JP3.10 WHY CUSTOMIZE FLASH FLOOD MONITORING AND PREDICTION WATERSHEDS?

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1. INTRODUCTION

The Flash Flood Monitoring and Prediction (FFMP) software was deployed nationally by the National Weather Service (NWS) in 2002 (Smith et al. 2000). The FFMP watersheds were defined by the National Basin Delineation (NBD) Project (Cox et al. 2001) at the National Severe Storms Laboratory (NSSL). Average Basin Rainfall (ABR) for each defined FFMP watershed is computed from Weather Surveillance Radar, 1988 Doppler (WSR-88D) radar rainfall estimates to estimate flash flood potential (Davis and Jendrowski 1996).

The NWS has sponsored eight "Basin Customization courses" from April 2002 to May 2003 at the Cooperative Program for Operational Meteorology, Education and Training (COMET) facility at the University Corporation for Atmospheric Research in Boulder, CO. The purpose of the Basin Customization course is to train one forecaster from each NWS field office to locally modify the FFMP watersheds of the NBD. The primary motivation to modify the FFMP watersheds is to correct errors in the original data set, and to provide enhancements that may improve flash flood detection.

2. THE FFMP NBD DATA SETS

The basin customization course begins by describing the Geographic Information System (GIS) used to create the two database files required to produce FFMP rainfall computations. The two required databases are the stream basin database and the WSR-88D bin assignment database.

The stream basin database is a polygon shapefile defining the outlines of each defined watershed (Fig. 1). The stream basin attributes associated with each watershed segment are shown in Figure 1. The WSR-88D radar bin file is a point shapefile (Fig. 2) showing the center point of each one-degree by one-kilometer polar radar grid. The attributes of each radar bin are shown in Figure 2.

The basin customization course defines the characteristics of these two data sets in great detail, and then goes on to describe how and why these datasets may be modified at each NWS office.

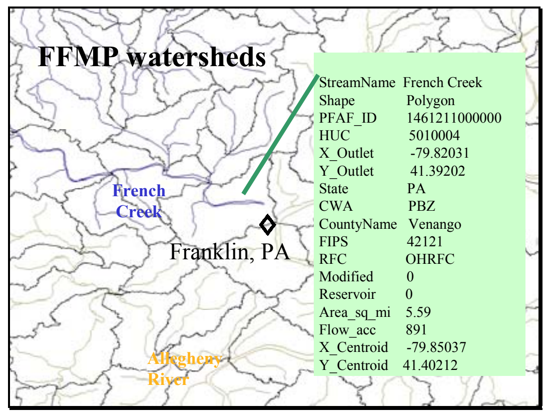

Fig. 1. A portion of the FFMP defined watersheds near Franklin, PA with associated data attributes. Black lines are the polygon shapefile. Blue/gold lines are streams and rivers.

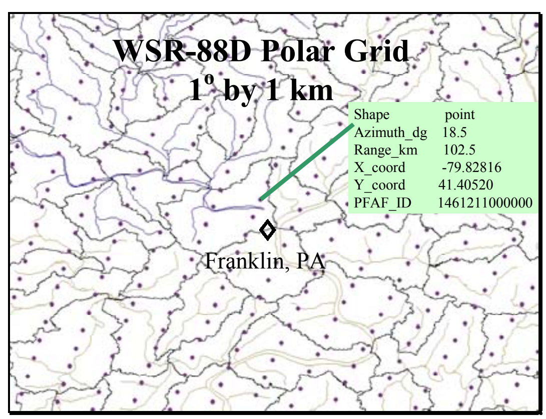

Fig. 2. WSR-88D point shapefile plotted on the stream basin polygon shapefile with associated attributes. Blue/gold lines are streams and rivers.

3. THE WATERSHED ATTRIBUTE TABLE

Procedures for making corrections, and adding new attributes to the watershed attribute

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table are covered in lecture and lab sessions. Correcting stream names in the data set is a high priority, since the stream names are used directly in the FFMP display. Instructions are provided for adding several new attributes to the database including the "Area ID" of the FFMP threat table display (Fig. 3) and the "Parent ID" which defines the next downstream watershed segment.

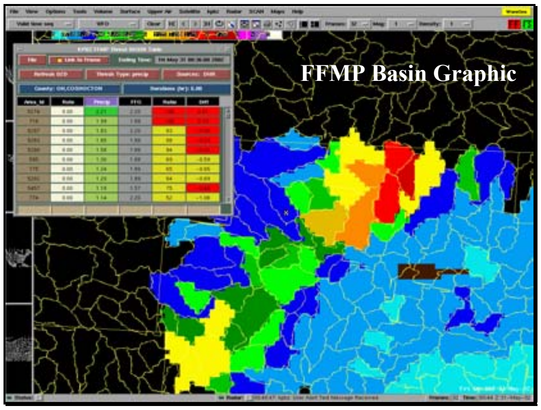

Fig. 3. FFMP color graphic showing ABR for streams in inches and the Threat Basin Table for the Pittsburgh, PA (KPBZ) WSR-88D.

3.1 *Correcting stream names*

The stream names in the database are extracted from the National Hydrography Data Set (NHD) of the United States Geological Survey (USGS) and the Environmental Protection Agency (EPA). Many of the small streams in the NHD data set have no names, and some of the named streams in NHD are incorrect. For example, the Mill Creek watershed shown in Figure 4 is broken into 19 watershed segments. Table 1 shows the names assigned to these segments by NHD and the correct names listed as FFMP name.

The stream names assigned in the FFMP name column use the "parent naming" convention where small stream segments with no name are assigned the name of their parent stream. Numbers are assigned in upstream order to stream segments with the same name. Abbreviations are used for frequently occurring words, such as L for Little, and Cr for Creek. For example, Little Mill Creek is divided into three segments, Little Mill Creek, Little Mill Creek (1), and Little Mill Creek (2). The small unnamed tributary of Mill Creek (Area_id = 8386) is named Mill Cr (2), since Mill Creek is its parent stream.

All corrections to the stream names in the FFMP stream database must be made manually by the local NWS forecast office.

3.2 *Add the FFMP attribute: Area_id*

The FFMP graphic display of the watersheds within a county (Fig. 3) shows the color coded ABR for each watershed, plus a text "Threat table" showing actual values of ABR (precip column) and Flash Flood Guidance (FFG column) for each watershed in the county. The tabular data is referenced by the Area_id column. The name of the stream can be displayed in a pop-up window by hovering the cursor over the Area_id column entry.

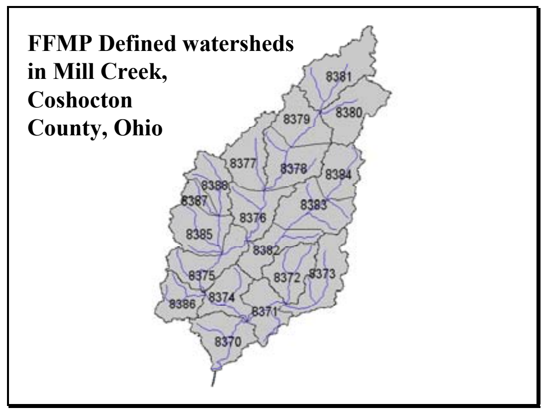

Fig. 4. Mill Creek watersheds segments in Coshocton County near Mound, OH.

Table 1. Stream name assignments for Mill Creek watershed showing NHD names and correct FFMP names.

Area_id	NHD Name	FFMP Name
8370	Spoon Cr	Mill Cr
8371	Spoon Cr	Spoon Cr
8372		Spoon Cr (1)
8373		Spoon Cr (2)
8374	Spoon Cr	Mill Cr (1)
8375	Spoon Cr	Mill Cr (3)
8376	Spoon Cr	Mill Cr (4)
8377		Beards Run
8378	Spoon Cr	Mill Cr (5)
8379	Spoon Cr	Mill Cr (6)
8380		Mill Cr (7)
8381		Mill Cr (8)
8382	Spoon Cr	L Mill Cr
8383	Spoon Cr	L Mill Cr (1)
8384	Spoon Cr	L Mill Cr (2)
8385	Spoon Cr	Turkey Cr
8386		Mill Cr (2)
8387	Spoon Cr	Turkey Cr (1)
8388	Spoon Cr	Turkey Cr (2)

The Area_id for each watershed is generated by FFMP during the installation procedure at the NWS forecast office. Therefore, the Area_id is not available as an attribute to the watershed shapefile in the delivered data set from NSSL. The procedure for generating the Area_id as a new attribute for the stream is provided in the basin customization class.

3.3 *Add the Parent_id as a new attribute*

The hydrologic connectivity of the defined watersheds is very important to real-time flash flood applications. When heavy rainfall is observed in a watershed, the flooding that occurs in the stream segment of that watershed may extend to the next downstream watershed. This "stream connectivity", the flow of the stream channel from one watershed segment to the next downstream watershed segment, can be added as an attribute of each watershed. The delivered FFMP stream database has no direct "stream connectivity" in the attribute set. Procedures taught in the basin customization course create stream connectivity for the stream database. Each defined watershed segment is assumed to have a single outflow point. The watershed segment into which that outflow point drains is defined as the "Parent stream". The Area_id of the parent stream is listed in the attribute table as the Parent_id attribute. For example, in the Mill Creek watershed (Fig. 4), Area_id 8387: Turkey Cr(1) and Area_id 8388: Turkey Cr(2) both have the same "Parent_id", Turkey Cr (Area_id 8385). The parent_id attribute provides stream connectivity for all defined watersheds.

The importance of watershed connectivity can be demonstrated by examining a case of flash flooding in the "Narrows" (watershed segment 1000 in Fig. 5) of Zion National Park in southern

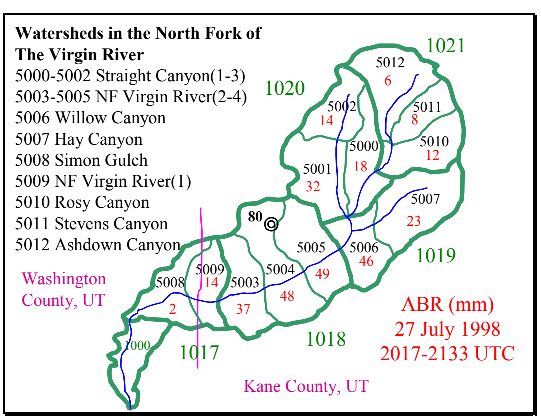

Fig. 5. Stream segments for the North Fork of the Virgin River. Green lines are watershed boundaries. Blue lines are stream channels. Purple line shows county boundary.

Utah. Figure 5 shows the distribution of rainfall across the North Fork of the Virgin River into the "Narrows".

Notice all of the rain fell in Kane County, but the stream flows into Washington County, where the "Narrows" is located, and both flash flood fatalities occurred. A flash flood warning was successfully issued for both counties, because the forecasters in Salt Lake City were aware of the "stream connectivity". The parent stream attribute provides this hydrologic connectivity for the FFMP watersheds.

4. CORRECT BASIN DELINEATION ERRORS

A portion of the basin customization course deals with locating delineation errors in the stream basin data set. Delineation errors frequently occur over lakes and wide rivers, where values of digital elevation are constant. Delineation errors can also occur at the intersection of USGS 8-digit Cataloging Unit boundaries. The NBD processing of streams was carried out for individual Cataloging Units. The small basins within these Cataloging Units were then merged together to complete the stream data set. Thus, some errors in the stream database may be related to the merging of watersheds along the Cataloging Unit boundaries.

The basin delineation course provides possible solutions for correcting the errors that have been identified. Only the errors that result in an assignment of WSR-88D radar bins to the wrong watershed need to be corrected for FFMP operations.

To repair these delineation errors, the line defining the border of the watershed must be moved. The line that defines the border is made up of a series of connected points. The vertex editing function can be used to move, add, or delete the points to modify the line. Vertex editing can be a tedious and time-consuming job if many points must be modified. The split polygon function, drawing a single line to divide the watershed into two parts, is a faster and easier way to repair the delineation errors.

4.1 *Repair errors by splitting polygons*

NBD analysis errors that impact a large number of radar bin mis-assignments can be easily dealt with by splitting polygons. One recurring source of these errors occurs with wide rivers or lakes. In the NBD process, a single line is used to represent the river or lake. The outflow point of a stream watershed into the river may fall anywhere in the river, rather than terminating at the river bank, resulting in an analysis error.

Figure 6 shows the actual Spruce Run watershed (shaded in purple) while the FFMP watershed boundary for Spruce Run is the green line. Notice that the green boundary extends well into the Ohio River (shaded light blue). The red lines are the NBD delineated stream and river channels. The WSR-88D radar bins assigned to Spruce Run are represented by the 35 orange dots. The 21 dots with a purple center are the correct bin assignments for Spruce Run. The 14 solid orange dots are not located in the Spruce

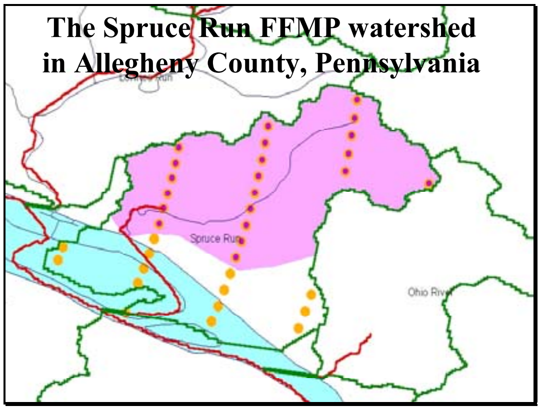

Fig. 6. FFMP watershed analysis for Spruce Run in Allegheny County, PA. Green lines are the FFMP watershed boundaries, and red lines are the delineated stream channels. Orange dots are the WSR-88D bin assignments. Orange dots with purple centers are the correct bin assignments for Spruce Run. Shaded light blue area is the Ohio River. Shaded purple area is the true Spruce Run watershed.

Run watershed and should not be a part of the ABR computation for Spruce Run. The bin assignment error can be repaired by splitting the Spruce Run polygon into two parts. In the corrected stream data set, the southern part of the original Spruce Run polygon will become a segment of the Ohio River.

4.2 *Repair errors by vertex editing*

Minor cosmetic corrections and small-scale radar bin assignment errors are more easily repaired by adding or deleting points to the lines that define the boundary (vertex editing). Figure 7 is a magnified view of the mouth of Mill Creek (shown in Fig. 4) showing the details of the minor delineation error. The green line is the original FFMP watershed boundary. Notice the long “pipe stem” error that results when the flat land adjacent to the river is encountered. These types of errors occur with some frequency, but many times do not result in radar bin mis-assignments. The red line is the new corrected watershed boundary, determined manually from topographic map analysis, created by vertex editing. None of the radar bins (gray circles) fell within the area of Mill Creek that was removed by the editing process. Since no WSR-88D bins assignments were modified, FFMP ABR computations will not be impacted by this delineation. The edit was done to improve the appearance of the FFMP watershed shapefile.

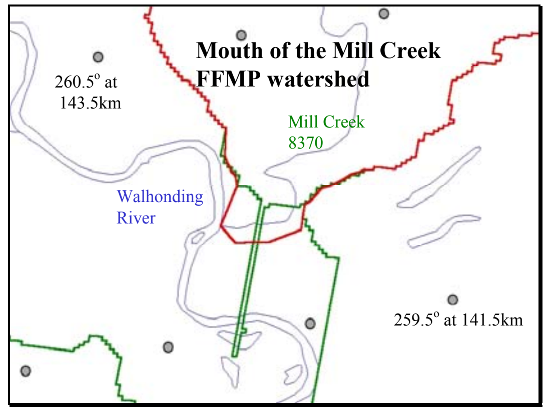

Fig. 7. Mouth of the Mill Creek watershed showing a “pipe stem” delineation error. The green lines are the FFMP watershed boundaries. The red line is the manually corrected boundary. The blue lines are the creeks and the river banks of the Walhonding River. The gray circles are the WSR-88D bin center points.

5. DIVIDE EXISTING FFMP WATERSHEDS

The FFMP watersheds were derived using a minimum drainage area threshold of 4.5 km^2 (1.74 mi^2), but not all derived watersheds are close to this minimum size. The distribution of watersheds by area (Fig. 8) shows there is quite a range of values. In the Pittsburgh, PA FFMP

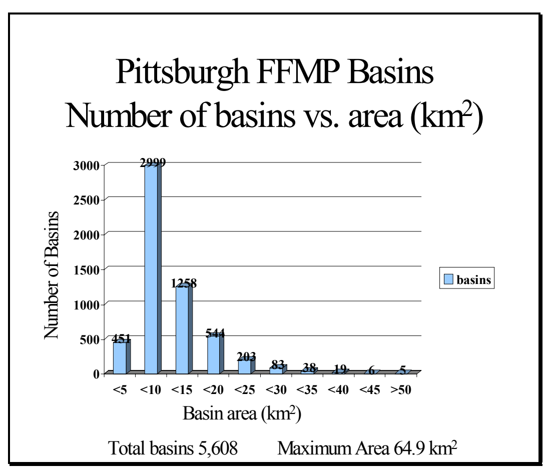

Fig. 8. Distribution of the number of FFMP basins by area (km^2).

stream database of 5,606 watersheds, 898 watersheds are larger than 15 km^2, and 151 watersheds are larger than 25 km^2.

The examination of flash flood case studies has shown that dividing watersheds into smaller segments tends to increase the flash flood detection capability of FFMP, and increase flash flood warning lead time (Davis 2002a, 2002b, 2001a). For these reasons, it may be desirable to divide FFMP watersheds larger than 10-15 km^2 into segments approaching the minimum drainage area threshold of 4.5 km^2.

The division of watersheds may be desirable to define watershed areas that impact specific locations, such as a bridge over a creek, a low water crossing, or a specific structure next to the creek (schools, homes, businesses, etc.).

5.1 *Divide the Little Pine Creek watershed*

The division of watersheds into smaller segments can result in improved flash flood detection and increased warning lead-time (Davis 2001a). The ABR and ABR rate data computed for the Etna, PA flash flood of 30 May 1986 in the Little Pine Creek watershed demonstrates this point. Little Pine Creek is defined as a single watershed in the original FFMP watershed database. Dividing the Little Pine Creek into three parts produces a clearer picture of the spatial and temporal distribution of ABR during the event. Figure 9 shows the ABR for Little Pine Creek (basin 1638) was 145 mm, while the headwaters of Little Pine Creek (basin 3631) received 180 mm of ABR.

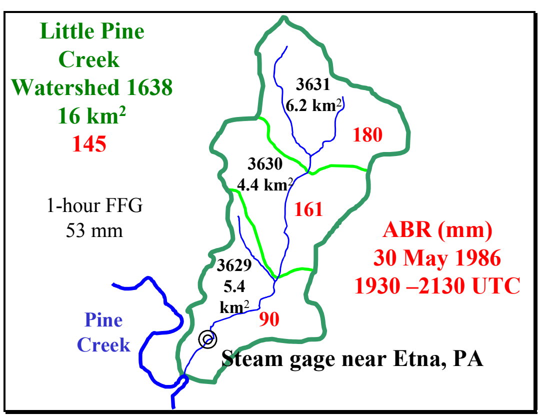

Fig. 9. Little Pine Creek watershed showing ABR (mm, in red), stream watershed identifiers and basin area in black, the original Little Pine Creek watershed boundary (dark green), the divided stream boundary (light green), and the stream and river channels (blue).

The "difference column" (Diff) in the FFMP threat basin table (Fig. 10) is computed by subtracting the Flash Flood Guidance (FFG) from the ABR. This difference computation has been described as the Flash Flood Index (FF-Index) that can be used to estimate the potential severity of flash flooding in near real time (Davis 2002b). The FF-Index is an estimate of the amount of runoff in inches (1mm = 0.03937 inches) contributing to stream rise above a bank full level. Since the amount of runoff is directly

Area_Id	Rate	Precip	FFG	Ratio	Diff
5274	0.11	2.17	1.50	145	0.68
716	0.07	1.92	1.26	152	0.66
5287	0.20	1.77	1.50	118	0.27
5283	0.15	1.58	1.26	125	0.32
5280	0.06	1.48	1.26	117	0.22
775	0.12	1.18	1.26	94	-0.08
5282	0.09	1.14	1.26	91	-0.12
774	0.15	1.10	1.50	73	-0.40
595	0.02	1.02	1.26	81	-0.24
715	0.09	0.96	1.26	77	-0.29

Fig. 10. Example of the FFMP threat basin table where Area_Id is the basin number, Rate is the ABR Rate (in h^{-1}), Precip is the ABR (in), FFG is the Flash Flood Guidance (in), Ratio is the ABR/FFG times 100, and Diff is the Flash Flood Index (in) = ABR – FFG.

related to the severity of the rise in stream level, the FF-Index can be considered a direct measure of potential flash flood severity. The FF-Index computation for ABR (mm) and FFG (mm) is given by,

$$\text{FF-Index} = 0.03937\ (\text{ABR} - \text{FFG}).$$

Table 2. Reference levels of the FF-Index.

FF- Index Reference Level	ABR–FFG (in)	ABR-FFG (mm)
FF0	0.00	0.0
FF1	1.00	25.4
FF2	2.00	50.8
FF3	3.00	76.2
FF4	4.00	101.6
FF5	5.00	127.0

Computation of the reference levels of FF-Index for western Pennsylvania case studies over the past 20 years shows that significant flash flooding occurs at FF1 and higher. Serious flash flooding consistently occurs when FF2 levels are reached, and severe flash flooding is very likely with reference values of FF3 or more.

When ABR reaches FFG, reference level FF0, minor flooding problems are often reported, but seldom any stream flooding. Reports of water in basements, or minor ponding of water on roads may be received, but significant stream flooding should not occur without additional rainfall. A flash flood warning may be issued around FF0 levels if the forecaster feels additional rainfall is imminent. Warning lead-time, the time from warning issuance to the start time of significant flash flooding, can be increased by warning around the time the FF0 level is reached.

The potential increase in warning lead-time can be computed by comparing the time of occurrence of the FF0 level for the ABR plots in Figure 11. The purple trace for the headwaters of Little Pine Creek crosses FFG (the green line) at 2000 UTC, while the blue trace for all of Little Pine Creek reaches FFG at about 2035 UTC. A flash flood warning issued around the time of the FF0 level for the small headwaters area would have an additional 35 minutes of lead-time over a warning issued based on ABR for all of Little Pine Creek. The increase in warning lead-time results directly from the division of Little Pine Creek into three parts.

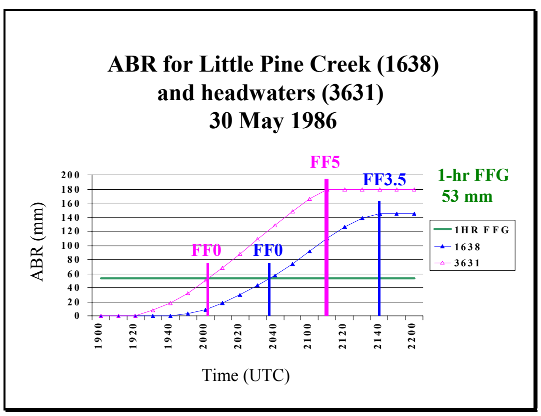

Fig. 11. ABR (mm) for Little Pine Creek (1638) is shown in blue and the headwaters of Little Pine Creek (3631) is shown in purple for 30 May1986. The time of occurrence of the FF-Index for the FF0 state and the maximum FF-Index is shown for each watershed. The one-hour FFG is shown in green.

Figure 12 shows the rapid stream rise that occurred on Little Pine Creek stream gage near Etna, PA with the flood peak occurring around 2130 UTC. Nine people drowned as their cars and trucks were swept off of Saxonburg Boulevard, the road that parallels Little Pine Creek in downstream watershed 3629.

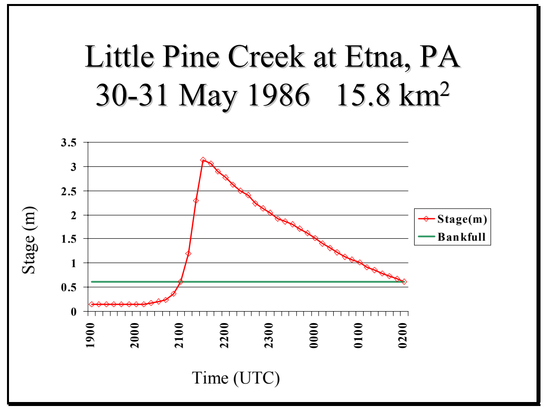

Fig. 12. Stream gage stage readings (m) on Little Pine Creek near Etna, PA on 30 May 1986.

Table 3. Time (UTC) of occurrence of the FF-Index reference levels for Little Pine Creek(1638) and the headwaters of Little Pine Creek(3631) on 30 May 1986.

FF-Index Reference Level	Time reached in basin 1638 (UTC)	Time reached In basin 3631 (UTC)
FF0	2035	2000
FF1	2050	2015
FF2	2110	2030
FF3	2120	2040
FF4	------	2055
FF5	------	2110

Not only is warning lead-time increased by examining ABR on small watersheds, but the detected intensity of the flash flood can also be dramatically increased. The maximum flash flood intensity was FF3.5 for the Little Pine Creek watershed, but the headwaters area was hit with an FF5 level flood.

The ABR in a watershed of 15-25 km^2 in area may be less than FFG, while a small tributary within that watershed (<10 km^2 in area) may have an ABR of FF1 to FF2 intensity. The ABR exceeding FFG may not be detected by FFMP unless the larger watershed is divided in smaller parts. Dividing larger FFMP watersheds into small segments can be critical to the detection of flash flooding.

5.2 *Divide highly urbanized watersheds*

Flash flooding in highly urbanized watersheds is becoming an increasing problem. The following list show examples of severe flash flooding in urban areas over the past ten years. Dallas, Texas on 05 May 1995 (Davis 2001a), Fort Collins, Colorado on 28-29 July 1997 (Davis 2001a), Kansas City, Missouri/Kansas on

05 October 1998 (Davis 2001b), Pitcairn, Pennsylvania on 01 July 1997 (Davis 2002b), and Forest Hills, Pennsylvania on 18 May 1999 (Davis 2000b). Infiltration of rain into the ground can be greatly reduced in urban areas due to a high percentage of impermeable soil. As a result, FFG in urban areas may be significantly lower than the county-based FFG.

FFMP can account for this increased flash flood threat if urban areas are divided into separate watersheds and FFG is reduced for these urban watersheds. The new version of FFMP distributed to the NWS office in late 2002 allows FFG to be manually adjusted for each defined watershed.

The NWS office in Pittsburgh, Pennsylvania has had good success in issuing flash flood warnings in urban areas as small as 2 km^2. Some examples of flash floods in small urban areas include: Franklin, Pennsylvania (Davis 2002a) in Chubb Run on 21 June 2001, and the eastern suburbs of Pittsburgh from McKeesport to Braddock, Pennsylvania on 18-19 May 1999 (Davis 2000b). The key to detecting these flash floods was in defining watersheds as small as 2 km^2 in area, and using a reduced FFG of 25 mm hr^{-1} for these highly urbanized areas.

By dividing the FFMP watersheds in highly urbanized areas into small watersheds (2 km^2 in area), the flash flood detection capability of FFMP can be greatly increased. Reduction of FFG in these urban areas will greatly improve the chance of detecting these potentially deadly flash floods.

6. CONCLUSIONS

The basin delineation course provided by the NWS will allow the forecasters in each forecast office to modify the FFMP stream basin data set to enhance FFMP's ability to detect flash floods.

The correction of delineation errors can increase the accuracy of the ABR computations. Correcting stream names, and adding stream names where none now exist, will improve the communication of "threat area" to the users of flash flood warnings. The stream names listed in the FFMP stream database can be included in the flash flood warnings and statements.

The division of existing FFMP watersheds into smaller segments will help increase warning lead-time and improve the detection of flash flood severity.

The analysis of highly urbanized areas, and the associated reduction of FFG in these areas, will greatly enhance the flash flood detection capability of the FFMP software.

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