this reason, education is needed at the federal, state, and local levels on the risks posed by high water including flash floods. These educational messages need to be repeated often and school children need to be taught as well. The NWS places emphasis on outreach and education about weather and flood hazards (see <http://www.weather.gov/education.php>).

Figure. 8. Turn Around Don't Drown street sign used to remind motorists of the deadly dangers of driving across flooded roadways.

In addition to publications and videos produced by NWS in association with other partners, NWS staff routinely give presentations to local groups and schools on the dangers of flash floods. A recent outreach initiative to address the flood hazard in automobiles is called 'Turn Around – Don't Drown' (see <http://www.nws.noaa.gov/floodsafety/index.shtml>). Another program recently promoted by the NWS is the High Water Mark (HWM) program in which WFOs partner with the USGS and local entities to establish signs that indicate the level of historical floods in an area (see <http://www.nws.noaa.gov/os/water/high_water/>). Routine SKYWARN training conducted by WFOs across the country, usually at the county level, provides information to storm spotters about the dangers of flash flooding and on what information to report to WFOs.

The NWS has been working with other agencies and the non-profit foundation Nurture Nature Foundation on a flood safety campaign in the Delaware River basin (see <http://focusonfloods.org>). During flood season, short 30 or 60 second public service announcements play on radio and television to remind people of the dangers. Most states hold annual flood safety awareness weeks, during which the NWS, state and local officials, and the media work together to educate the public about flood dangers. Some counties and cities hold tabletop flood exercises or functional exercises (FEMA 2010a, 2010b, 2010c) every 1-3 years during which all agencies involved in flood warning and flood response work through a flood scenario and simulate communication and decision making. Each WFO is staffed with a Warning Coordination Meteorologist and a Hydrologic Service Program Manager. Recently, every RFC added to their staff a Service Coordination Hydrologist. These people work with their staffs on projects and activities designed to educate the public about the dangers of hazardous weather such as flash flooding.

Figure. 9. Refrigerator magnet distributed at flood outreach events to encourage the public to go to the National Weather Service river forecast pages and look-up their local flood stage.

7. EVOLUTION OF SERVICES – Next 5-10 YEARS

Despite large improvements in the flash flood lead time and accuracy, flash flooding is still a significant threat to lives and property in the United States. Challenges remain in objectively identifying and communicating the expected location, magnitude and impact of flash floods across multiple hydrologic regimes. These challenges are evidenced by comparing the analytical and dissemination capabilities within the flash flood warning services to the analytical and dissemination capabilities within the river forecast services. The river forecast warning process relies on river gage locations which, by default, allows for easier communication of the location of river floods. Flash floods by contrast may occur in small ungaged streams and washes or entirely outside of the channel. Flash Floods may occur in the immediate vicinity of heavy precipitation, or a significant distance downstream as runoff from multiple head water basins is funneled into a single location. The magnitude of river flooding is communicated in terms of minor, moderate or major flooding based on impacts coordinated with the local emergency management community. A report commissioned by the NWS confirms that this method of communicating the expected impact and risk of flooding is meaningful to the emergency management community (Wolpert 2008). By contrast, the current paradigm for flash flood detection and warning simply communicates a binary threat with no objective assessment of the magnitude of flooding. In other words, the current flash flood techniques lack the ability to characterize the impacts that range from small-scale flash flood events that may close low-water crossings to catastrophic flash flood events that devastate entire communities. The NWS flash flood services should grow to develop new tools and techniques that better identify the specific locations of flash flood events and meaningfully communicate the magnitude or risk associated with the event.

Meeting these goals requires the application of robust hydrologic models to improve the flash flood analysis, forecast, and warning processes. These hydrologic models must operate on a fine temporal resolution to match the scale of rapid onset flooding. Similarly a fine spatial scale is required to accurately simulate the hydrologic response from small to large precipitation events over very small watershed to large watersheds. Techniques such as KINEROS and DHM-TF, discussed in section 4, are examples of current capabilities that may be potential hydrologic modeling solutions. Moreover, there are next-generational components of the Community Hydrologic Prediction System (CHPS) and the Integrated Water Resources Science and Service (IWRSS) initiative that will form the infrastructure to facilitate the adoption of hydrologic modeling into the flash flood services concept of operations.

CHPS is the new operational hydrologic modeling software architecture and business model that will enable NOAA's water research and development enterprise and operational service delivery infrastructure to be integrated and leveraged with other federal water agency activities, academia, and the private sector. CHPS allows any hydrologic model, through the development of an adapter, to be incorporated into the forecast system at the River Forecast Center. As new distributed and semi-distributed hydrologic models specific to flash flooding are developed they can be implemented within the CHPS environment. Through client-server connections, it is envisioned that WFO forecasters may be able to remotely initialize, run, and evaluate the results of such a model. Such a model, implemented within CHPS, would benefit from the RFC's expertise in calibration, model state maintenance and regionally consistent forcings datasets while allowing Service Hydrologist at the WFO to simulate small scale basins deemed critical within the WFO's area of responsibility. Together this collaboration leverages the strengths of both the RFC and WFO expertise in providing estimates of discharge to determine if a flash flood warning is necessary, or to indicate and communicate the magnitude of expected flooding within the warning message.

IWRSS is an innovative partnership of federal agencies with complementary operational missions in water science, observation, prediction and management. It envisions a highly collaborative and integrative framework for providing a seamless suite of water resources information that leverages the particular expertise from each of the federal consortium members. Perhaps the most critical aspect of IWRSS is the vision for a summit-to-sea suite of high-resolution water resource information. This information will be realized as a comprehensive forcings data service and land surface, hydrologic modeling framework at very fine spatial and temporal resolutions (Cline 2009). Implementing statistical post-processing of surface discharge from such a model, similar to the DHM-TF technique, could produce fine scale, nationally consistent surface flow simulations in real-time. This guidance would depict the location and relative magnitude of flash flood or areal flood events. With input from stakeholders in communities across the country, model results could be refined into simple yet consistent flooding indices. Presented as a digital mapping stream to WFOs and expert level stakeholders, this type of information would clearly communicate the location and specific risk from flood events. Such information could also be incorporated into the warning products to help specify the location, appropriate action and relative risk from a particular event. Furthermore, advances in short-term high-resolution QPF could be incorporated into the modeling framework and guidance products potentially increasing the lead-time of warning products. A 'spiral path' of development is planned to bring the scientific and technical capabilities to the flash flood program. In this development model, advances in modeling and dissemination are incrementally applied to pilot projects where results and impacts on services are evaluated. Results from these evaluations are returned to the development process and the project is enhanced. In this manner, the program is developed with critical feedback from users and stakeholders.

A key component of the NWS vision for IWRSS is the establishment of a National Water Center to be located on the University of Alabama campus in Tuscaloosa, AL. This center of excellence for water resource information is designed to facilitate IWRSS concepts, principally ensuring data and forecast consistency, providing national level hydrologic Impact Based Decision Support Service (IDSS) to core partners, and strengthening national partnerships. In concert with RFCs, the National Water Center will produce national analyses and short- through extended-range, gridded, geo-referenced, analyses and probabilistic forecasts of water resource variables from high-resolution 'summit-to-sea' distributed hydrologic models. Of critical importance to the Flash Flood Program, these models will form the foundation for high spatial and temporal resolution analysis and forecast, similar to that of weather data sets, within a Data Cube to create a Common Operating Picture (COP) for the nation from the smallest watershed to the national scale. Initial modeling output will likely include geo-referenced water resource variables such as snow cover, snow depth, snow water equivalent, runoff, stream flow, soil moisture, precipitation, evapo-transpiration, water quality and groundwater. This list could be expanded to establish a CONUS wide implementation of a threshold-frequency technique and rapidly updated gridded flash flood guidance. Whether implemented at the RFCs, National Water Center, or some combination thereof, forecasters at the WFO level would benefit from a more consistent, objective source of high resolution guidance for flash flood prediction.

8. CONCLUSIONS

Beginning with IFLOWS networks in the 80s, Doppler radar in the 90s, and improved data analysis tools of the 00s, NWS work to enhance each step of the end-to-end flash flood warning process is saving lives and paying dividends through improved flash flood warning accuracy and lead time. However, each year there still are too many deaths and millions in property losses from flash flooding that could be prevented. More can be done to reduce these impacts. The NWS plans to take several significant steps over the next 5-10 years in its continuing efforts to improve flash flood warning and related decision support. These include making use of better rainfall estimates from dual pol radar and better 0-3hr rainfall forecasts by combining multisensor and mesoscale model based techniques. CHPS provides a new software architecture that is expected to lead to greater collaboration with our partners and breakthroughs in the use and application of high resolution distributed hydrologic models. In order to better leverage complimentary work in other federal agencies, NWS is working with the USGS and USACE to form the IWRSS partnership which has the potential to further improve the NWS flash flood program through interagency partnerships and improved infrastructure for interagency sharing of data. NWS Forecaster analysis tools and training resources will also continue to improve.

In addition to science and technology improvements, NWS has recognized that a substantial flood awareness and education program is key to the success of any warning and response system. Local officials and the general public need to be informed regarding the causes of flash floods, their risks, the warning system, emergency safety measures they need to be ready to take, and inherent uncertainty in the forecast and warning process. Local warning plans need to be reviewed and practiced on a regular basis. This knowledge needs to be prevalent in the community, so that when a warning is issued or flash flood development is observed, time critical safety measures are implemented without delay. The highest priority must be taking actions to prevent loss of life, with secondary attention to saving property.

The warning dissemination system is also critical and the U.S. is implementing a significant improvement in 2012, CMAS cell tower broadcasts of flash flood warnings to cell phones.

Figure. 10. Still image from animated 9 minute flood safety story developed by Nurture Nature Foundation and funded through a NOAA grant. This animated story has no copyright restrictions and is available at http://focusonfloods.org/the-day-of-the-flood and http://www.youtube.com/watch?v=iOjEtowTGag.

Figure. 11. National Weather Service flood outreach and education exhibit using a flood model to demonstrate the factors that influence flood severity.

The dissemination system needs to relay warnings via multiple robust communication paths that aren't prone to failure in severe weather. Local officials and the general public have a need to get warnings reliably and nearly instantaneously, since every additional minute of warning is critical. Seconds can mean the difference between life and death. Because of the uncertainty in the forecast and warning processes, everyone must be educated concerning their personal responsibility to protect themselves. The NWS will continue to look for new and innovative ways to improve dissemination and promote flood awareness and education in collaboration with our many federal, state, and local partners.

All of these steps will contribute to the broader NOAA initiative to build a "Weather-ready" nation in partnership with other government agencies, researchers, and the private sector (see http://www.nws.noaa.gov/com/weatherreadynation/). Since flash flooding is a also a global problem, we must also share successful flash flood warning technologies and best practices amongst nations with the goal of improving everyone's end-to-end warning systems so that fewer lives are lost during future destructive storms.

9. ACKNOWLEDGEMENTS

Many people contributed to the writing/review of this paper. For help with the presentation and paper we'd like to thank Patti Wnek, David Ondrejik, Bill Marosi, Kevin Hlywiak, Rachel Hogan Carr, George Mckillop, Reggina Cabrera, Ken Johnson, Rick Watling, Dave Radell, Peter Jung, Mike Evans, and David Kitzmiller. Each of your contributions to this project are greatly appreciated.

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