J1.2 LOCALLY MODIFYING FLASH FLOOD GUIDANCE TO IMPROVE THE DETECTION CAPABILITY OF THE FLASH FLOOD MONITORING AND PREDICTION PROGRAM

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1. INTRODUCTION

The Flash Flood Monitoring and Prediction (FFMP) program of the National Weather Service (NWS) compares Average Basin Rainfall (ABR) with Flash Flood Guidance (FFG) to determine the potential occurrence and severity of flash flooding in pre-defined watersheds (Davis 2003). The watersheds used by FFMP are the original basins provided by the National Basin Delineation (NBD) project, or a locally customized version of the original NBD data set (Davis et al. 2003).

With the spring 2003 release of FFMP version 2.1, each NWS office can locally modify the FFG produced by the River Forecast Center (RFC) used by FFMP. The detection capability of FFMP can be improved if the FFG can be modified to more closely approximate the actual hydrologic condition of the watershed. The editing of FFG is accomplished with a command line text editor. A graphical user interface will replace the command line editor in the spring of 2004 (http://www.nws.noaa.gov/mdl/ffmp).

The purpose of this paper is to show how FFG can be modified to improve the flash flood detection capability of FFMP. Flash flood case studies will demonstrate various scenarios where modified FFG will aid in the issuance of FFMP based warnings.

2. THE ROLE OF FFG IN FFMP

The purpose of FFG is to estimate the amount of runoff produced by the observed ABR in a watershed. The ABR multiplied by the area of the watershed is the volume of water that has been deposited on the watershed. Some ABR evaporates, some is intercepted by vegetation, or surface detention, and some infiltrates into the soil. The remainder of the ABR flows as surface runoff directly into streams. The surface runoff produces the rapid rise in the stream level that causes the flash flooding (Davis 2001).

The RFC computation of FFG given by

$$FFG = TR + SM, \quad (1)$$

where FFG = flash flood guidance (mm) for a specific period of time (1-hour, 3-hour, or 6-hour), TR = a constant value of threshold runoff (mm), and SM = a factor based on the soil moisture content of the soil, i.e. a measure of soil infiltration capacity (mm).

The FFG computation is based on the following assumptions: [1] The stream is at low flow levels when runoff begins. [2] A constant value of threshold runoff is based on each stream's hydrologic parameters. The threshold runoff is defined as the amount of runoff needed to bring the stream from low flow to a bank full condition, i.e. the amount of runoff needed to initiate flooding. [3] The ABR is distributed evenly in time and space across the watershed segment. [4] No additional ABR has occurred in the watershed since the last data cutoff (0000 UTC, or 1200 UTC) for rainfall input (ABR) into the RFC hydrologic model. [5] The soil moisture accounting of the RFC hydrologic model is assumed to be representative of the soil moisture condition of each defined FFMP basin. The "Mean Areal Precipitation" (MAP) basins used in the RFC soil moisture accounting computation are much larger in area (200-1000 km^2) than the FFMP basins (5 to 50 km^2). If these assumptions are no longer valid, the FFG should be modified to more accurately reflect the hydrologic condition of the watershed.

The NWS RFC updates the FFG every 12 hours. The rainfall input for the FFG update is cut off at 0000 UTC and 1200 UTC. The FFG becomes available to the

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NWS forecast offices 4-5 hours after the data cutoff times, by 0500 UTC or 1700 UTC after the completion of the hydrologic model runs.

The role of FFG in FFMP is to estimate the potential for flash flooding by subtracting FFG from the ABR for each defined watershed segment. The difference between ABR and FFG is a direct estimate of the amount of runoff that contributes to a stream rising above a bank full level (Davis 2002b). The difference between ABR and FFG can be represented by a Flash Flood Index (FF-Index), defined by,

$$FF = 0.03937\ (ABR - FFG), \qquad (2)$$

both ABR and FFG are in mm (Davis 2002b). The FF-Index appears in the "FFMP Threat Basin Table" as a "Diff" column and is defined as the difference between ABR and FFG in inches. The coefficient in (2) converts the ABR/FFG difference in mm to inches.

Reference values of FF-Index can be defined for specific values of ABR-FFG difference. Table 1 shows FF-Index reference values that will be used in the case studies to follow. The FF-Index reference values are universal for any size watershed, provided the FFG is valid for the given watershed.

Table 1. FF Index reference values and the corresponding runoff that will contribute to a stream rise above a bank full condition.

FF-Index Reference	Runoff (in)	Runoff (mm)
FF0 (FF=0.00)	0.00	0.00
FF0.5 (FF=0.50)	0.50	12.7
FF1 (FF=1.00)	1.00	25.4
FF1.5 (FF = 1.50)	1.50	38.1
FF2 (FF=2.00)	2.00	50.8
FF3 (FF=3.00)	3.00	76.2
FF4 (FF=4.00)	4.00	101.6
FF5 (FF=5.00)	5.00	127.0

A negative value of FF-Index indicates the amount of ABR needed to bring the stream to a bank full condition. Historical case studies at the NWS Pittsburgh, PA (PBZ) office have demonstrated that minor flooding occurs at FF-Index reference values near FF0, significant flash flooding occurs at values near FF1, serious flash flooding occurs at FF2, and disastrous flash flooding at levels of FF3 or higher. These thresholds will likely vary for different areas of the United States based primarily on physical basin characteristics. Higher FF-Index values may be needed in areas of relatively flat terrain to produce similar flash flood severity.

3. MODIFY FFG USING HISTORY OF ABR

The RFC river forecast model uses a 6-hour MAP rainfall to update the variable soil moisture component of the FFG. Each 12-hour update of the FFG is computed using two 6-hour MAP values. If a small FFMP basin receives less ABR than the computed MAP value for a six-hour period FFG may be too low. When the observed ABR in the FFMP watershed is greater than the rainfall computed for the MAP, the FFG might be too high. The computation of the difference between MAP and ABR can be accumulated over a period of several days to estimate if the FFG as computed by the RFC is representative of the soil moisture conditions in the small FFMP basin.

The procedure for updating the FFG using the comparison of MAP and ABR is demonstrated by a case study for the flash flood on 20 June 2003 in the city of Washington, PA. Significant flash flooding

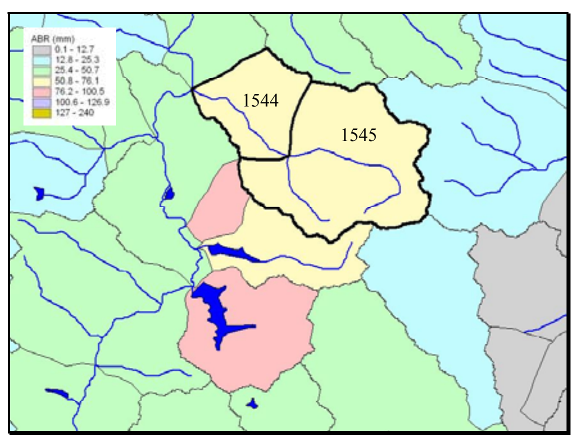

Fig. 1. Six-hour ABR in Washington County, PA on 20 June 2003 from 1700 to 2300 UTC. Black outline shows the Catfish Run Watershed, AMBER basins 1544 + 1545 (Area 12.4 km^2). Blue lines are streams and lakes. AMBER basin identification numbers in black.

occurred on the Catfish Run watershed around 2200 UTC. The six-hour ABR ending at 2300 UTC for a portion of Washington County, PA is shown in fig. 1. Catfish Run flows through the city of Washington and is broken into upstream (1545) and downstream (1544) basins in the FFMP database. Most of the Washington urban area is contained in basin 1544.

Examine the FFG for the headwaters of Catfish Run (basin 1545) shown in Table 2 for the 72 hours leading up to the flash flood event. The FFMP FFG from the RFC should remain constant or rise slightly if no rainfall is observed in the MAP area that contains the headwaters of Catfish Run. Figure 2

Table 2. FFMP FFG for the Catfish Run headwaters, AMBER basin 1545, in Washington County, PA.

June 2003 Day/UTC	1hr FFG (mm)	3hr FFG (mm)	6hr FFG (mm)
17/1200z	38.1	50.8	55.9
18/0000z	22.9	35.6	38.1
18/1200z	27.9	40.6	45.7
19/0000z	30.5	43.2	45.7
19/1200z	22.9	33.0	38.1
20/0000z	27.9	38.1	43.2
20/1200z	30.5	40.6	45.7
21/0000z	17.8	30.5	35.6

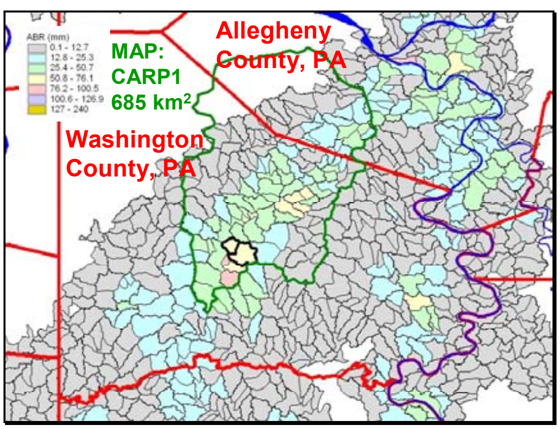

Fig. 2. Six-hour ABR in Washington County, PA on 20 June 2003 from 1700 to 2300 UTC. Dark green line shows the Carnegie (CARP1) MAP. The black outline shows the Catfish Run Watershed (Area 12.4 km^2). Red lines are county boundaries.
Blue lines are major rivers.

shows the Carnegie MAP area that contains Catfish Run.

The rainfall used in the RFC model to update the MAP soil moisture computation is shown in Table 3 for the Carnegie MAP area. If significant rainfall is observed in the Carnegie MAP area, then FFG should fall by some amount equal to or less than the observed MAP rainfall for the 12 hour period since the last FFG update, barring hydrologic model adjustments.

If the rainfall in the Carnegie MAP equals the Catfish Run ABR, then the updated FFG should be representative of the soil moisture conditions in Catfish Run. If the ABR in Catfish Run is significantly higher (lower) than the Carnegie MAP rainfall, then the FFG may be too low (too high). The amount of "FFG modification" (FFGMOD) can be estimated by subtracting the ABR for basin 1545 from the Carnegie MAP rainfall. The FFGMOD computation is give by

$$FFGMOD = MAP - ABR. \quad (3)$$

The FFGMOD values are then summed through a minimum of 72 hours (Table 3) to create a running value of FFGMOD. The FFGMOD value is basin specific for each FFMP basin, based on the ABR for that

Table 3. MAP, ABR, and FFGMOD for the Catfish Run watershed, AMBER basin 1545, in Washington County, PA.

June 2003 Day/UTC	CARP1 MAP (mm)	1545 ABR (mm)	FFGMOD (mm)
17/12-18z	6.4	2.3	4.1
17/18-00z	4.1	0.3	7.9
18/00-06z	2.8	0.8	11.9
18/06-12z	0.0	0.0	11.9
18/12-18z	0.0	0.0	11.9
18/18-00z	0.0	0.0	11.9
19/00-06z	0.0	0.0	11.9
19/06-12z	0.0	0.0	11.9
19/12-18z	0.3	0.0	12.2
19/18-00z	0.0	0.0	12.2
20/00-06z	0.0	0.0	12.2
20/06-12z	0.0	0.0	12.2
20/12-18z	0.0	0.0	12.2
20/18-00z	12.7	63.5	-38.6
21/00-06z	3.0	2.5	-33.6
21/06-12z	0.0	0.0	-33.6

basin. All basins contained in the Carnegie MAP area would use the CARP1 MAP values for the FFGMOD computation.

A positive value of FFGMOD indicates that the FFG may be too low (FFGMOD could be added to FFG), while a negative value of FFGMOD indicates the FFG may be too high (FFGMOD could be subtracted from FFG). The computation of FFGMOD should be done for each FFMP basin to see if representative rainfall went into the FFG update for each basin.

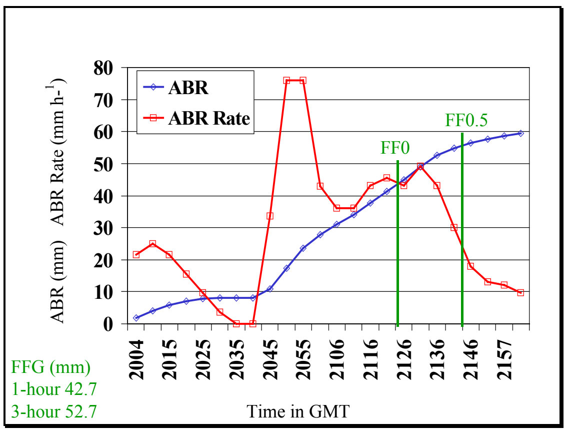

Fig. 3. FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 20 June 2003 from 2004 to 2203 UTC in the Catfish Run (1) watershed (Area 8.9 km^2). Green line shows the time of Flash Flood Index value FF0.

The FFMP software produces a line plot of accumulated ABR, FFG, and ABR Rate for each defined FFMP basin. Figure 3 shows a plot similar to the FFMP display of the accumulated ABR (blue line) and ABR Rate (red line). The blue ABR trace is a time accumulation of the observed 5-6 minute ABR amounts. A blue diamond is plotted at the observation time of each 5-6 minute ABR value. The red ABR Rate curve shows the 5-6 minute ABR amount converted to a one-hour rate. Red squares are plotted for each 5-6 minute observation. At 2055 UTC the ABR Rate is 76 mm h^{-1}. The ABR Rate is computed from the five minute ABR amount (6.33 mm) from 2050 UTC to 2055 UTC. If the five-minute rate of ABR continued for one hour, 76 mm of ABR would accumulate. Flash floods occur where high ABR Rates persist for a significant period of time. The "rain burst" was defined by (Davis 2003), as a minimum of three consecutive 5-6 minute WSR-88D volume scans with ABR Rates >25.4 mm h^{-1}. Figure 3 shows a "rain burst" of twelve consecutive observations from 2045 UTC to 2141 UTC with rates above 25 mm h^{-1}. This burst of rainfall produced the flash flood in Catfish Run.

The FFG value is shown in green in the lower left hand corner of Fig. 3. The RFC FFG of 30.5 mm (Table 2) may be 12.2 mm too low based on the FFGMOD computation in Table 3. The 1-hour FFG has been changed to a value of 42.7 based on the FFGMOD.

The time of occurrence of the FF-Index reference values may be plotted on the ABR plot. The FF0 level (green line) is plotted for accumulated ABR (blue line) equal to the 1-hour FFG value of 42.7 mm. The FF1 level would be plotted as a second green line if the accumulated ABR reaches a value of 68.1 mm (25.4 mm, or one inch over the 1-hour FFG). Since the FF1 level is not reached (ABR peaks near 59 mm), significant flash flooding should not be expected, but minor flooding may result. However, significant flash flooding did occur along Catfish Run (see section 4.1).

4. LOWER FFG IN URBAN BASINS

Urbanization of watersheds results in reduced infiltration rates due to paving of roads and parking lots, and the construction of homes and businesses. FFG should be lowered in all FFMP watersheds with a high percentage of urbanization (Davis 2000b). The NWS PBZ office has had good success using a maximum 1-hour FFG of 25.4 mm for all urbanized watersheds. Since less rainfall is needed to flood highly urbanized watersheds, the same urban watersheds tend to flood more frequently than their more rural counterparts.

The local modification of FFG provides three major advantages to the flash flood warning scenario. First, the lowering of the FFG can result in a significant increase in warning lead-time, the time from the warning issuance until the time of the observed flooding. Lead-time is critical in a flash flood event, as the local police or emergency management officials must have time to close roads and possibly evacuate residents in danger. Second, the decision to warn, or not to warn, can be improved dramatically if the FFG is changed to a more hydrologically correct value. And third, the severity of flash flooding, as measured by the FF-Index can be estimated in near real time. The case studies that follow will demonstrate these potential gains in lead-time, warning detection, and flash flood severity.

4.1 Washington, PA Flash Floods

On 20 June 2003 significant flash flooding occurred in the both the headwaters portion of Catfish Run (1545) and the Washington, PA urban area (1544). Cars were stranded in several major intersections in the city of Washington. The headwaters portion of Catfish Run suffered significant flood damage as well. The upstream segment of Catfish Run (1545) contains two separate streams that join at the location of the Washington and Jefferson College football stadium. During the 20 June 2003 flash flood the newly installed artificial surface at the stadium was covered with several feet of water, resulting in significant damage to the new surface. Flood damage also occurred in the newly constructed team dressing rooms. On 9 July 2003 both the city of Washington and the athletic facilities at Washington and Jefferson college were flooded for a second time when almost two inches of rain fell in less than 30 minutes on the same areas of Catfish Run.

By locally modifying the FFG for the highly urbanized Catfish Run watershed, the NWS PBZ office was able to successfully warn for both of these significant flash floods. Without the local modification of FFG, FFMP would not have supported a warning issuance for these urban floods.

Figure 4 shows the same ABR, ABR Rate plot (as in Fig. 3) using the urban adjusted FFG of 25.4 mm. The drop in 1-hour FFG from 42.7 mm to 25.4 mm results in FF0 level being reach at 2100 UTC instead of 2126 UTC, about 25 minutes earlier. The FF-Index, a measure of flash flood severity, exceeded the FF1 level, indicating significant flash flooding is likely. If the original FFG had been used for these watersheds in FFMP, warnings may not have been issued.

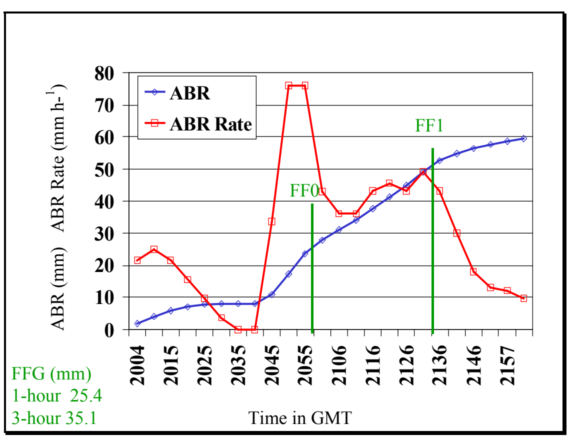

Fig. 4. Modified FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 20 June 2003 from 2004 to 2203 UTC in the Catfish Run (1) watershed. Green lines show the time of Flash Flood Index values (0 to 1).

4.2 Franklin, PA Flash Floods

Similar flash floods have been observed in many cities in the NWS PBZ county warning area (CWA). The city of Franklin, PA in Venango County suffered a similar fate in the summer of 2003 with multiple floods in the Chubb Run watershed.

Chubb Run has experienced a string of flooding events beginning with a severe flash flood in 1996. On 19 July 1996, Route 8 was completely washed out where Chubb Run crosses under the highway near the city of Franklin (Davis 2000a). A sandwich shop

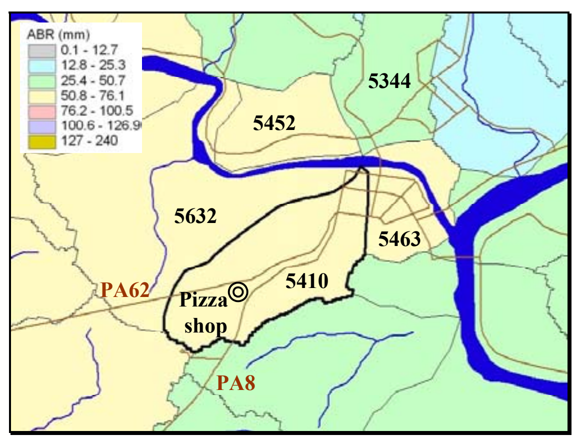

Fig. 5. Six-hour ABR in Venango County, PA on 16 August 2003 from 1700 to 2300 UTC. Black outline shows the Chubb Run Watershed (Area 3.2 km^2). Blue lines are rivers and streams. Brown lines are roads. AMBER basin identification numbers in black.

in the headwaters of Chubb Run was flooded on 21 Jun 2001 with water up to the hoods of the automobiles in the parking lot (Davis 2002a). This same sandwich shop, reopened as a pizza shop (Fig. 5) in the spring of 2003, was damaged during the 16 August 2003 flash flood. The shop was more severely damaged on 26 August 2003 with the second round of flooding in Chubb Run.

Table 4. FFMP FFG for the Chubb Run watershed, AMBER basin 5410, in Venango County, PA.

August 2003 Day/UTC	1hr FFG (mm)	3hr FFG (mm)	6hr FFG (mm)
13/1200z	38.1	50.8	53.3
14/0000z	40.6	50.8	55.9
14/1200z	40.6	53.3	58.4
15/0000z	43.2	55.9	58.4
15/1200z	43.2	55.9	61.0
16/0000z	45.7	55.9	61.0
16/1200z	45.7	58.4	63.5
17/0000z	33.0	45.7	48.3

Table 5. MAP, ABR, and FFGMOD for the Chubb Run watershed, AMBER basin 5410, in Venango County, PA.

August 2003 Day/UTC	FRKP1 MAP (mm)	5410 ABR (mm)	FFGMOD (mm)
13/12-18z	0.0	0.0	0.0
13/18-00z	0.0	0.0	0.0
14/00-06z	0.0	0.0	0.0
14/06-12z	0.0	0.0	0.0
14/12-18z	0.0	0.0	0.0
14/18-00z	0.0	0.0	0.0
15/00-06z	0.0	0.0	0.0
15/06-12z	0.0	0.0	0.0
15/12-18z	0.0	0.0	0.0
15/18-00z	0.0	0.0	0.0
16/00-06z	0.0	0.0	0.0
16/06-12z	0.0	0.0	0.0
16/12-18z	4.8	0.0	4.8
16/18-00z	8.9	55.9	-51.1
17/00-06z	3.8	1.3	-48.6
17/06-12z	0.0	0.0	-48.6

The Franklin (FRKP1) MAP area containing the Chubb Run watershed received no rainfall in the 72 hours leading up to the flood (Table 5). About 5 mm of rainfall was observed in the FRKP1 MAP area during the morning of the event, this rainfall would not be reflected in the FFG until the 0000 UTC model run at the RFC.

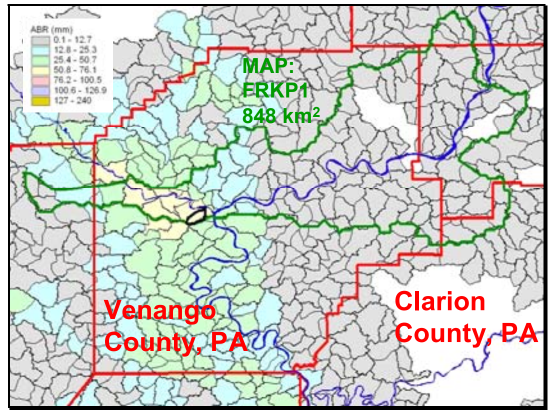

Fig. 6. Six-hour ABR in Venango County, PA on 16 August 2003 from 1700 to 2300 UTC. Dark green line shows the Franklin, PA (FRKP1) MAP area. Black outline shows the Chubb Run Watershed (Area 3.2 km^2). Red lines are county boundaries. Blue lines are major rivers.

Figure 6 shows the six-hour ABR across Venango County during the flooding event. The Chubb Run watershed highlighted in black shows over 50 mm of rainfall occurred in the basin. Figure 5 shows an expanded view of the watershed contained in the Franklin urban area. The heart of the Franklin business district is contained in basin 5463 and the downstream half of basin 5410.

Figure 7 shows the plot of ABR and ABR Rate for Chubb Run during the 20 June 2003 event using the FFMP FFG from the RFC. Notice the FF0 state is reached about 2227 UTC. The FF1 level would be reached at an ABR of 71.1 mm, but the ABR accumulation only reaches about 55 mm. This level of FF-Index indicates only minor flooding problems, and would probably not result in a flash flood warning.

The Chubb Run watershed is highly urbanized and contains very steep terrain. The fixed urban FFG of 25.4 mm is always used for this watershed in FFMP. Figure 8 shows the ABR/ABR Rate plot of Fig. 7, using the reduced urban FFG value of 25.4 mm. The FF0 state is now reached at 2212 UTC, about 15 minutes earlier than shown in Fig. 7 using the standard FFG. The intensity

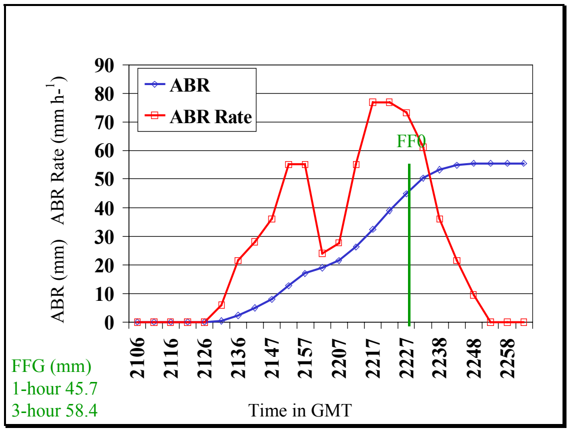

Fig. 7. FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 16 August 2003 from 2304 to 2203 UTC in the Chubb Run watershed. Green lines show the time of Flash Flood Index value FF0.

of the flooding reaches the FF1 state, indicating substantial flash flooding may be occurring. Using the urbanized FFG resulted in the timely issuance of a flash flood warning for Venango County and the city of Franklin.

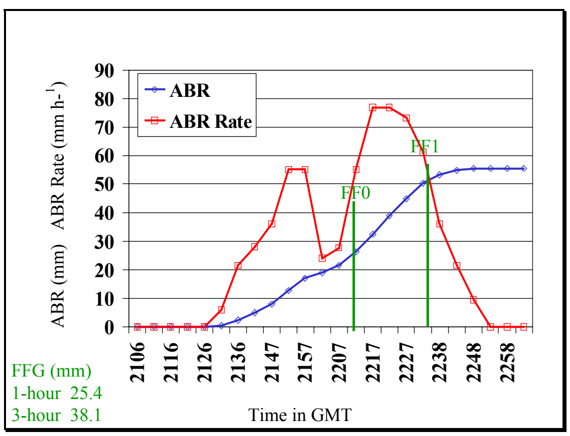

Fig. 8. Modified FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 16 August 2003 from 2203 to 2304 UTC in the Chubb Run watershed. Green lines show the time of Flash Flood Index values (FF0-FF1).

Flooding reports on the 26 August 2003 flash flood in Venango County indicate the flooding was significantly more severe than the flooding observed on 16 August 2003. Looking at the plot of ABR and ABR rate for the two hours of the peak of the flooding shortly after 1300 UTC (Fig. 9), slightly less ABR seems to have occurred than the flooding observed on 16 August 2003.

Table 6. FFMP FFG for the Chubb Run watershed, AMBER basin 5410, in Venango County, PA.

August 2003 Day/UTC	1hr FFG (mm)	3hr FFG (mm)	6hr FFG (mm)
23/1200z	48.3	61.0	63.5
24/0000z	48.3	61.0	66.0
24/1200z	50.8	61.0	66.0
25/0000z	50.8	63.5	68.6
25/1200z	50.8	63.5	68.6
26/0000z	50.8	63.5	68.6
26/1200z	35.6	48.3	53.3
27/0000z	17.8	30.5	35.6

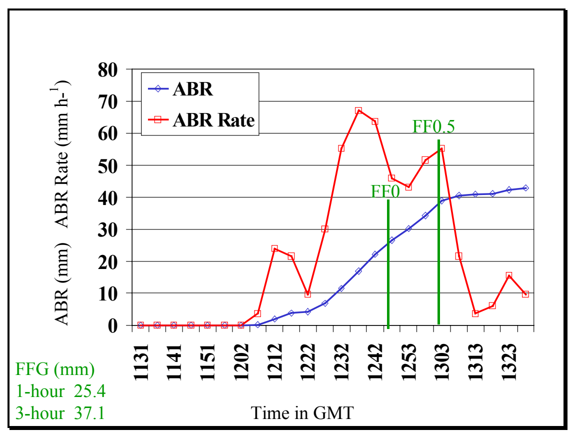

Fig. 9. Modified FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 26 August 2003 from 1131 to 1328 UTC in the Chubb Run watershed. Green lines show the time of Flash Flood Index values (FF0 to FF0.5).
for 16 August 2003 (Fig. 8).

Examination of the ABR history for Chubb Run explains this apparent disparity. Table 6 shows the FFMP FFG leading up to the flash flood event. FFG fell to 35.6 mm at 1200 UTC on 26 August 2003, but recall that the NWS office does not receive the updated FFG until about 1700 UTC. The FFG in use at 1300 UTC was the 0000 UTC FFG for 26 August 2003.

Significant rainfall occurred in the Chubb Run watershed (5410) between 0000 UTC and 1200 UTC (Fig. 10) on 26 August 2003. The ABR history in Table 7 shows that

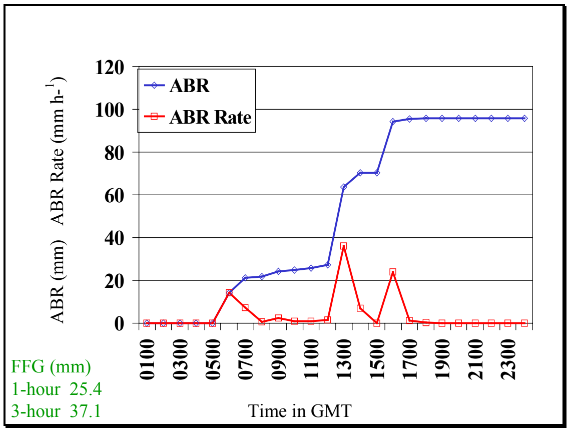

Fig. 10. ABR sum (mm), and ABR Rate (mm h^{-1}) on 26 August 2003 from 0100 UTC to 27 August 2003 at 0000 UTC in the Chubb Run watershed.

27.4 mm of ABR is not accounted for in the 26 August 2003 0000 UTC FFG. The urban 1-hour FFG value of 25.4 mm is used for the Chubb Run watershed. The rain ending at 1200 UTC saturated the soil, and the stream was at high flow levels by 1200 UTC. In this scenario, the effective 1-hour FFG is close to zero. Additional rainfall will most likely be converted directly to runoff.

Table 7. MAP, ABR, and FFGMOD for the Chubb Run watershed, AMBER basin 5410, in Venango County, PA.

August 2003 Day/UTC	FRKP1 MAP (mm)	5410 ABR (mm)	FFGMOD (mm)
23/12-18z	0.0	0.0	0.0
23/18-00z	0.0	0.0	0.0
24/00-06z	0.0	0.0	0.0
24/06-12z	0.0	0.0	0.0
24/12-18z	0.0	0.0	0.0
24/18-00z	0.0	0.0	0.0
25/00-06z	0.0	0.0	0.0
25/06-12z	0.0	0.0	0.0
25/12-18z	0.0	0.0	0.0
25/18-00z	0.0	0.0	0.0
26/00-06z	0.8	14.2	-13.4
26/06-12z	8.1	13.2	-18.5
26/12-18z	30.2	68.3	-56.6
26/18-00z	1.3	0.0	-55.3
27/00-06z	0.0	0.0	-55.3
27/06-12z	0.0	0.0	-55.3

Figure 11 shows a modified version of Fig. 9 with the FFG reduced to near zero. The FF-Index now reaches past the FF1 level indicating that significant flash flooding is likely to occur. Note that the FF-Index reaches over the FF1.5 level, a greater intensity than the FF1 level reached during the storm on 16 August 2003.

The intensity of flash flooding can be greatly enhanced by the same amount of ABR when the ground becomes saturated and the stream at a high flow level before the onset of the heavy rainfall burst. These multiple rainfall events may not be taken care of by FFG if the preceding rainfall occurs before the updated FFG is received.

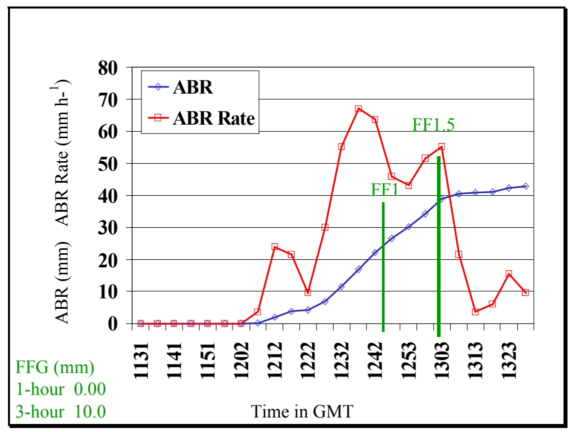

Fig. 11. Modified FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 26 August 2003 from 1131 to 1328 UTC in the Chubb Run watershed. Green lines show the time of Flash Flood Index values (FF1 to FF1.5).

5. REDUCE FFG IN STRIP-MINED BASINS

Strip mining is prevalent across much of eastern Ohio and western Pennsylvania. Trees and vegetation are stripped off the ground, resulting in increased runoff. FFG should be reduced in basins where strip mining has occurred. How much the FFG should be reduced is a question for debate.
The FFG as provided to FFMP is shown in Table 8 for 27 August 2003. The FFG for this case is further complicated by a significant rainfall event the previous evening as indicated by the MAP/ABR of Table 9. The FFGMOD shows that 23.2 mm of rainfall that fell in basin 8588 as of 1200 UTC on 27 August 2003 is not accounted for in the 1200 UTC FFG.

Table 8. FFMP FFG for the Flint Run watershed, AMBER basin 8588, in Coshocton County, OH.

August 2003 Day/UTC	1hr FFG (mm)	3hr FFG (mm)	6hr FFG (mm)
24/1200z	55.9	73.7	81.3
25/0000z	55.9	73.7	81.3
25/1200z	55.9	73.7	81.3
26/0000z	55.9	73.7	81.3
26/1200z	55.9	73.7	81.3
27/0000z	55.9	73.7	81.3
27/1200z	48.3	63.5	63.5
28/0000z	35.6	50.8	61.0

Table 9. MAP, ABR, and FFGMOD for the Flint Run watershed, AMBER basin 8588, in Coshocton County, OH.

August 2003 Day/UTC	WHDO1 MAP (mm)	8588 ABR (mm)	FFGMOD (mm)
24/12-18z	0.0	0.0	0.0
24/18-00z	0.0	0.0	0.0
25/00-06z	0.0	0.0	0.0
25/06-12z	0.0	0.0	0.0
25/12-18z	0.0	0.0	0.0
25/18-00z	0.0	0.0	0.0
26/00-06z	0.0	0.0	0.0
26/06-12z	0.0	0.0	0.0
26/12-18z	0.8	3.8	-2.0
26/18-00z	1.3	2.5	-3.2
27/00-06z	9.7	30.7	-24.2
27/06-12z	1.0	0.0	-23.2
27/12-18z	0.0	13.2	-36.4
27/18-00z	31.0	132.3	-137.7
28/00-06z	0.0	0.0	-137.7
28/06-12z	0.0	0.0	-137.7

Figure 12 shows the six-hour ABR that fell across Coshocton County. The Walhonding MAP area is ten times larger than the Simmons Run watershed where the severe flash flooding occurred.

Figure 13 shows an expanded view of the Simmons Run broken into seven distinct basins. Simmons run is not urbanized but portions of the watershed have been strip-mined. Comparing the 2-hour ABR in Fig. 13 with the 6-hour time rainfall in Fig. 12, most of the rain fell in a two-hour period.

The flash flooding did not impact the town of Warsaw, but Ohio Route 60 (Fig. 14) suffered significant damage. A bridge that crosses Flint Run, AMBER basin 8588, was washed out about one mile southwest of Warsaw.

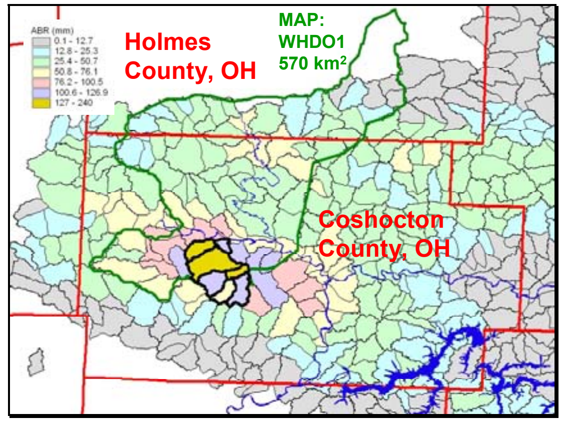

Fig. 12. Six-hour ABR in Coshocton County, OH on 27 August 2003 from 1400 to 2000 UTC. Dark green line shows the Walhonding (WHDO1) MAP area. Black outline shows the Simmons Run watershed (Area 43.0 km^2). Red lines are county boundaries.

Fig. 13. Two-hour ABR in Coshocton County, OH on 27 August 2003 from 1800 to 2000 UTC. Black outline shows the Simmons Run watershed (Area 43.0 km^2). Blue lines are streams and rivers. The white circle is the town of Warsaw. AMBER basin identification numbers in black.

Using the FFMP FFG for this event the FF0 state is reached about 1818 UTC (Fig. 15) indicating that enough ABR had occurred to bring the stream to a bank full condition. If additional rainfall is expected to continue in the basin, a flash flood warning might be issued by this time. If a warning is issued after the FF0 state, the possibility of a zero lead-time warning may result. At 1845 UTC Flint Run has reached FF1 state indicating significant flash flooding is likely. At 1915 UTC Flint Run has reached FF3 and disastrous flash flooding may occur.

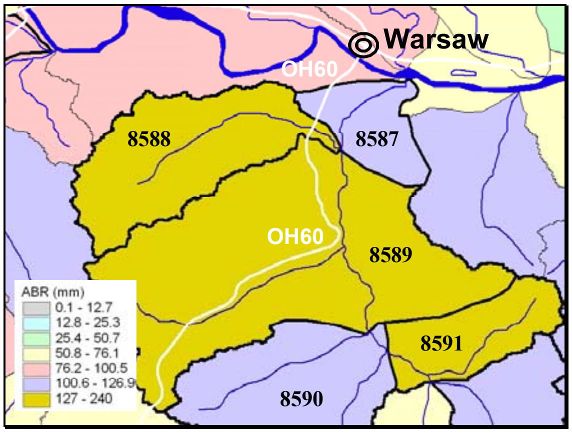

Fig. 14. Two-hour ABR in Coshocton County, OH on 27 August 2003 from 1800 to 2000 UTC. Black outline shows a portion of the Simmons Run watershed (Area 5.8 km^2). Blue lines are streams and rivers. The black circle is the town of Warsaw. AMBER basin identification numbers in black. White lines are highways.

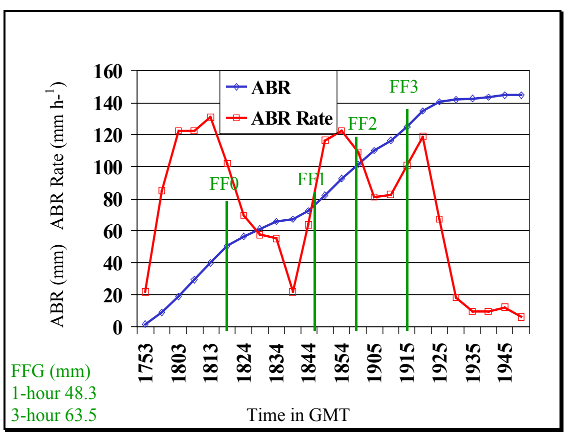

Fig. 15. FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 27 August 2003 from 1753 to 1951 UTC in the Flint Run watershed (Area 5.8 km^2). Green lines show the time of Flash Flood Index values (FF0 to FF3).

Two different factors must be accounted for when reducing the FFG for basin 8588. The rainfall that occurred through 1200 UTC on 27 August 2003 (Table 9) indicates that the FFG may be over 20 mm too high based on the accumulated FFGMOD value of -23.2 mm. The 1-hour FFG is dropped from 48.3 mm to 28.3 mm based on the FFGMOD factor that was not accounted for in the 1200 UTC FFG. The FFG should also be reduced for increased runoff due to the impact of strip mining in the basin. An arbitrary value of 10 mm is subtracted from the FFG to allow for some adjustment for the increased runoff from the strip-mined area, dropping the 1-hour FFG to 18.3 mm.

Compare Fig. 16 with Fig. 15 to see the impact of locally reducing the FFG. Lead time is increased as FF0 is now reached at 1803 UTC, 15 minutes earlier than the original FFG, and FF1 is reached 26 minutes earlier at 1818 UTC. More severe flash flood intensity is also indicated using the modified FFG, the FF5 level is nearly reached compared to high FF3 state with the original FFMP FFG.

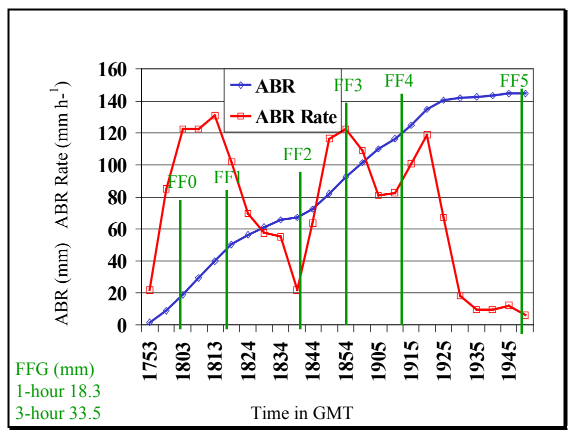

Fig. 16. Modified FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 27 August 2003 from 1753 to 1951 UTC in the Flint Run watershed. Green lines show the time of Flash Flood Index values (FF0 to FF5).

6. REDUCE FFG IN STEEP TERRAIN

The FFG from the RFC comes with the disclaimer “steep terrain can greatly reduce the apparent index”. The FFG should be reduced for watersheds with steep terrain. The amount of reduction of FFG for steep terrain is arbitrary and is likely a function of both stream bed slope, stream channel cross section, and slope of the valley walls that would directly impact overland runoff. The runoff is increased on steep slopes because the water tends to run downhill under the force of gravity, rather than infiltrate into the soil. Table 10 shows the FFG for the 72 hours preceding the event.

Table 10. FFMP FFG for the North Branch of the Potomac River (13), AMBER basin 3473, in Garrett County, MD.

August 2003 Day/UTC	1hr FFG (mm)	3hr FFG (mm)	6hr FFG (mm)
09/1200z	27.9	40.6	45.7
10/0000z	12.7	25.4	30.5
10/1200z	20.3	30.5	35.6
11/0000z	27.9	38.1	40.6
11/1200z	22.9	33.0	35.6
12/0000z	15.2	27.9	30.5
12/1200z	17.8	27.9	30.5
13/0000z	17.8	27.9	30.5

Table 11 shows that significant rainfall occurred in the days leading up to the flash flood. As a result of the multiple rainfall events, FFG was already very low. Streams were not at low flow levels, and the ground was very saturated. In this scenario FFG can be assumed to be near zero, meaning that most rainfall will convert directly to runoff, and flooding will commence shortly after any significant runoff producing rainfall.

Garrett County, MD has some of the steepest terrain in the NWS PBZ CWA. A very serious flash flood occurred in southern Garrett County on 12 August 2003. Figure 17 shows the six-hour ABR for Garrett County, MD. The North Branch of the Potomac River is Garrett County's eastern border with Grant County, MD. The rainfall maximum of over 50 mm of ABR fell directly on the county line.

The rainfall maximum is displayed in Fig. 18. Damaging flash flooding occurred in the town of Bayard, WV. A new asphalt highway had been paved in Bayard during the morning hours of 12 August 2003. The intense runoff produced by ABR amounts of over 125 mm washed the new road into the river. Most of this area of eastern Garrett and western Grant counties is heavily forested with little population, reducing the impact of an otherwise extreme flash flood event.

Table 11. MAP, ABR, and FFGMOD for the North Branch of the Potomac River (13), AMBER basin 3473, in Garrett County, MD.

August 2003 Day/UTC	KITM2 MAP (mm)	3473 ABR (mm)	FFGMOD (mm)
09/12-18z	0.5	0.5	0.0
09/18-00z	13.2	26.4	-13.2
10/00-06z	0.0	0.0	-13.2
10/06-12z	0.0	0.0	-13.2
10/12-18z	0.3	0.0	-12.9
10/18-00z	5.1	0.0	-7.8
11/00-06z	2.5	0.0	-5.3
11/06-12z	3.3	8.9	-10.9
11/12-18z	1.0	0.0	-9.9
11/18-00z	8.6	0.3	-1.6
12/00-06z	0.0	0.0	-1.6
12/06-12z	0.0	0.0	-1.6
12/12-18z	1.3	58.7	-59.0
12/18-00z	15.7	114.3	-157.6
13/00-06z	0.0	0.0	-157.6
13/06-12z	0.0	0.0	-157.6

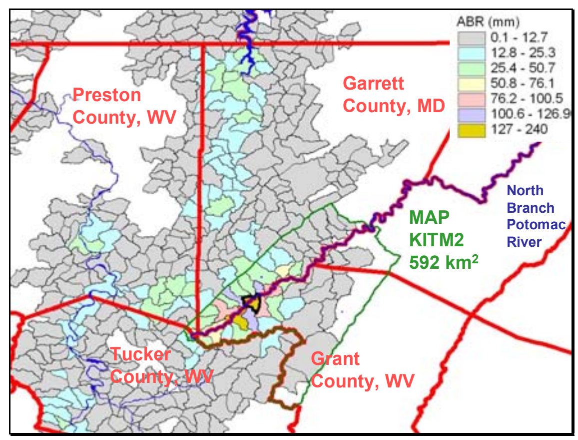

Fig. 17. Six-hour ABR in Garrett County, MD and Grant County, WV on 12 August 2003 from 1400 to 2000 UTC. Dark green line shows the Kitzmiller (KITM2) MAP area. Black outline shows the North Branch of the Potomac River (13) basin (Area 6.1 km^2). Red lines are county boundaries.

The plot of ABR/ABR Rate in Fig. 19 shows the intense rainfall rates that occurred during this three-hour rainfall event. Flash floods are typically caused by bursts of intense rainfall. These "rain bursts" have been defined (Davis 2003), as at least three consecutive WSR-88D observations (5-6 minutes for each observation) of ABR

Rate greater than 25.4 mm h^{-1}. Each of the flash floods in this paper was caused by at least one rain burst with a minimum of 8 consecutive observations over 25.4 mm h^{-1}. The first three events, Washington, PA (12-five minute scans), first Franklin, PA (12-five minute observations), second Franklin, PA

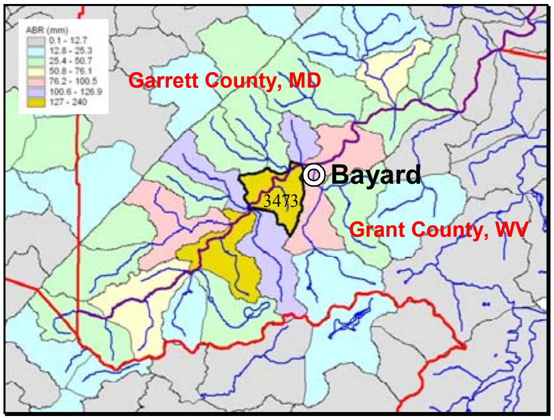

Fig. 18. Six-hour ABR in Garrett County, MD and Grant County, WV on 12 August 2003 from 1400 to 2000 UTC. Blue lines show rivers and streams. Black outline shows the North Branch of the Potomac River (13) basin (Area 6.1 km^2). Red lines are county boundaries. White circle locates the town of Bayard, WV. AMBER basin identification number in black.

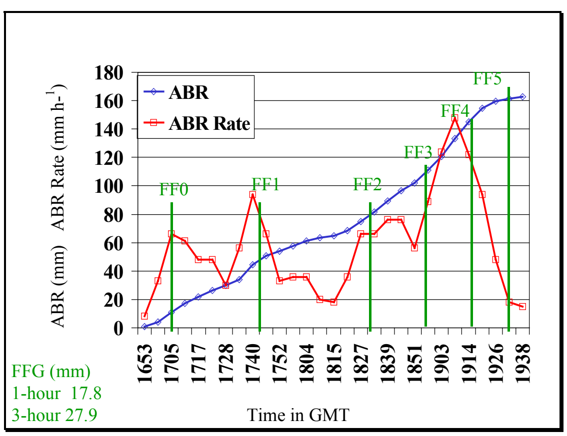

Fig. 19. FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 12 August 2003 from 1705 to 1920 UTC in the North Branch of the Potomac River (13) watershed. Green lines show the time of Flash Flood Index values (FF0 to FF5).

(8 – five minute scans), were all caused by single rain bursts. The next two more serious flash flood events were both caused by multiple rain bursts. The Flint Run flood was caused by 8-five minute scans, followed by 9-five minute observations, separated by a five-minute break. The Garrett County case is an example of a near worst-case scenario, with two rain bursts of 12-six minute observations separated by a 12-minute break with ABR Rates less than 25.4 mm h^{-1}. High ABR Rates are almost always present in deep moist convection (Davis 2001). The determining factor that produces flash flooding is if those high ABR Rates persist over the same watershed for a significant period of time.

7. MULTIPLE RAINFALL EVENTS

Multiple rainfall events separated by more then six hours in time offer a special challenge for the application of FFG in FFMP. Since the maximum time display interval in FFMP is six hours, no rainfall occurring prior to the previous six hours can be displayed. This fact came directly into play for a significant flash flood event in Monongalia County, WV, the same day as the 27 August 2003 flash flood in Coshocton County, OH described earlier in this paper.

Table 12. FFMP FFG for the Kelly Run watershed, AMBER basin 2522, in Monongalia County, WV.

August 2003 Day/UTC	1hr FFG (mm)	3hr FFG (mm)	6hr FFG (mm)
24/1200z	40.6	53.5	58.4
25/0000z	40.6	53.5	58.4
25/1200z	40.6	53.3	58.4
26/0000z	40.6	53.3	58.4
26/1200z	40.6	53.3	58.4
27/0000z	40.6	53.3	58.4
27/1200z	25.4	35.6	40.6
28/0000z	10.2	22.9	27.7

The FFG for the 3 days leading up to the flooding event is shown in Table 12. The FFG was basically constant through 0000 UTC on 27 August 2003. Table 13 shows that 20.1 mm of rain fell in the PMAW2 MAP area that contains Kelly Run from 0000 UTC to 1200 UTC on 27 August 2003. The

PMAW2 MAP rainfall was used to update the FFG at 1200 UTC, reducing the 1-hour FFG from 40.6 mm to 25.4 mm. The Kelly Run watershed received 62.5 mm of ABR in the same time period, with the FFGMOD calculation indicating that the FFG could be over 40 mm too high.

Figure 20 shows the six-hour ABR for Monongalia County, WV. Note the location of the PMAW2 MAP area and the Kelly Run watershed contained within. An expanded view of the Kelly Run watershed area is shown in Fig. 21. Notice the high values of ABR, over 75 mm in basins 2524 and 2514. The green line that is the eastern border of the PMAW2 MAP area runs along Chestnut Ridge, a long continuous mountain ridge running from the eastern border of Monongalia county, WV northeast into Fayette County, PA. In the hours around sunrise, the Pittsburgh, PA WSR-88D will frequently experience ground clutter returns from this ridge. The six-hour ABR readings of Fig. 21 are contaminated by ground clutter. Basin numbers 2512, 2514, 2518, 2519, and 2524 all have Chestnut ridge as the eastern border of their watersheds. Ground clutter contamination resulting from WSR-88D returns from the ridge-line may result in radar rainfall estimates much higher than the actual observed rainfall.

Table 13. MAP, ABR, and FFGMOD for the Kelly Run watershed, AMBER basin 2522, in Monongalia County, WV.

August 2003 Day/UTC	PMAW2 MAP (mm)	2522 ABR (mm)	FFGMOD (mm)
24/12-18z	0.0	0.0	0.0
24/18-00z	0.0	0.0	0.0
25/00-06z	0.0	0.0	0.0
25/06-12z	0.0	0.0	0.0
25/12-18z	0.0	0.0	0.0
25/18-00z	0.0	0.0	0.0
26/00-06z	0.0	0.0	0.0
26/06-12z	0.0	0.0	0.0
26/12-18z	0.0	0.0	0.0
26/18-00z	0.3	0.3	0.0
27/00-06z	10.7	8.9	1.8
27/06-12z	9.4	53.6	-42.4
27/12-18z	6.6	3.0	-38.8
27/18-00z	31.2	65.0	-72.6
28/00-06z	0.3	0.0	-72.3
28/06-12z	0.0	0.0	-72.3

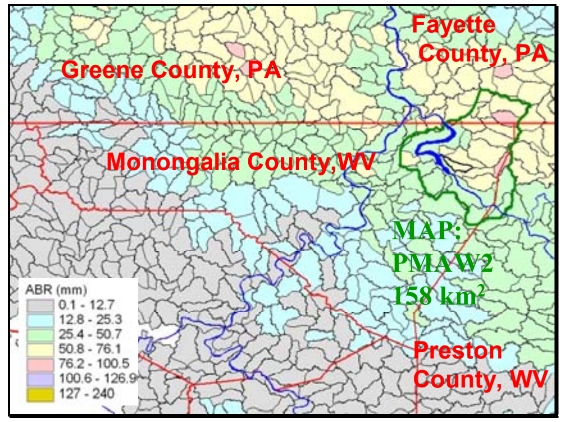

Fig. 20. Six-hour ABR in Monongalia County, WV on 27 August 2003 from 0700 to 1300 UTC. Green line shows the Lake Lynn, WV MAP area (PMAW2). Black outline shows the Kelly Run watershed (Area 3.0 km^2). Red lines are county boundaries. Blue lines are major rivers.

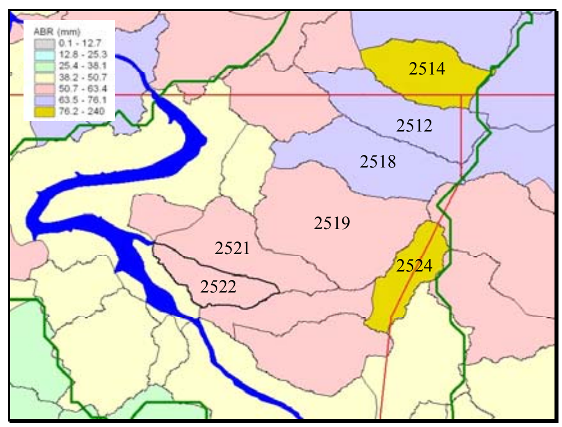

Fig. 21. Six-hour ABR in northeast Monongalia County, WV on 27 August 2003 from 0700 to 1300 UTC. Black outline shows the Kelly Run watershed (Area 3.0 km^2), AMBER basin 2522. The green line is the border of the PMAW2 MAP area. Red lines are county boundaries. Blue lines are rivers and lakes. AMBER basin identification numbers in black.

Figure 22 shows the two-hour ABR for 1100 UTC to 1300 UTC that eliminates much of the ground clutter contamination that occurred in the 6-hour ABR of Fig. 21 from 0700 UTC to 1100 UTC. Notice that the ABR along the ridge-line is reduced quite a bit, but the Kelly Run ABR value changes very little. This is a good indication that the

ABR in Kelly Run is mostly actual rainfall and not heavily contaminated by the ground clutter. Figure 23 shows the ABR/ABR Rate distribution for Kelly Run. The FF0 state is reached within 30 minutes of the start of the rainfall, but some of the rain in the first peak may be contaminated by the ridge ground clutter, as indicated by the sharp peak in the ABR Rate. Rainfall rate in the WSR-88D precipitation algorithm is capped at a user selectable value. An hourly rainfall cap of

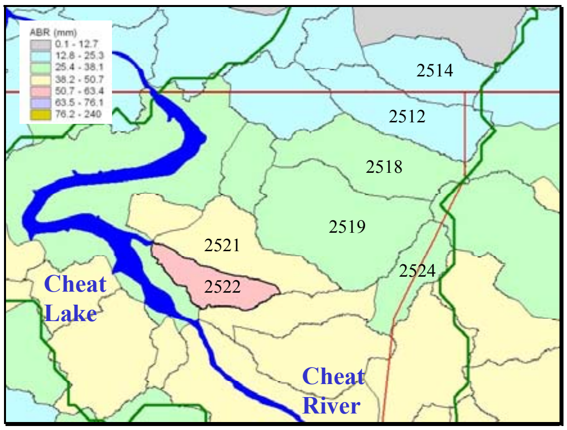

Fig. 22. Two-hour ABR in northeast Monongalia County, WV on 27 August 2003 from 1100 to 1300 UTC. Black outline shows the Kelly Run watershed (Area 3.0 km^2). Red lines are county boundaries. Blue lines are rivers, lakes, and streams. AMBER basin identification numbers in black.

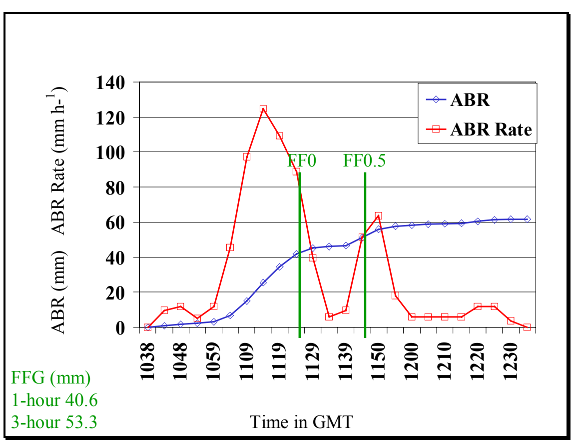

Fig. 23. FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 27 August 2003 from 1038 to 1235 UTC in the Kelly Run watershed. Green lines show the time of Flash Flood Index values (FF0 to FF0.5).

127 mm was used in all of the case studies presented in this paper. ABR Rate values close to the cap value may indicate hail or ground clutter contamination of the WSR-88D rainfall estimates. The Kelly Run watershed is heavily forested with little population and no flooding was reported with this first round of rain.

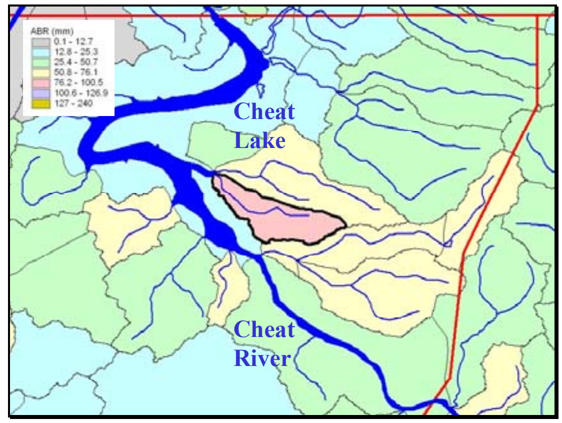

Fig. 24. Six-hour ABR in northeast Monongalia County, WV on 27 August 2003 from 1400 to 2000 UTC. Black outline shows the Kelly Run watershed (Area 3.0 km^2). Red lines are county boundaries. Blue lines are rivers, streams, and lakes.

Additional map backgrounds may be added to the FFMP display of basins to aid in the interpretation of the flash flood threat. An expanded view of the six-hour ABR in Kelly Run is shown in Fig. 24 with the second round of ABR that fell about seven hours after the drenching around daybreak. Streams have been added to the FFMP display as an additional map background in Fig. 24 compared to Fig. 22. The streams map background aids in the interpretation of where the flood waters will flow as the flood wave moves downstream. Notice that Kelly Run, shaded in pink in both figures, flows directly into Cheat Lake. The flash flooding occurring on Kelly Run will not be transported downstream as the lake absorbs the flood wave. Lakes and major rivers serve as natural barriers to the downstream progression of flash floods.

Roads are also an important map background to use for flash flood applications, since so many flash flood fatalities occur in automobiles (Davis 2001). The intersection of roads with the stream network can provide important clues to the location of potential flash flood problems. Specific roads or bridge crossings can be identified as potential hazard locations in the flash flood warnings and statements, if their locations can be identified in near-real time. Figure 25 shows the two-hour ABR that produced the flash flooding in Kelly Run. Roads have been added to the ABR display showing potential trouble spots where the highways cross the stream. Interstate 68 passes through the Kelly Run basin, but the bridges across the creek are too high to allow flooding of the roadway. However, West Virginia Route 857 is at a lower elevation than the interstate highway, and the second wave of rainfall took out the bridge over Kelly Run.

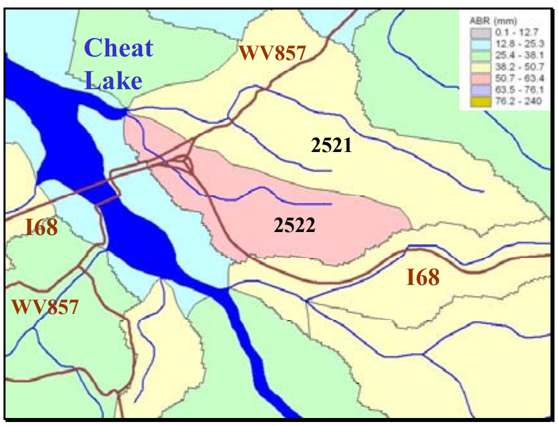

Fig. 25. Two-hour ABR in northeast Monongalia County, WV on 27 August 2003 from 1905 to 2057 UTC. Black outline shows the Kelly Run watershed (Area 3.0 km^2). Brown lines are highways. Blue lines are streams, rivers, and lakes. AMBER basin identification numbers in black.

Figure 26 shows the ABR/ABR Rate plot using the 1-hour FFG updated from the RFC with the 1200 UTC model run. Recall that FFGMOD from Table 11 showed that the updated 1200 UTC FFG (25.4 mm) might be over 40 mm too high. Notice that FF0 state is reached in about 30 minutes after the start of the rainfall, and FF1 by 1950 UTC. In effect the FFG in Kelly Run just seven hours after the morning rainfall should be near zero. Enough rain fell in the morning to bring the creek to near bank full or a little above, meaning the threshold runoff was reduced to zero, unless the stream has receded

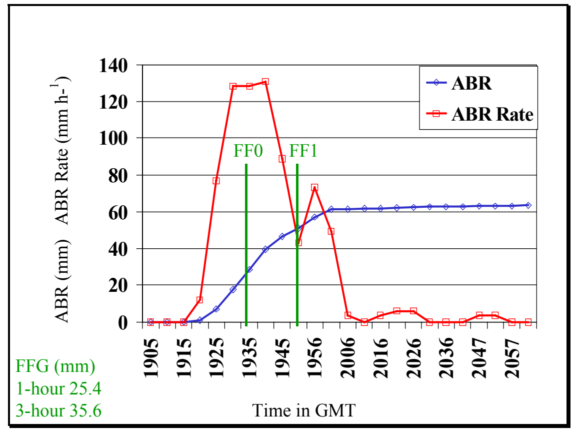

Fig. 26. FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 27 August 2003 from 1905 to 2102 UTC in the Kelly Run basin. Green lines show the time of Flash Flood Index values (FF0 to FF1).

significantly back into its banks. The ground will be close to saturation from the earlier rain, resulting in most of the ABR being converted directly into runoff.

With the modified FFG of zero used in Fig. 27, Kelly watershed now reaches FF2, with much more serious flooding indicated than the FF1 level indicated by the original FFG (Fig. 26). The FF1 level is reached 15 minutes earlier with the modified FFG, resulting in increased warning lead-time. The Kelly Run flash flooding is occurring at the same time as the disastrous flooding in Coshocton County, OH (section 5).

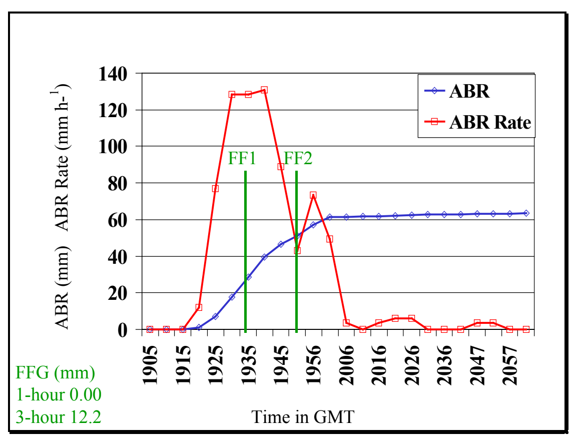

Fig. 27. Modified FFMP FFG, ABR sum (mm), and ABR Rate (mm h^{-1}) on 27 August 2003 from 1905 to 2102 UTC in the Kelly Run watershed. Green lines show the time of Flash Flood Index values (FF1 to FF2).

8. CONCLUSIONS

FFG is an important tool in determining the risk of flash flooding in the FFMP software. The correct application of the FFG requires the understanding of the assumptions used to compute the FFG values. If those assumptions are no longer valid, the FFG must be modified to more accurately reflect the hydrologic condition of the watershed. A history of the past 72 hours of rainfall in the basin is the best way to gage the validity of the FFG assumptions. If no significant rainfall has fallen in the basin during the previous 72 hours the assumption of low flow conditions for the stream should be a reasonable estimate. For watersheds in relatively flat terrain the period of stream recession may be significantly longer than 72 hours, so a longer period of ABR history may be more effective. For MAP rainfall incorporated into the FFG, the FFGMOD, can be an important tool for the local adjustment of FFG. For FFMP ABR that has not been incorporated into the FFG, the FFG can be updated based on the observed ABR in the basin since the FFG data cutoff. These corrections based on the history of ABR can provide important local modifications to RFC FFG, that may result in more accurate flash flood warning detection.

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