# J9.3 USE OF A GIS-BASED FLASH FLOOD POTENTIAL IN THE FLASH FLOOD WARNING AND DECISION MAKING PROCESS

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## 1. INTRODUCTION

Flash flood monitoring and prediction is considered integral to successful severe weather operations across the intermountain western United States. Further complicating the ability to detect and warn for these events is the fact that – due to impervious rock, numerous dry washes and narrow canyons, and the general lack of vegetation – flash floods may be produced with a relatively small amount of rainfall, thus diverging from conceptual flash flood models applied to areas further east in the contiguous United States.

The National Weather Service (NWS) Weather Forecast Office (WFO) in Salt Lake City, Utah (SLC) has numerous detection and warning tools available in operations to assist in the flash flood warning decision making process. The Flash Flood Monitoring and Prediction (FFMP, Smith et al 2000) program, deployed nationally across the NWS in 2002, assists in the flash flood warning decision making process by mapping reflectivity information from radar bins to pre-defined hydrologic basins. The derived Average Basin Rainfall (ABR) is compared to Flash Flood Guidance (FFG) provided by NWS River Forecast Centers (RFC). The complex terrain and soil characteristics of the intermountain West, however, introduce several deficiencies to FFG derivations and any associated techniques to locally modify this guidance.

To help address this deficiency, the Colorado Basin River Forecast Center (CBRFC) has developed a Relative Flash Flood Potential Index (RFFPI; Smith 2003). The RFFPI uses high resolution GIS datasets to better define the physiographic character of hydrologic basins in FFMP. This paper will first present a brief summary of current operational flash flood warning tools, then discuss the derivation of the RFFPI and present a severe flash flood case that took place in southern Utah on 23-24 August 2003 to demonstrate the use of this tool to compliment other flash flood warning decision tools in operations at the SLC WFO.

## 2. AN OVERVIEW OF FLASH FLOOD WARNING DECISION TOOLS

NWS forecast offices are able to use several key guidance tools in flash flood detection and warning operations. The Advanced Weather Interactive Processing System (AWIPS) allows forecasters to view, combine and manipulate a multitude of datasets, including radar and satellite imagery, surface observations and analyses, and high resolution model output. The use of satellite imagery – including the ability to create imagery loops combined with graphics – has greatly improved recognition of strong convective signatures. However, detection and analysis of severe convection, including convection that results in flash flooding, heavily depends on the WSR-88D radar and output from its Precipitation Processing Subsystem (PPS; Fulton et al 1998) that computes rainfall amounts for each radar range bin based on theoretical Z-R relationships. Forecasters using AWIPS are further able to combine reflectivity, or PPS imagery in the form of storm totals, 1- or 3-hr amounts, with high-resolution topography imagery to help detect potential flash flood situations in areas of complex terrain. However, since it is the amount and rate of rainfall that is accumulated in a hydrologic basin that ultimately determines the occurrence of a flash flood, with the basin's response determined primarily by its physiographic character (all of which are not considered in the WSR-88D precipitation algorithms), it is critical to translate this theoretical precipitation amount to truer basin accumulation.

### *2.1. The Flash Flood Monitoring and Prediction (FFMP) Program*

The core function of FFMP is to map reflectivity information from radar bins to pre-defined hydrologic basins. The program uses the WSR-88D's 4 x 4 km Digital Hybrid Reflectivity (DHR) product to derive rainfall rates and associated rainfall accumulations from each volume scan on each hydrologic basin under the radar umbrella, and over user-specified time periods (as little as 30 min and as much as 6 hr). The derived Average Basin Rainfall can be compared to Flash Flood Guidance provided by NWS River Forecast Centers, thus producing what has been described as a Flash Flood (FF) index (Davis 2002) that is intended to be used as a direct measure of flash flood severity. Forecasters may view this information in table form or graphically in AWIPS whereby ranges of rainfall accumulation, rate, and FF index are color-coded (by default, darker red shades equate to heavier accumulations, rates, and FF threats). A particularly powerful display capability in FFMP provides this same information

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in line-graph form for each basin by displaying each parameter from the last volume scan backwards (to the right on the graph) to 8 hours (Fig 1).

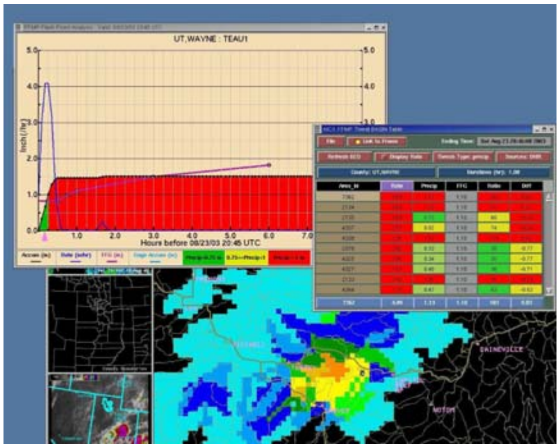

*Fig. 1. Example of FFMP output on AWIPS with Flash Flood Analysis Graph, Threat Basin Table, and ABR (plan view) display.*

The use of FFMP in SLC warning operations, starting with the 2003 convective season and preceded by the use of a similar (non-AWIPS) program called the Areal Mean Basin Estimated Rainfall program (AMBER; Jendrowski and Davis 1998) beginning in 2000, has greatly improved office flash flood warning performance (Fig. 2).

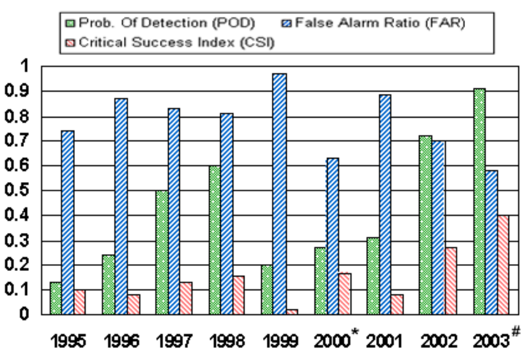


*Fig 2. Salt Lake City WFO flash flood verification statistics, 1995-2003. The* * *indicates first year using Amber program in warning operations; the* # *indicates transition from Amber to FFMP program. Verification sources include river gauges and spotter, media, and state and county reports.*

Though this tool presents a significant advancement in technology, it still carries several key deficiencies – especially in the intermountain western United States. Namely, extensive work is required to initially set up and customize the basins, incorrectly mapping DHR bins to basins, the user must still understand streamflow from basin to basin, and radar limitations – such as inaccurate precipitation estimates from hail contamination, or poor radar coverage caused by beam blockage or cell overshooting – still exist.

Other parts of FFMP also require careful derivation and configuration. Two key components of FFMP are the basin configurations and the FFG. Since a significant rise due to runoff can move downstream into basins other than those experiencing heavy rainfall, it becomes critical to accurately define each basin configuration, and the connectivity of the basins in the "base layer" network. WFO Hydrologists and hydrology focal points attend a basin customization course designed to provide instruction on using Geographic Information System (GIS) tools to incorporate more detail into FFMP basins, and build basin connectivity into the "base layer" network (Davis 2003). This is still considered to be a capability in future versions of FFMP. This modification is made even more difficult by the shear number of basins associated with radars within areas of complex terrain.

The FFG can be derived using pre-existing rules of thumb, the modernized Threshold Runoff/FFG system, and other local applications. By design, the modernized FFG/Threshold runoff was implemented to provide a standard methodology for producing gridded FFG to be utilized in FFMP. The modernized method relies heavily on the soil moisture states of the Sacramento Soil Moisture Accounting (SAC-SMA) model being used operationally at NWS River Forecast Centers. It is also possible to locally modify and improve FFG using a technique described by Davis (2004), whereby a history of basin rainfall (e.g., over the past 72 hrs) is used to modify FFG provided by an RFC.

However, numerous problems exist with applying FFG derivation techniques to its use in the intermountain West, including using the process to locally modify FFG. Namely, scale problems are encountered when trying to use the SAC-SMA for flash flood applications in regions with small basins. While forecast segments for the SAC-SMA model were developed for river basins generally ranging from 50 to as much as 200 square miles in size, basins in the intermountain West can average 2 to 10 square miles in size. The model also operates on a 6 hourly time step, which does not fit well with the typical temporal scales of flash flooding in this region.

Additionally, the soil moisture states in the SAC-SMA generally indicate large deficits in the semi-arid West. These deficits, which must be overcome before significant runoff is generated, are a primary cause for generating FFG values that are much higher than reasonable. This further emphasizes that, while soil moisture does play a role in flash flooding, rainfall intensity and the physical characteristics of the river basin are of greater influence in much of the West. It is then necessary to develop alternative methods of representing the hydrologic response of basins in the intermountain West, including establishing a way to represent the oftentimes complicated physiographic character of a basin – such as soil type, slope, forest cover, and land use.

### *2.2 The Relative Flash Flood Potential Index*

As stated earlier, the inability of FFMP to discern physiographic character from basin to basin – in addition to the ineffectiveness of the modernized FFG component used in FFMP discussed in the previous section – can significantly limit the program's full effectiveness as flash flood warning guidance. Thus, unless the proper FFG (or any other representation of flash flood potential) detail is provided, basin rainfall accumulations, rate, and FFG-exceeding values will appear equal between two equally-sized basins receiving similar rainfall amounts and at equal rates. These limitations oftentimes manifest themselves in the form of higher flash flood warning false alarm rates. To address this, the CBRFC developed the RFFPI to better represent a level of hydrologic response to heavy rainfall for each basin. The RFFPI considers four basin physiographic characters in its derivation: soil type, forest cover, land use, and slope. Subjective factors of importance have been applied to each of these parameters to derive an index of 1 to 10.

The data used to create the RFFPI is obtained from several GIS datasets. As with many applications that use these datasets, analysis limitations are frequently encountered due to varying resolution between datasets, which in this case range from 30 m to 1 km grid cells. Perhaps the most important dataset in the CBRFC area is slope, which is derived from a Digital Elevation Model (DEM) dataset. The DEM data, obtained from the United States Geological Survey (USGS), is available in 3-arc second resolution, or approximately a 90-meter grid cell. This dataset was re-sampled to 400 meters, considered an arbitrary mid-point between all datasets used. This resolution is not the most desirable since the minimum basin area that can accurately be defined is approximately 60 $km^2$.

The dominant soil texture (or soil type) dataset used in this preliminary analysis is from the State Soil Geographic (STATSGO) soils data that was compiled by the Natural Resources Conservation Service (NRCS). Where detailed maps are unavailable, geological, topographical, vegetation, and climate information have been combined with Land Remote Sensing Satellite (LANDSAT) images to determine probable classification and extent of soils. For the dominant soil texture class there are 11 standard soil layers in the vertical soil profile. Twelve soil texture classes are defined, ranging from sand to clay. Organic material, water, bedrock, and undefined or no data classes are included for a total of 16 texture classes. Although the resolution of the STATSGO data is pushing the limits of application at the flash flood scale, it still carries the concept of collecting rasterized datasets representing physiographic characteristics, and relating them to a hydrologic response to heavy rainfall. The land use dataset is developed from 30 m early 1990's Landsat Thematic Mapper data purchased by the Multi-Resolution Land Characterization (MRLC) Consortium.

For forestation, the RFFPI uses the U.S. Department of Agriculture (USDA), Forest Service, Southern Forest Experiment Station, Forest Inventory and Analysis (SO-FIA) unit's forest density dataset using NOAA's Advanced Very High Resolution Radiometer (AVHRR) satellite data. While the data does not differentiate between forest types – an important consideration for a future analysis – it expresses forest density as a percent of forest cover at a 1-km resolution.

This index, originally computed on a 400-m grid, has been interpolated to each FFMP basin and viewable at the SLC WFO using ArcView software (Fig. 3). This allows the user to interactively roam and zoom across the RFFPI grid, plus toggle on and off various overlays with RFFPI – such as spotter locations, rivers, highways and roads. Currently, forecasters view the RFFPI on a platform separate from AWIPS since ArcView is not available for the Linux operating system. This, however, only slightly reduces its value in a flash flood warning situation.

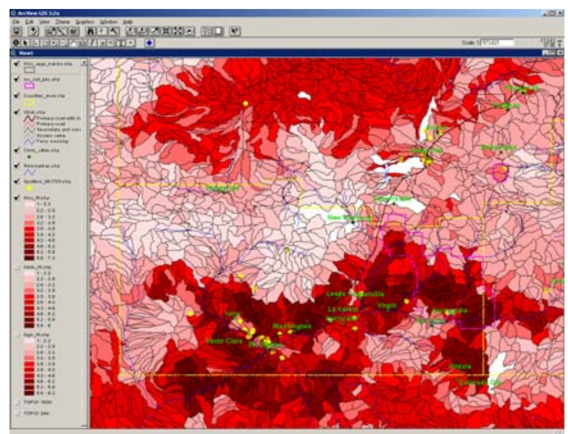

*Fig. 3. RFFPI for portion of Cedar City (KICX) WSR-88D radar umbrella in southwest Utah, including the Arcview interface used to adjust view and overlays. Darker shades indicate a higher flash flood potential.*

The RFFPI is especially useful when monitoring flash flood potential in areas of complex terrain. Southern Utah basin characteristics range, for example, from gradually-sloped or flat, forested or non-forested terrain (Fig. 4), to dry washes and steep, slick rock canyons (Fig. 5). These steeply sloped and sparsely vegetated areas are especially capable of inducing dangerous flash flooding with precipitation amounts that would be considered

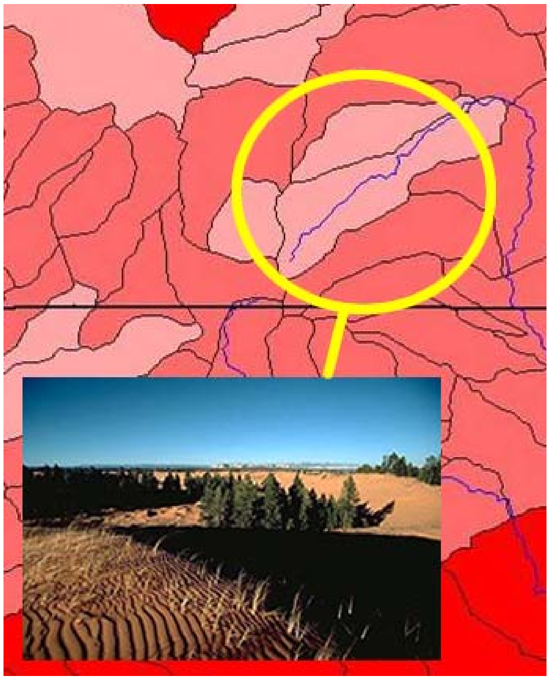

*Fig. 4. Example of low RFFPI area. Basins are located in Coral Pink Sand Dunes State Park, Utah. Photo courtesy of Ray Wheeler.*

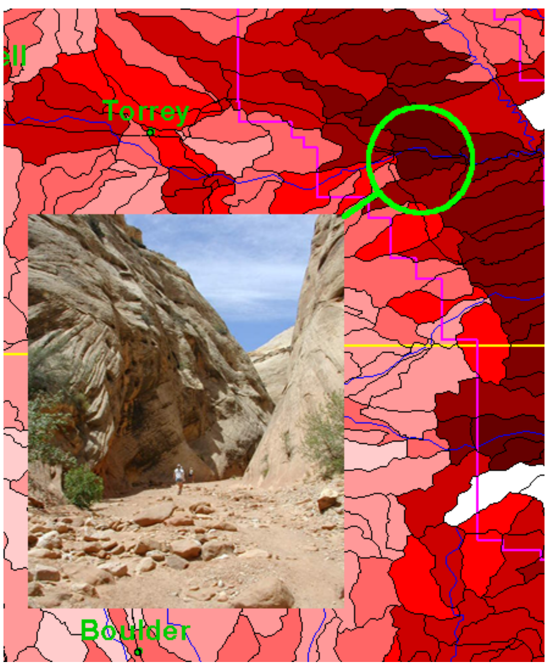


*Fig. 5. Example of a high RFFPI area. Dark areas represent high flash flood potential. Basins are located in Capitol Reef National Park.*

relatively light in areas east of the Rocky Mountains. The RFFPI essentially enables the warning forecaster to further differentiate the flash flood threat created by convective cells producing similar rainfall amounts and rates over equally sized basins.

**3. SOUTHERN UTAH FLASH FLOOD EVENT OF 23-24 AUGUST 2003**

The following section describes use of these warning decision tools during the severe flash flood event that took place in southern Utah on 23-34 August 2003. Numerous flash floods were observed and reported during the afternoon of the 23rd, extending into the evening hours of the 24th. The SLC WFO issued nine flash flood warnings during this event. Following a brief overview of the synoptic factors of the event, and a description of the overall convective development, the use of warning decision making tools as applied to two potential flash flood events from this case will be described. For the sake of brevity, the actual operation of FFMP (i.e., the "knobology") will not be given here. A description of its general operation can be found in Davis (2003b).

***3.1 Synoptic Scale Overview***

Establishing situational awareness is important to effectively warn for any severe weather phenomena, including flash flooding. Thus it is important to first describe the synoptic and mesoscale situation associated with this case. The general synoptic pattern in place over the western United States at midday on 23 August 2003 was characterized by a long wave trough centered over coastal British Columbia, Canada, with a short wave trough just moving onshore into central California. Abundant moisture was being pumped northward through the desert southwest and eastern Great Basin as clearly evident in the GOES WV imagery at 1800 UTC 23 August 2003 (Fig. 6).

This moisture plume is also depicted in the GOES-derived precipitable water (PW) product (Fig. 7), showing PW amounts of over 1 inch along the plume's axis, decreasing to around half an inch extending northwest from this axis into extreme northwest Utah. This was considered above average for this time of year. As is typical in the western United States, this moisture plume was a significant factor in the development of severe convection and flash flooding over southern Utah. Finally, a weak short wave trough was evident over southern Nevada in the GFS 400 mb analysis at 1800 UTC 23 August 2003 (see Fig. 6), and forecast to eject northeast into southwestern Utah over the course of the afternoon. The moist conditions, combined with this weak upper level triggering mechanism and daytime heating off the higher terrain in southern Utah, were likely the primary ingredients responsible for convective development that afternoon. Though ideally most flash flooding conditions in Utah are a result of above average PW, an unstable air mass, and

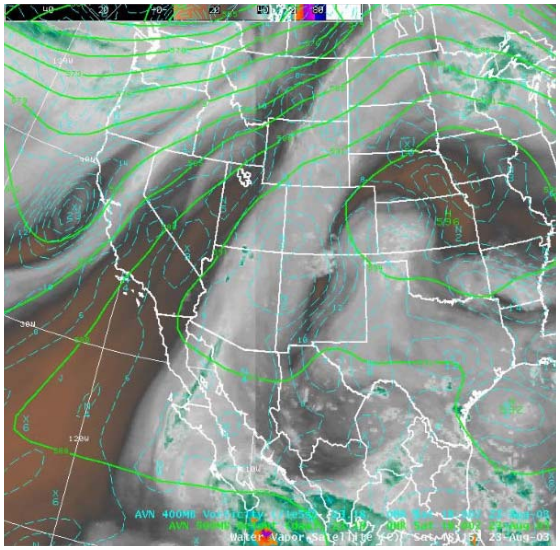

*Fig. 6. GOES Water Vapor Imagery – 1800 UTC 23 August 2003. GFS 400 mb Height/Vorticity analysis*

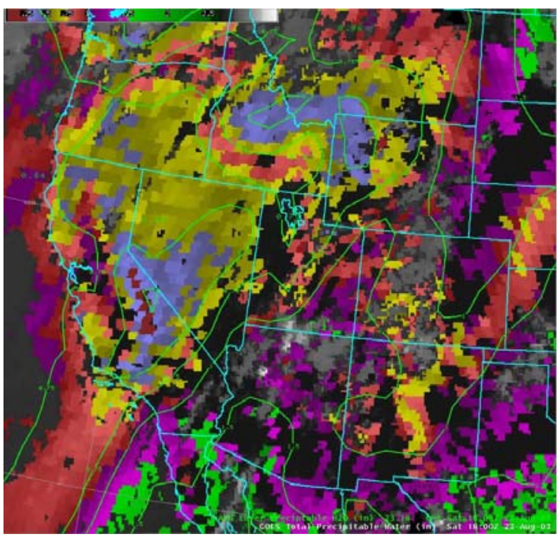

*Fig. 7. GOES Precipitable Water Image – 1800 UTC 23 August 2003. GFS Precipitable water analysis overlaid.*

weak mid-level winds – producing very slow-moving cells with heavy rain – the vertical shear profile was conducive to cell backbuilding and training.

### *3.2 Overview of Convective Development*

By early afternoon, relatively weak convection was decreasing over extreme southern Utah, and subsequently developed further north over higher terrain – depicted by GOES visible satellite imagery at 2000 UTC 23 August 2003 (Fig. 8). A closer examination of this activity in its early stages is shown in figure 9, displaying the composite

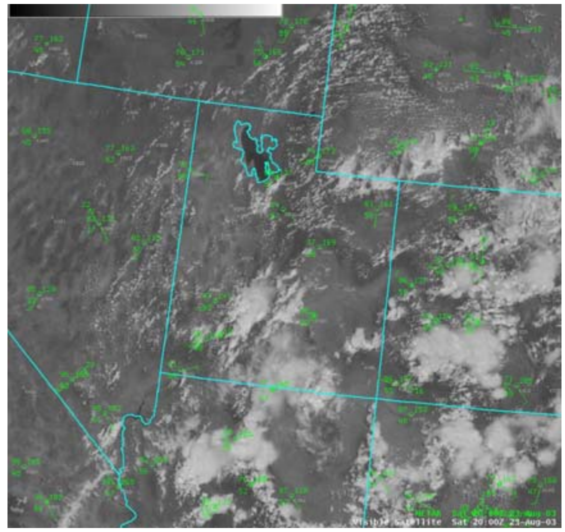

*Fig. 8. GOES Visible Image from 2000 UTC 23 August 2003.*

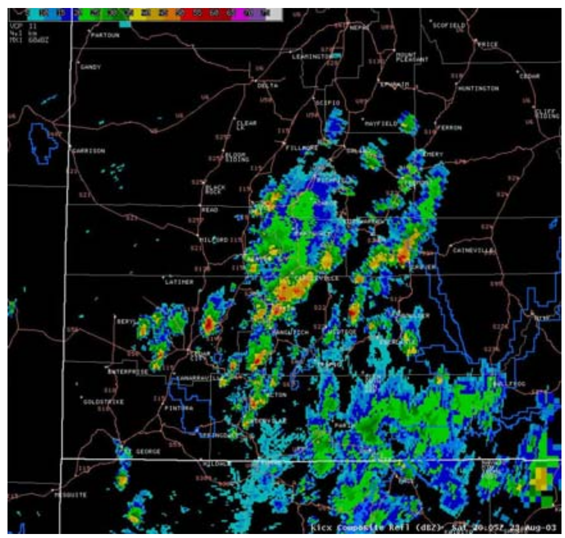

*Fig. 9. KICX Composite Reflectivity at 2005 UTC 23 August 2003.*

reflectivity detected by the Cedar City, Utah (KICX) WSR-88D at 2005 UTC 23 August 2003. The remainder of this paper will focus on two areas of heavy precipitation – one that produced a flash flood and another that did not. The use the RFFPI to complement WSR-88D and FFMP information will be given.

### *3.3 Considering the Flash Flood Potential In and Around North Creek*

At 2035 UTC 23 August 2003, a strong thunderstorm cell was moving through the North Creek drainage that feeds into the upper stretches of the Escalante River flowing through Escalante State Park in south central Utah (Fig. 10). WSR-

88D storm total amounts for this storm were between 1.5 and 2.0 inches up to this time (Fig.11).

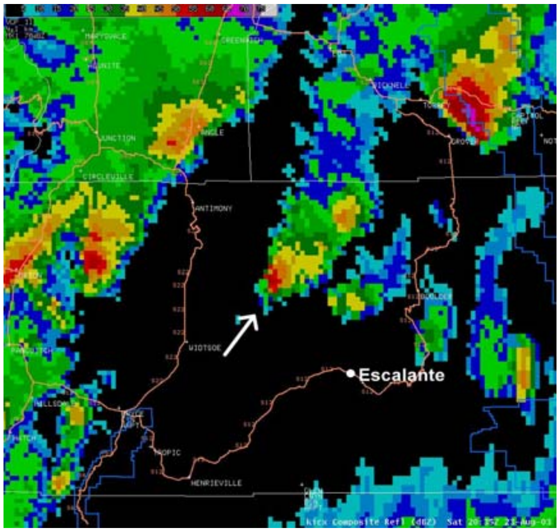


*Fig. 10. KICX Composite Reflectivity (dBZ) at 2035 UTC 23 August 2003.*

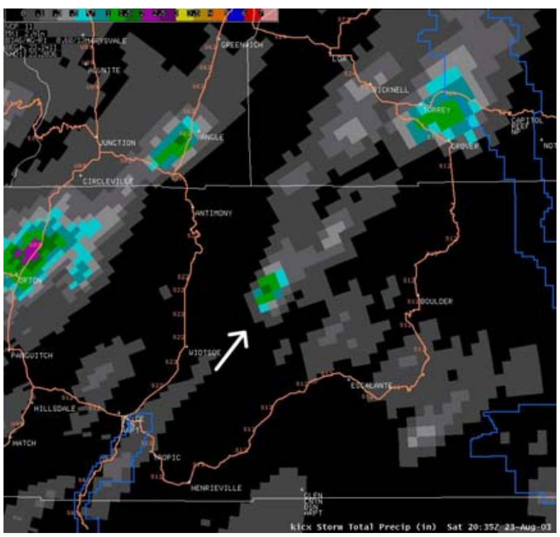

*Fig. 11. KICX Storm Total (inches) at 2035 UTC 23 August 2003. Arrow pointing to accumulations impacting North Creek basins.*

Meanwhile, the FFMP program at this time was indicating that two North Creek basins had received over an inch of rainfall (i.e., ABR) in the last hour (Fig. 12). These same basins were also receiving rainfall at a rate of 2.01 (#4671) and 1.44 (#1563) inches per hour, respectively. Further examination of the flash flood potential using the FFMP Flash Flood Analysis graph for basin #4671 showed the FFG was exceeded by over a half an inch (Fig. 13).

The RFFPI for this area (Fig. 14) indicates however, that the physiographic make up of these basins – which are on the eastern slope of the Escalante Mountains in the Dixie National Forest – is not conducive to supporting flash flood conditions (RFFPI between 2.8 and 3.2 on a 1-10 scale). This is primarily due to their forested character, and despite being located on a slope. Although FFG was exceeded at that time, the consideration of the RFFPI influenced the decision not to issue a flash flood warning for this thunderstorm. No reports of flash flooding – either within North Creek or downstream into the Escalante River – were received, including from the relatively rich spotter database in and around Escalante State Park and the town of Escalante itself.

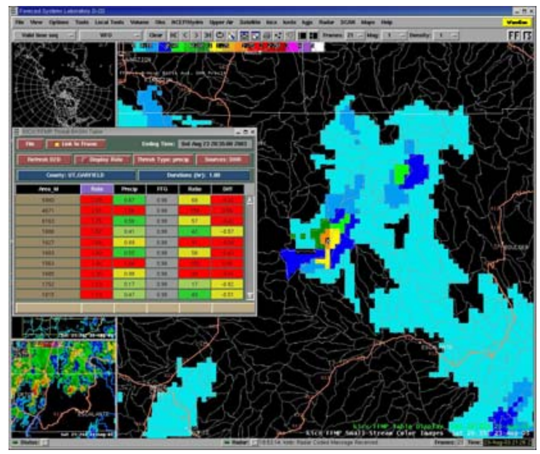

*Fig. 12. FFMP Threat Table and plan view ABR (1 hr) at 2035 UTC 23 August 2003.*

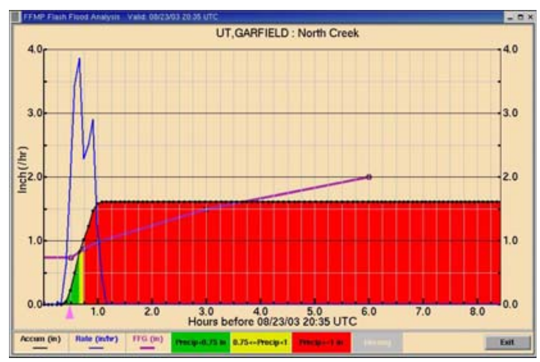


*Fig. 13. FFMP Flash Flood Analysis graph for North Creek basin # 4671 at 2035 UTC 23 August 2003.*

### *3.4 The Capitol Reef National Park Flash Flood*

Figure 15 shows the composite reflectivity image from KICX at 2040 UTC 23 August 2003. A strong thunderstorm was moving east – also moving to the right of the area mean storm motion – as it approached the northern areas of Capitol Reef National Park (NP). Further making this a dangerous situation is the fact that this cell was moving downstream and along the drainages feeding the Fremont River, which runs nearly parallel to Utah State Highway 24 through the park. The KICX PPS algorithm calculated peak STP amounts from this cell of 1.0 to 1.5 inches (Fig. 16).

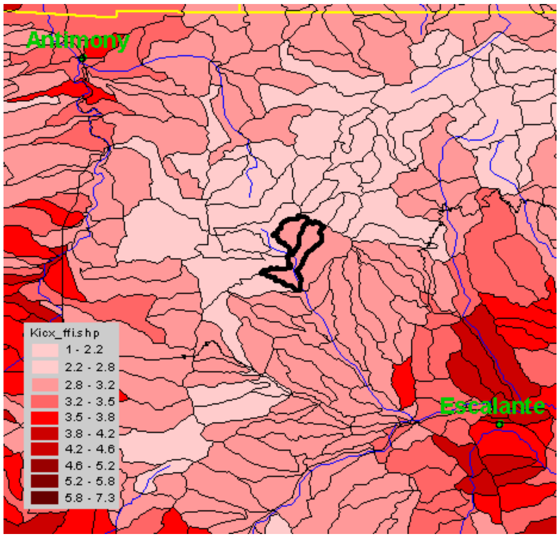


*Fig. 14. RFFPI for area in around North Creek basins. Basins experiencing highest 1 hr rainfall accumulation and rate (see Fig. 12) are highlighted in black.*

Peak ABR from FFMP at 2040 UTC 23 August 2003 (Fig. 17) was between 1.25 and 1.50 inches over a one hour time period in a basin of Sulphur Creek, and feeding the Fremont River in the northwest fringe of Capitol Reef NP. When

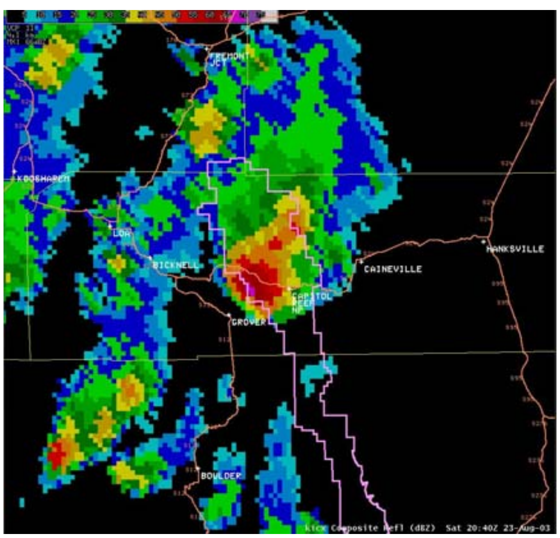


*Fig. 15. KICX composite reflectivity (dBZ) at 2040 UTC 23 August 2003*

ranking basins by rainfall rate and clicking on a basin of interest in the threat display window – a useful feature of FFMP – this shifts the FFMP display map to center the "X" on the that basin. This is depicted by the "X" in figure 17, where the display shows that the basin with the highest rainfall rate was actually displaced from the basin with the highest ABR, yet still along the Fremont River. The Flash Flood Analyses graph at this time for Sulphur Creek basin #4338 (Fig. 18) shows it received nearly 1.5 inches of rainfall over an hour, while also experiencing a rainfall rate of nearly 4 inches per hour just prior.

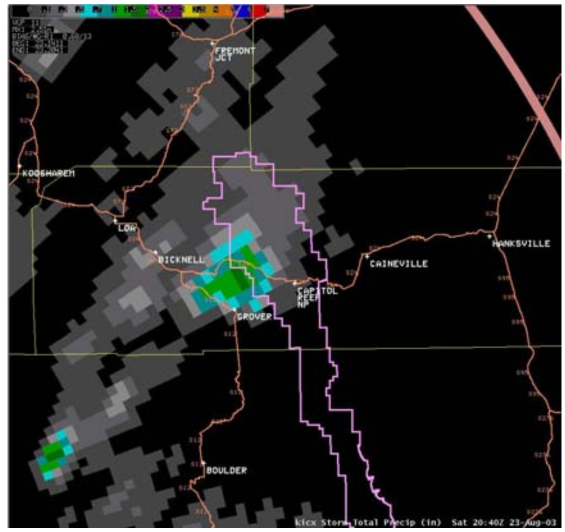


*Fig. 16. KICX Storm Total (inches) at 2040 UTC 23 August 2003*

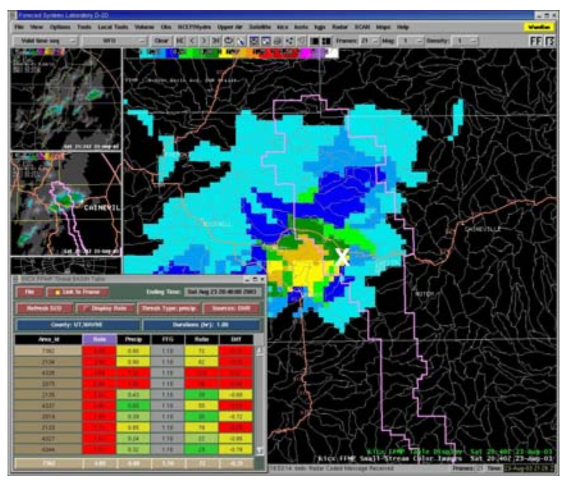


*Fig. 17. FFMP plan view ABR (1 hr) at 2040 UTC 23 August 2003. "X" is positioned on basin with heaviest rainfall rate at this time.*

The physiographic character of basins in and around this area of Capitol Reef NP is vividly depicted by the RFFPI in figure 19. The area, which is characterized by dry washes and narrow, steep slick rock canyons, is particularity susceptible to flash flooding – just as occurred in this case. This

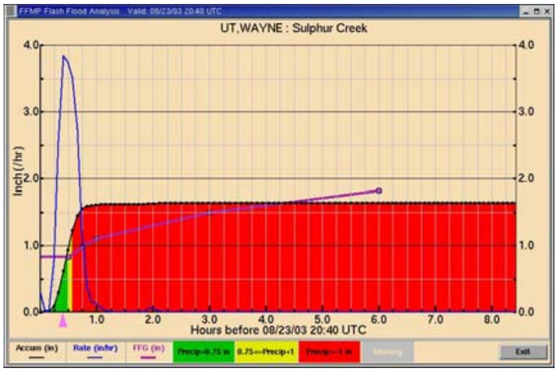


*Fig. 18. Flash Flood Analysis Graph for Sulphur Creek Basin (#4338) at 2040 UTC 23 August 2003*

high RFFPI near the cell of interest, and especially downstream from the area of heavy rainfall, provided the warning forecaster with valuable information to use in the flash flood warning decision making process.

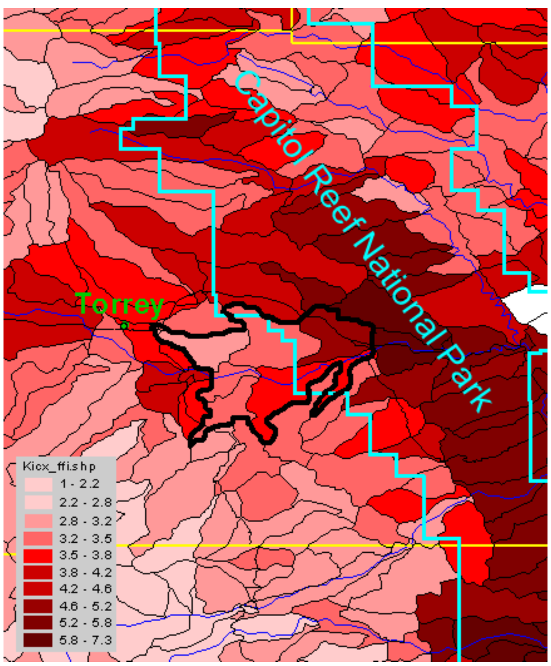


*Fig. 19. RFFPI for area in and around Capitol Reef National Park. Black outline shows basins with heaviest rainfall and rainfall rate.*

A flash flood warning was issued at 2041 UTC 23 August 2003 for Western Wayne County in Utah, including for areas along the Fremont River in and near Capitol Reef NP, effective until 2245 UTC. Utah State Highway 24 was closed from Caineville to Capitol Reef NP due to near bankfull conditions along the Fremont River which is fed from the Sulphur and Deep Creek drainages. Water was also reported across Highway 24 in several locations, along with reports of boulders being carried across the highway. Later that evening at approximately 0000 UTC 24 August 2003, a river gauge along the Fremont River in Caineville – located just downstream from Capitol Reef NP – recorded a 7 ft rise and a volume flow increase of nearly 10000 cubic feet per second (Fig. 20).

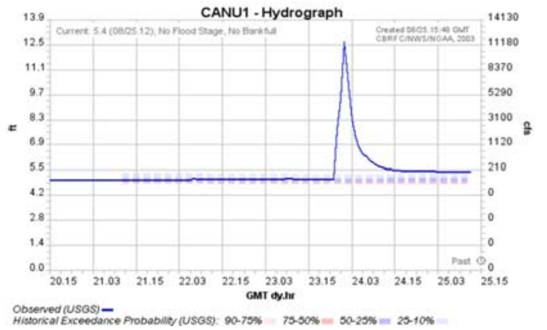


*Fig. 20. Fremont River hydrograph for gauge near Caineville, Utah – ending at 1500 UTC 25 August 2003.*

## 4. CONCLUSIONS AND FUTURE WORK

A summary of flash flood warning decision making tools currently available to NWS Weather Forecast Offices has been discussed, with emphasis on the use of WSR-88D and FFMP. Deficiencies in FFMP – especially in the derivation of the Flash Flood Guidance (FFG) used in FFMP – limit its use in the complex terrain and semi-arid climate of the intermountain West. To address these limitations, the NWS CBRFC has developed an index intended to indicate the severity of flash flood potential termed the Relative Flash Flood Potential Index (RFFPI), designed to better represent the physiographic character of underlying basins in FFMP. The southern Utah flash flood events 23-24 August 2003 have been presented to demonstrate the valuable utility of the RFFPI as flash flood warning guidance.

Future plans to enhance RFFPI most notably include the addition of dynamic layers, including the indication of soil moisture – whereby a gridded output from the Multi-Precipitation Estimator (MPE) is used as a possible source. Other improvements include incorporating a finer resolution DEM for deriving slope information, inclusion of a more comprehensive vegetation type data layer, attempts to improve upon the resolution of the soil type dataset used, and development of a method for regular incorporation of new fire event information as well as a process for removing the affects of fire as an area re-vegetates.

The ability to display the RFFPI on the current AWIPS platform – removing the ArcView requirement – will also be explored. However, system infrastructures may severely limit this effort. Finally, an important goal of generating finer resolution FFG from the RFFPI output will continue to be pursued. This is possible through developing statistical relationships between observed historical flash flood event data and fine resolution RFFPI indices. The lack of a reliable historical flash flood event database makes building this relationship more difficult. Much of the historical event information must be manually acquired and input into a database prior to this part of the analysis moving forward.

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