8B.6 ADVANTAGES OF ADDING "BASIN UPSTREAM RAINFALL" (BUR) TO THE FLASH FLOOD MONITORING AND PREDICTION (FFMP) PROGRAM

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1. INTRODUCTION

The National Basin Delineation (NBD) (http://www.nssl.noaa.gov/projects/basins/) Project by the National Severe Storms Laboratory (NSSL) created the small stream database used by FFMP at all National Weather Service (NWS) offices in the continental United States. While the basin boundaries of the NBD small stream database are routinely used by FFMP, several other parameters created by the NBD have not been operationally implemented for use in FFMP. Two of these unused parameters include the area and the flow accumulation for each FFMP basin segment.

The NBD also created hydrologic connectivity between each of the defined stream basins. FFMP does use this hydrologic connectivity to create the upstream/downstream trace functionality as described in the FFMP OB9 Guide for Users (http://www.nws.noaa.gov/mdl/ffmp/FFMPA_Guide_Users_OB9.pdf). The hydrologic connectivity is provided by several NBD parameters, specifically Basin_ID, Parent_ID, and upstream(1-9) data fields. These NBD parameters would also allow the computation of "Basin Upstream Rainfall" (BUR). This paper will describe the potential operational value of adding area, flow accumulation, and BUR to FFMP for improving the detection of flash flood threat on larger watersheds.

2. IMPORTANCE OF BASIN AREA

Area of a watershed is an important parameter for determining flash flood risk. Small watersheds have rapid hydrologic response times, especially in areas of steep terrain. These small watersheds can be easily inundated with heavy rainfall, in short time periods of two hours or less, from a single slow-moving thunderstorm. Larger watersheds have slower hydrologic response times, and are much more difficult to flood. These larger watersheds require numerous showers to train over their larger basin areas, for longer time periods of 3 to 6 hours or more. Because of these differences in hydrologic response and mesoscale mechanisms needed to create the required rainfall, watershed area has a direct impact on the forecaster's situational awareness of any stream flood threat.

The FFMP program was based on the Areal Mean Basin Estimated Rainfall (AMBER) program started at the Pittsburgh National Weather Service Forecast Office (NWSFO) in 1985. AMBER was designed to answer two questions. What stream will be impacted by the heavy rainfall? Has enough rain fallen to cause the stream to flood? A database of stream watershed boundaries is needed to answer these questions. The initial 1985 AMBER minimum basin size was an area of 10 mi^2 (25.9 km^2) for basins terminating in a major river. Fig.1 shows the AMBER stream database for Allegheny County in Pennsylvania.

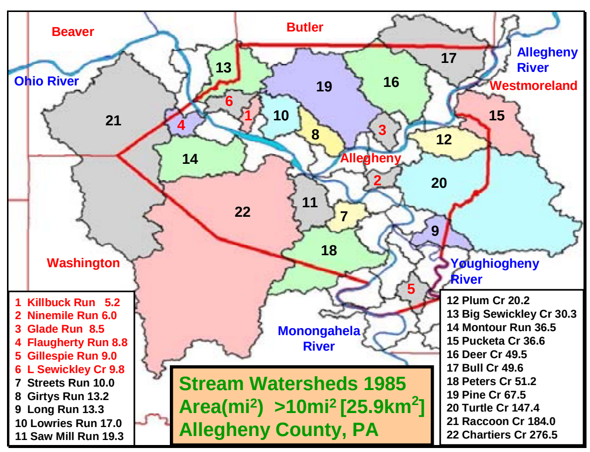

Fig. 1. Black number streams show the AMBER database for Allegheny County, PA in 1985. Red number streams added in 1987 for a minimum basin area of 5 mi^2.

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After the Etna, PA flash flood of 1986, when nine people died in the 6 mi^2 (15.5 km^2) Little Pine Creek watershed (a small tributary of Pine Creek, stream 19 in Fig. 1), the AMBER "minimum basin area" (MBA) was reduced to 5 mi^2 (13 km^2) in 1987.

In the years from 1985 to 1989 the AMBER program consisted of digitized map backgrounds (like the display of Fig. 1) for each county in the Pittsburgh NWSFO warning area, that were displayed on a RADAP-II graphic display called ICRAD (Davis and Rossi 1986). Radar rainfall estimates of 1-hour, 3-hour and storm total through 24 hours could be displayed. The computer graphic display for the polar rainfall data grid of RADAP-II was so slow that almost 60 seconds were needed to display the rainfall for Allegheny County. The slow display speed limited the utility of the software. The comparison of Flash Flood Guidance (FFG) with the RADAP-II rainfall required Average Basin Rainfall (ABR) for each stream watershed. So the lead author wrote the initial AMBER software that let the computer calculate ABR for each stream and then print out basins approaching FFG. With the first version of the AMBER software completed by May of 1990, the computation of ABR from radar rainfall estimates began.

The very first event using the AMBER was the Shadyside, OH flash flood of 1990 where 26 people died. AMBER's first attempt could hardly be called a success as shown in Fig. 2. The ABR was less than FFG and the program seemed a total failure.

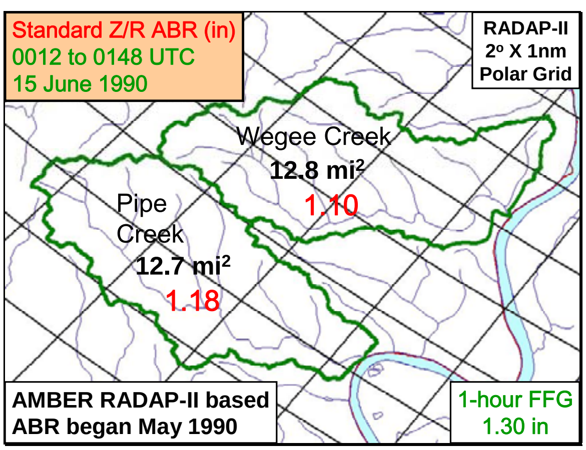

Fig. 2. Standard Z/R ABR for Shadyside, OH flash flood based on RADAP-II radar rainfall estimates.

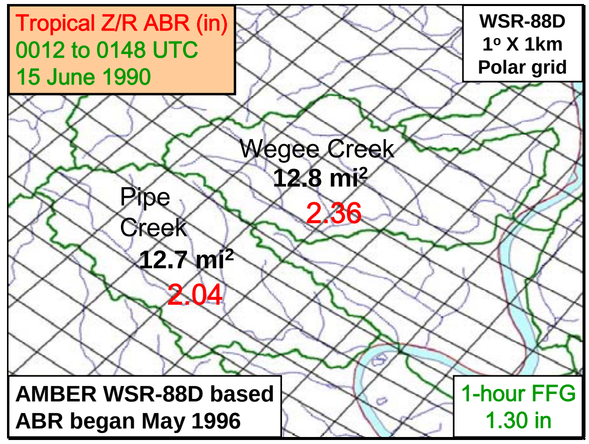

Fig. 3. Tropical Z/R ABR for Shadyside, OH flash flood based on RADAP-II radar rainfall estimates using the WSR-88d grid.

Two primary factors led to the apparent underestimation of rainfall in Pipe and Wegee Creek. First this was a tropical Z/R event, not related to any tropical storm (Davis, 2004b). Recalculating the ABR for the tropical Z/R relationship produces the results in Fig. 3. The Tropical ABR increases to about an inch over FFG for both creeks.

The second major factor that impacted the detection of the severe flash flooding that occurred near Shadyside, was the size of the watershed area. If the Pipe and Wegee watersheds are subdivided into smaller watershed segments, a very different ABR picture unfolds in Fig. 4.

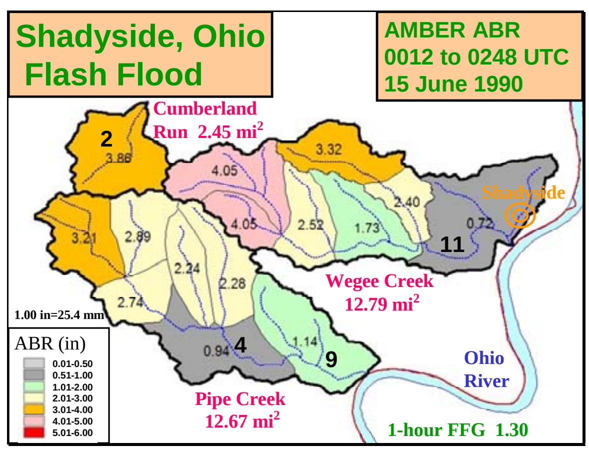

Fig. 4. Tropical Z/R ABR for Shadyside, OH flash flood on subdivided watersheds, based on RADAP-II radar rainfall estimates using the WSR-88d grid. Bold black numbers show location of flood fatalities.

Dividing both Pipe and Wegee Creek watersheds into seven basin segments, results in a much better depiction of the tremendous variation in rainfall that occurred across these two basins, both about 13 mi^2 (33.7 km^2) in area. By dividing these streams into 7 different stream segments, averaging less than 2 mi^2 (5 km^2), the ability of AMBER to detect the severe flash flood potential was greatly increased.

The Shadyside flood was a real watershed event in the development of AMBER. First tropical rainfall rates do occur in mid-latitudes without the presence of tropical storms. Using the tropical Z/R relationship about doubles the estimated ABR based on standard convective Z/R.

Notice in Fig. 3 the ABR in Wegee Creek is now larger than the ABR in Pipe Creek unlike the ABR in Fig. 2. This occurs because of the increased resolution of the WSR-88D rainfall grid compared to the grid of the RADAP-II rainfall (Davis and Drzal, 1991). The increased spatial resolution of the WSR-88D grid also allows for the computation of ABR in the small basin segments of Fig. 4. The coarser radar grid of the RADAP-II could not support ABR computations in these small watersheds.

In Fig. 4 notice that two people died in Cumberland Run, a watershed only 2.45 mi^2 (6.35 km^2) in area. Several additional flash floods through the 1990s in the Pittsburgh NWSFO county warning area clearly showed that watersheds of < 2 mi^2 (5 km^2) could produce significant flash flooding, indicating the need to display ABR for smaller flash flood basins.

When the National Basin Delineation project had to decide on a MBA for the FFMP stream basin database, the lead author proposed a value of 2 mi^2 (5 km^2). The actual MBA used by NBD project was 5,000 grid cells or 1.74 mi^2 (4.5 km^2).

Fig. 5 shows the FFMP basins created for Allegheny County in 2002 as delivered by NBD to the Pittsburgh NWSFO. Notice the average area of the basins in Allegheny County is 3.91 mi^2 (10.1 km^2), and some basins are larger than 14 mi^2 (36.3 km^2). While most of the large stream basins of Fig. 1 are broken into smaller stream segments in Fig. 5, several of the streams remain intact (black numbers in Fig. 5) intact. How does a stream like Girtys Run (Stream 8 in Fig. 1), with an area over

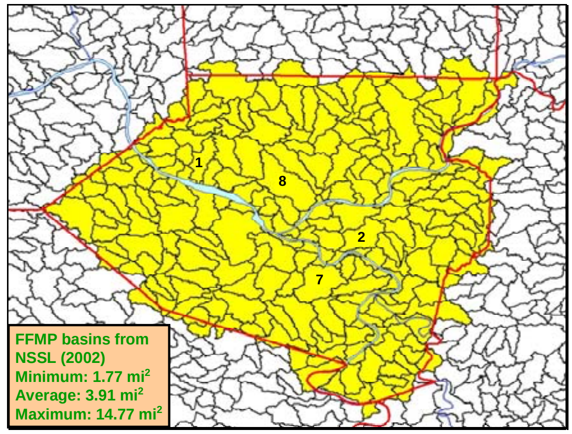

Fig. 5. FFMP NBD basins for Allegheny County PA in 2002. Black numbers identify undivided basins from Fig. 1.

13 mi^2 (34 km^2) remain as a single basin? In order for a stream to be subdivided by NBD, the stream must have a tributary larger than the MBA of 1.78 mi^2. Fig. 6 shows the stream channels in the Girtys Run watershed. Notice that the largest tributary in Girtys Run is Rochester Run, only 1.5 mi^2 (3.9 km^2) in area. Since no tributaries are larger than the MBA, Girtys run is delivered by NBD as a single watershed. The area of the Girtys Run basin is almost identical to the area of Pipe and Wegee Creeks from the Shadyside, OH event.

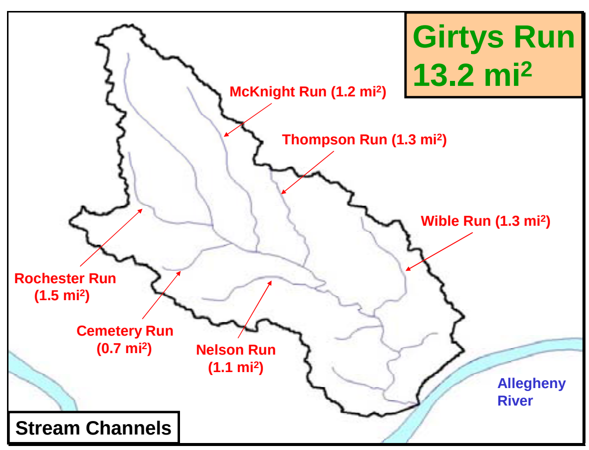

Fig. 6. Stream channels in the Girtys Run watershed.

As the Shadyside, OH event clearly shows, subdividing FFMP basins larger than 10 mi^2 (25.9 km^2) into smaller tributaries can be very important to FFMP's capability of detecting flash flooding. Heavy rain may fall in Rochester Run, while the Average Basin Rainfall (ABR) computed by FFMP for the entire Girtys Run watershed may not reflect the true flash flood threat in Rochester Run.

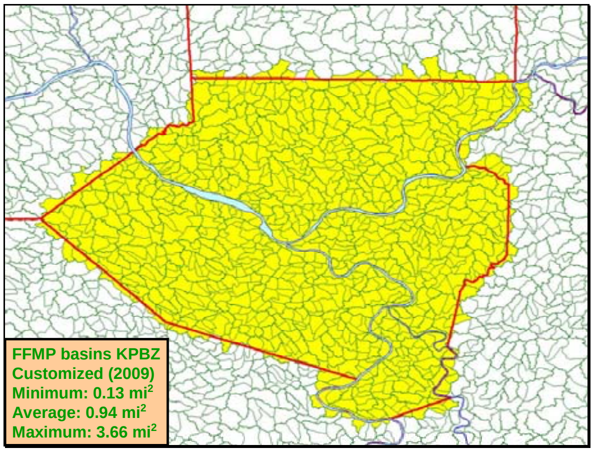

Fig. 7. Customized FFMP basins for Allegheny County, Pennsylvania

Fig. 7 shows the Pittsburgh NWSFO customized basins for the highly urbanized county of Allegheny in Pennsylvania, which includes the city of Pittsburgh. In Fig. 7 the average basin area of the customized basins (0.94 mi^2, 2.43 km^2) is less than the MBA (1.78 mi^2, 4.61 km^2) of the delivered NBD watersheds shown in Fig. 5. Dividing larger watersheds into smaller basin areas is one of the most effective means of improving the flash flood detection capability of FFMP.

The small stream layer of FFMP is uniquely designed to detect these small scale flash floods. The "area" of these FFMP small basin segments is the critical factor in determining the ability of FFMP to detect flash flooding. If certain FFMP basins, as delivered by the NBD are too large, each NWS forecast office has the ability to customize the NBD basins (Davis, R.S., A . T. Arthur, and P. Jendrowski, 2003). In the customization process, large basins can be divided into smaller basins, improving the detection of flash floods in FFMP. Basin customization can greatly enhance the capability of FFMP to detect flash floods, especially in highly urbanized watersheds.

Since basin area is such a critical factor in flash flood detection, adding area as a column in the FFMP basin table would provide very useful information to the flash flood forecaster.

3. TYPES OF FFMP BASINS

For the purpose of this paper, a "basin" will be defined as any of the individual FFMP stream basin segments that makes up the "county layer" or "small basin layer" of FFMP (basins in Fig. 5 and Fig. 7 for example). This paper will go into some detail about the nature of these FFMP "basins" describing not only their physical characteristics such as "area" and "flow accumulation", but also describing how the ABR computed by FFMP relates to flash flood threat in each of these "basins".

The small stream layer of FFMP is designed to detect the short duration, high rainfall rate events common to the great majority of flash floods. Most of these flash floods occur in watersheds less than 25 mi^2 (65 km^2) in area. Flash floods can and do occur on much larger watersheds. The ABR for a specific FFMP basin provides little support for detecting flash floods on watersheds with areas of 25 to 500 mi^2 (65 to 1295 km^2). FFMP provides no support for detecting flooding of major river watersheds, defined in this paper as watersheds greater than 500 mi^2 in area.

Before proceeding to describe the different types of FFMP basins, the "flow accumulation" provided by the NBD analysis must be defined. Flow accumulation can be defined as the total upstream contributing area of any single FFMP basin. Flow accumulation is an area measurement and is provided in units of square miles in the NBD data set. The flow accumulation for a specific FFMP basin is computed by summing the area of all upstream contributing basins to that specific basin, plus the area of the specific FFMP basin.

The stream connectivity of the FFMP basins provided by NBD allows the computation of flow accumulation. The NBD connectivity is created by first assigning each FFMP basin a numeric "Basin_ID". Since each FFMP basin is allowed to have only a single outflow point, each FFMP basin flows into only one downstream FFMP basin. Every FFMP basin is then assigned a "Parent_ID", which is the Basin_ID of its downstream basin. With a "Parent_ID" assigned to each FFMP basin, the upstream contributing basins to any FFMP basin can be determined and their Basin_IDs stored in the upstream(1-9) parameters of the NBD database. With the upstream contributing basins defined for each FFMP basin, the flow accumulation can be calculated.

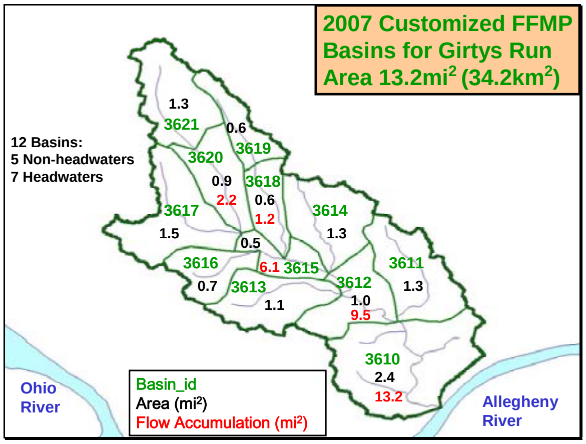

Fig. 8. Plot of Area, Flow Accumulation, and Basin_ID for the Girtys Run watershed. Green numbers are Basin_IDs. The black number is basin area. The thin blue lines are stream channels. The red numbers are flow accumulation for all non-headwaters basins.

Fig. 8 shows the Girtys Run watershed of Fig. 6 is divided into 12 FFMP basins. The stream channels of Fig. 8 allow the visual determination of upstream and downstream basins. For example, segment 3612 has a Parent_ID of 3610, since the stream segment in 3612 flows into 3610. Basin 3612 in Fig. 8 has three upstream inflow basins (3613, 3614 and 3615). These three Basin_IDs would appear as Upstream1, Upstream2, and Upstream3 entries in the NBD database for basin 3612.

The Parent_ID and Upstream(1-9) parameters allow NBD to calculate the flow accumulation, which is defined as the total upstream contributing area of any FFMP basin. The values of flow accumulation in Fig. 8 are shown for non-headwaters basins only. In a headwaters basin segment such as segment 3611, the area of the basin is equal to the flow accumulation, since 3611 has no upstream contributing area. The flow accumulation of basin 3610 is the area on the entire Girtys Run watershed.

This headwaters vs. non-headwaters designation defines the two different types of FFMP basins. The type of basin becomes significant to FFMP since the ABR for headwaters vs. non-headwaters basins provides very different guidance for potential flash flood threat as will be described in the next section. The FFMP basin type could be most easily determined by displaying the basin "area" and "flow accumulation" of the basin in the FFMP basin threat table. Currently there is no way to differentiate these two basin types in the basin threat table. As a quick fix at the Pittsburgh NWSFO, area and flow accumulation have been appended to the basin name.

4. DETERMINING FLOOD THREAT IN DIFFERENT TYPES OF FFMP BASINS

Not all FFMP basins are created equal. The headwaters and non-headwaters basins described in the last section provide very different guidance on the potential for flash flooding for the stream channels contained in the basin. Look at an extreme example of two FFMP non-headwaters basins in Fig. 9.

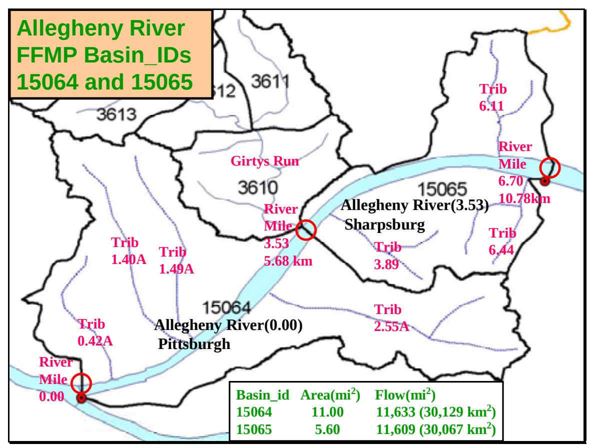

Fig. 9. FFMP River segment basins 15064 and 15065 near Girtys Run. Tributaries and river miles are labeled in red.

Basins 15064 and 15065 contain segments of the Allegheny River. Basin 15064 contains the Allegheny River segment from river mile 0.00 to river mile 3.53. The FFMP "Diff" Column (ABR-FFG) for basin 15064 would not correctly identify a flash flood threat on the Allegheny River channel. The flow accumulation of 11,633 mi^2 for basin 15064 clearly indicates this basin is a river segment (flow accumulation > 500 mi^2). However, the FFMP "Diff" column entry in the FFMP basin table for 15064 would correctly identify the flash flood threat for the small tributaries of Basin_ID 15064 in Fig. 9, such as Tributaries: 0.42A, 1.40A, 1.49A and 2.55A. These small tributaries, which do not have stream names, are named in FFMP based on the river mile of the tributary mouth into the Allegheny River. The name of Tributary 0.42A appears in the FFMP basin table as “Allegheny River_trib(0.42A)”.

While the main stem river segment in a FFMP basin would not be viewed as a potential flash flood threat, the same can not be said for a stream channel in a FFMP non-headwaters basin. The flash flood threat for a main stem stream or creek in any non-headwaters basin of FFMP can not be determined by the “Diff” column entry for that single basin. This fact has important consequences for all non-headwaters basins in the FFMP basin table.

FFMP determines flash flood threat in the ‘Diff” column of the FFMP basin table by subtracting Flash Flood Guidance (FFG) from the Average Basin Rainfall (ABR) for that particular basin. This use of the “Diff” Column entry in FFMP to determine flash flood threat is valid for all stream channels contained in any headwaters basin. In the Pittsburgh NWSFO stream database 6,074 of 11,353 basins are headwaters basins. In addition, 473 of the 11,353 basins are river segment basins. In these river segment basins, the “Diff” Column does indeed indicate real flash flood potential for the small tributaries flowing into the main stem river. The only basins that are not correctly indicating the true flash flood potential in the FFMP basin table are the remaining 4,806 non-headwaters basins with flow accumulations less than 500 mi^2.

Each non-headwaters FFMP basin contains a main stem stream segment that can be a flowing stream, a dry arroyo, or a dry valley bottom. To determine flood risk of any stream segment in a non-headwaters basin, the observed ABR for the entire upstream contributing must be examined. In Fig. 10 the main stream channel segments are shows as bold blue arrows. The figures that follow show the upstream contributing area for each of these stream segments. Look at the following figures to see how the flash flood threat can be determined for the Girtys Run main stem basins, by computing ABR for the upstream contributing area

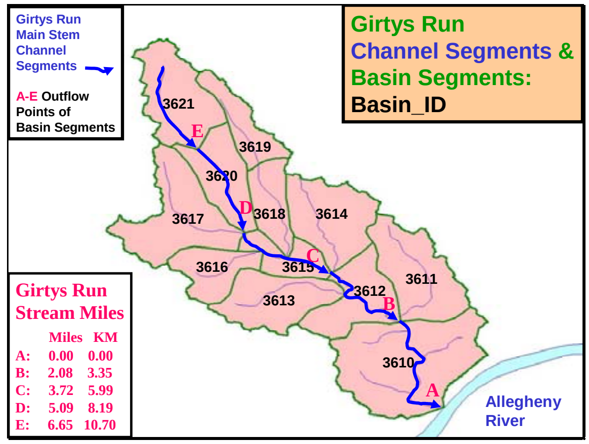

Fig. 10. Stream channel segments along the main stem of Girtys Run. Black numbers are Basin_ID and red letters are outflow points of each main stem basin.

shaded in pink. The upstream contributing area will become larger for each main stem stream segment further downstream. As the upstream contributing area becomes larger the chance of the upstream ABR being different from the local ABR increases dramatically. Fig.11 shows the upstream contributing area for basin 3620. The combined ABR of basins 3620 and 3621 is needed to determine the flood threat on the stream segment shaded in heavy blue in basin 3620.

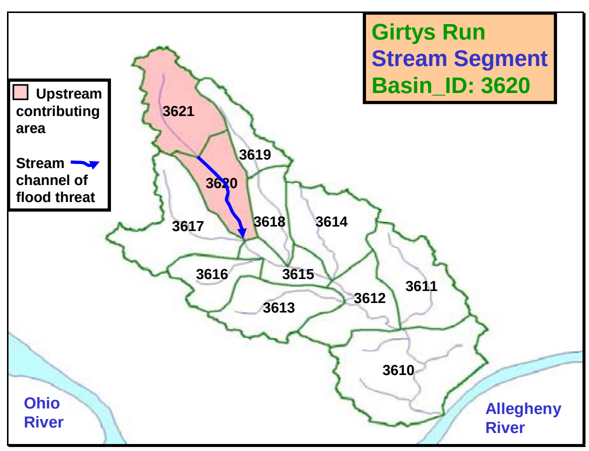

Fig. 11. Upstream contributing area (shaded in pink) for the non-headwaters basin 3620.

Figs. 12 to 15 show the contributing upstream area for the remaining four non-headwaters basins of Girtys Run.

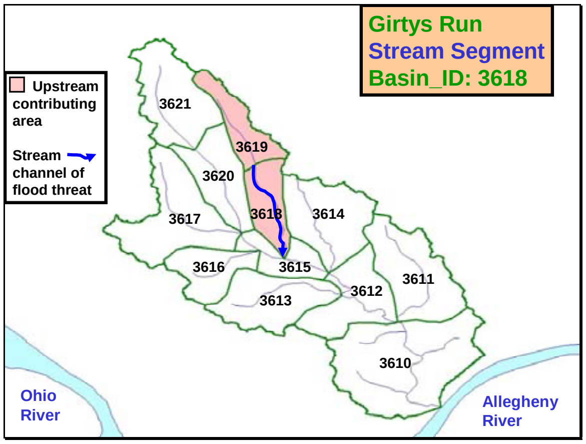

Fig. 12. Contributing upstream area for non-headwaters basin 3618 in Girtys Run.

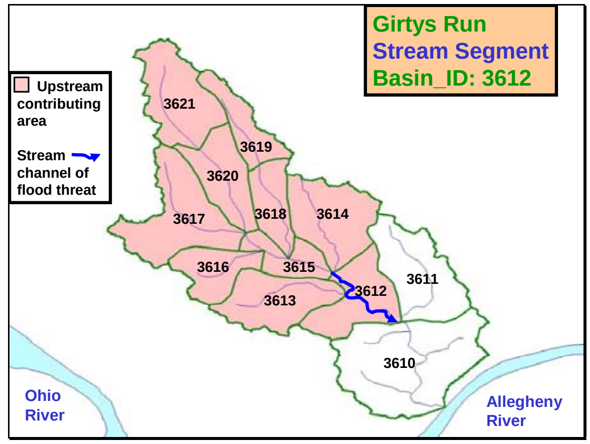

Fig. 14. Contributing upstream area for non-headwaters basin 3612 in Girtys Run

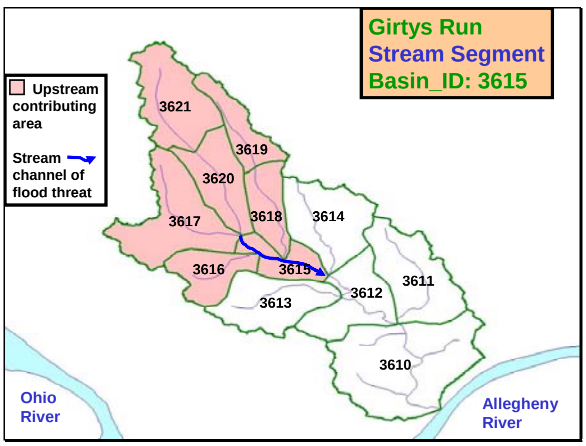

Fig. 13. Contributing upstream area for non-headwaters basin 3615 in Girtys Run.

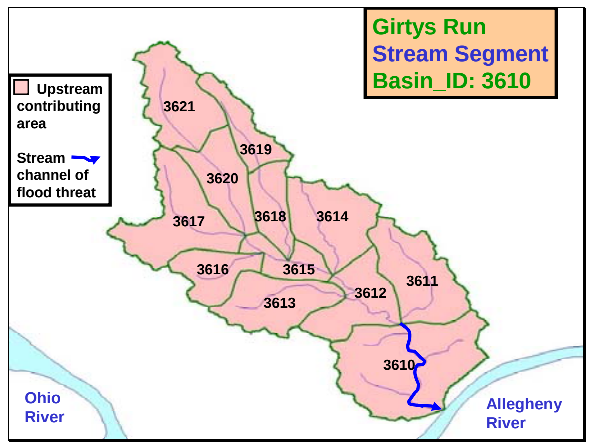

Fig. 15. Contributing upstream area for non-headwaters basin 3610 in Girtys Run

As a general rule, the larger the upstream contributing area, the further downstream the basin segment, and the more unlikely the local ABR in the single FFMP non-headwaters basin will reflect the true flash flood threat of the main stream channel in that basin. The FFMP user must recognize that the flash flood threat for the heavy blue stream segment in basin 3615 is not correctly depicted by the "Diff" Column for basin 3615. If the forecaster does not recognize this short coming of FFMP, a flash flood warning may be issued that is not needed. More importantly a necessary warning may not be issued, or the warning may be issued, but may not be extended far enough downstream.

This does not mean that the FFMP entry in the basin table for a non-headwaters basin such as 3610 of Girtys Run should be ignored. On the contrary, the FFMP "Diff" column (ABR –FFG) for basin 3610 may indicate a serious flash flood risk for the three small tributaries of basin 3610 (thin blue lines in Fig. 15). The "Diff" column for basin 3610 will not indicate the true flood risk along the main stream channel of 3610, represented by the heavy blue arrow.

These impacts will become even more serious in watersheds of 100 mi^2 (250 km^2) to 500 mi^2 (1,295 km^2) in area, like the Chartiers Creek watershed of Fig. 1. Is there a way for FFMP to address this shortcoming of failing to detect the potential for flash flooding in these larger watersheds?

5. BASIN UPSTREAM RAINFALL (BUR)

A possible solution for determining flash flood potential in the larger watersheds is to compute the ABR for the entire upstream contributing area of each non-headwaters basin. This upstream ABR could be called "Basin Upstream Rainfall" (BUR) to distinguish the ABR of the upstream contributing area from the local ABR as now displayed in FFMP. The BUR could be added as an optional column in the FFMP basin table, with both the ABR and the BUR displayed for each basin.

All the parameters needed to calculate BUR are currently available in FFMP. The parameters required for the computation of BUR are the area of each basin, and the ABR of each basin, which is already computed in FFMP. The upstream basin connectivity will provide the required list of upstream basins needed for each BUR computation. The BUR is computed by multiplying the ABR for a basin times the basin's area. This product is a volume of water for each basin. The volume of water for each basin is summed and the grand total divided by the total area of all basins.

The sections that follow will compare ABR as currently displayed in FFMP with the BUR for several flash flood events. Several of the case studies will show more examples of the extreme gradients of rainfall that can occur in relatively small basins. The observed tight gradient of rainfall rates is typical of rainfall in deep warm convection. Davis (2001) shows the observed rainfall rates for standard Z/R in a typical supercell covers only about 8 mi^2 (20 km^2) for > 3 in hr^{-1} rainfall rates (75 mm hr-1) and just 2 mi^2 (5 km^2) for >5 in hr^{-1} (125 mm hr^{-1}) rainfall rates. For the Tropical Z/R relationship, these areas increase some, but are still only 16 mi^2 (40 km^2) for rainfall rates > 3 in hr^{-1} and 8 mi^2 (20 km^2) for rainfall rates >5 in hr^{-1} (125 mm hr^{-1}). This limited areal extent of extreme rainfall rates is the primary reason that the great majority of flash floods occur in basins < 25 mi^2 (65 km^2) in area.

6. SHADYSIDE, OH 1990

The Shadyside, OH flash flood in 1990, as shown in Fig. 4, was an event where heavy rain fell in the headwaters of both Pipe and Wegee Creek. Much less rain fell in the downstream basins where most of the people were swept away. The ABR in the headwaters reached 4 inches in a little more than one hour, while the downstream areas received around an inch or less of rain. The BUR in Fig. 16 clearly shows an increased flood threat in the basins near the mouth of both creeks where most of the deaths occurred. Notice the BUR in the basin near the mouth of each creek, 2.36 inches for Wegee and 2.04 inches for Pipe Creek, are the same values of ABR in Fig. 3 for each creek as a whole.

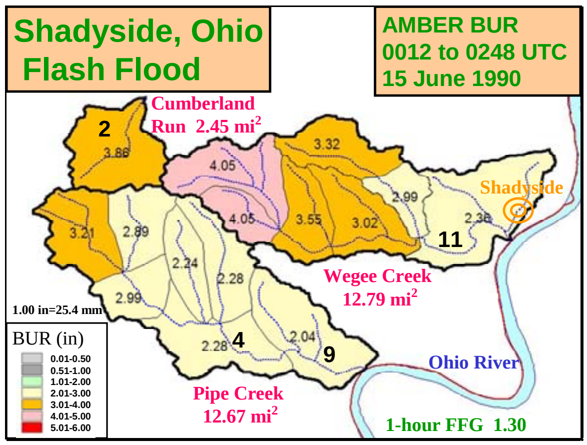

Fig. 16. Tropical Z/R BUR for Pipe and Wegee Creeks 15 June 1990 from 0012 to 0248 UTC. Bold black figures shows the fatalities in each basin.

7. LITTLE PINE CREEK – 30 MAY 1986

The short duration, high intensity rainfall flash flood is the most difficult to detect and provides the least opportunity for significant lead time. These high intensity events tend to occur in very small watersheds and result from slow-moving or nearly stationary thunderstorms. Taking a small basin (6.16 mi^2, 15.95 km^2) such as Little Pine Creek near Etna, PA and dividing the watershed into three nearly equal basins can provide increased lead time.

In the figures that follow, the Little Pine Creek watershed has been given a Basin_ID of 30011, while the three FFMP basin segments of the watershed are identified by Basin_IDs 3629, 3630, and 3631 from the mouth to the headwaters. Saxonburg Boulevard parallels the stream channel through basin 3629. By 2100 UTC nine

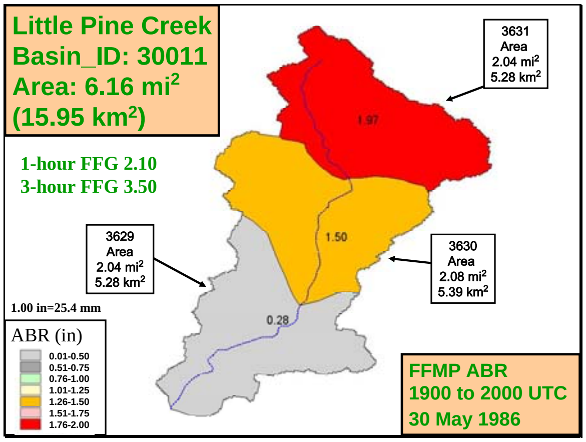

Fig.17. Standard Z/R ABR for Little Pine Creek, 30 May 1986 for 1900 to 2000 UTC.

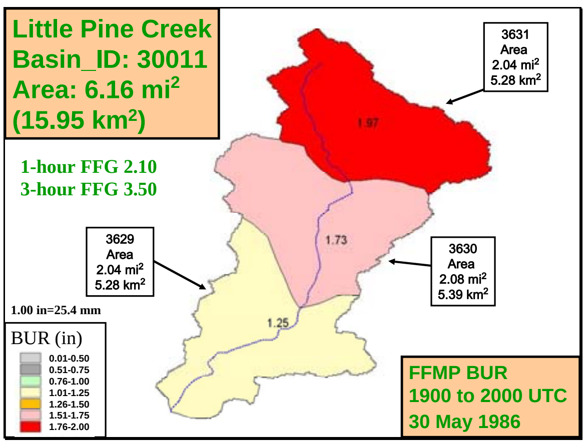

Fig.18. Standard Z/R BUR for Little Pine Creek, 30 May 1986 for 1900 to 2000 UTC.

people in their automobiles and trucks were swept off the road. At 2000 UTC the plot in Fig. 17 shows the ABR that would correspond to the FFMP one-hour time duration display. Almost no rain has fallen in basin 3629, while basin 3631 in the headwaters of the creek has received almost two inches of rain. The BUR plot for 2000 UTC in Fig. 18 shows the increased flood threat in the downstream basin where the BUR is almost an inch higher than the ABR from Fig. 17.

The most intense rainfall for the event falls from 2000 to 2100 UTC and the ABR display corresponding to the FFMP 2-hour time duration ending at 2100 UTC is shown in Fig. 19. While almost 3 inches of rain has now fallen in basin 3629 over 6 inches has

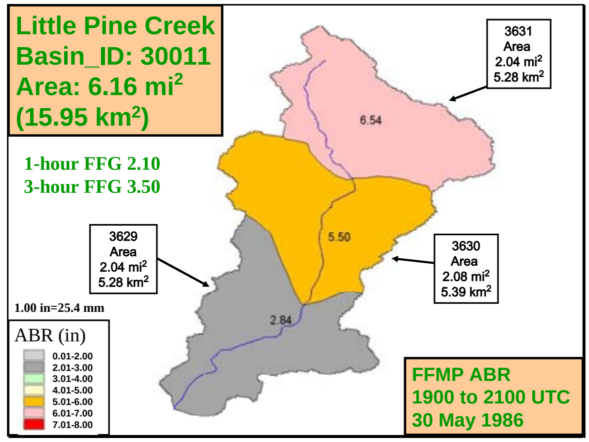

Fig.19. Standard Z/R ABR for Little Pine Creek, 30 May 1986 for 1900 to 2100 UTC.

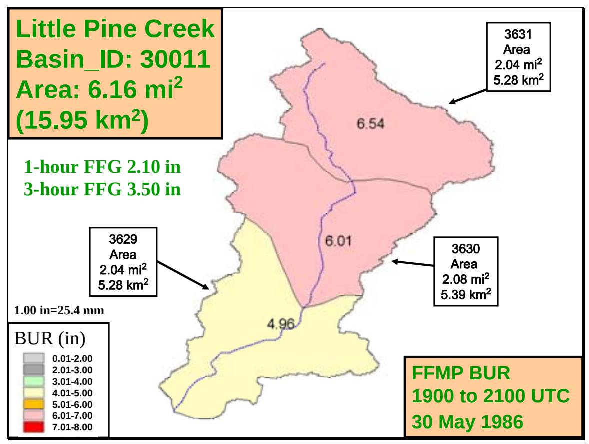

Fig.20. Standard Z/R BUR for Little Pine Creek, 30 May 1986 for 1900 to 2100 UTC.

inundated the headwaters (basin 3631) of Little Pine Creek and the flood wave is moving downstream. The severe flood threat in the downstream basin (3629) is now clearly defined by the BUR estimate of almost 5 inches of rain.

By 2200 UTC the rain is tapering of in the headwaters with less than one inch additional rain in the last hour. The lead author participated in the bucket survey after this flood, and two independent observers who measured 8+ inches of rain were found. Both observers were near the northern border of the headwaters basin (3631) and both observers were located in the single radar RADAP-II range bin that had the heaviest rainfall estimate. The final ABR rainfall total in Fig. 21 shows that over 7 inches of rain fell in the headwaters

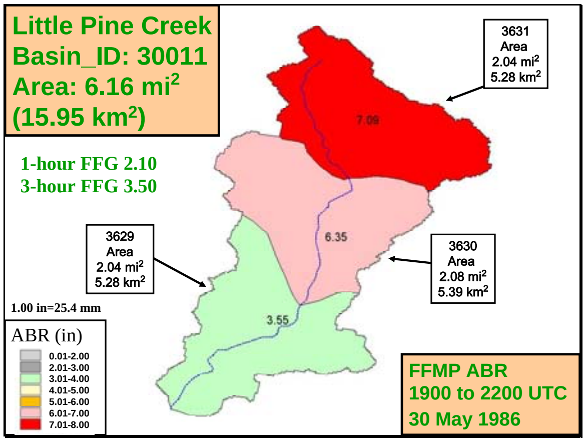

Fig.21. Standard Z/R ABR for Little Pine Creek, 30 May 1986 for 1900 to 2200 UTC.

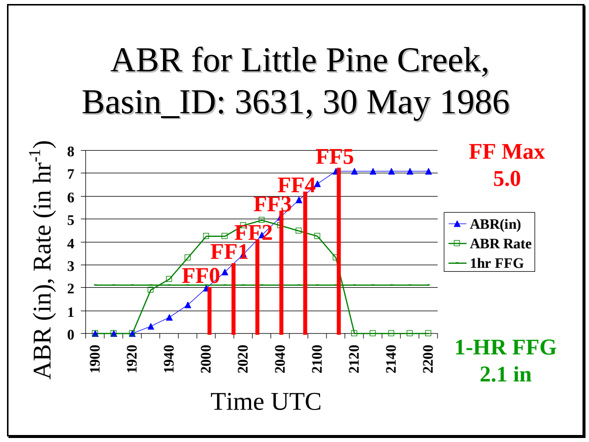

Fig. 23. FFMP basin trend graph for Basin_ID 3631 showing the ABR, ABR Rate and FFG for the 30 May 1986.

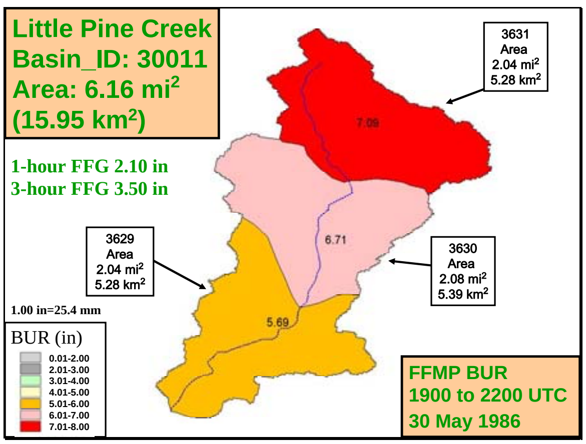

Fig.22. Standard Z/R BUR for Little Pine Creek, 30 May 1986 for 1900 to 2200 UTC.

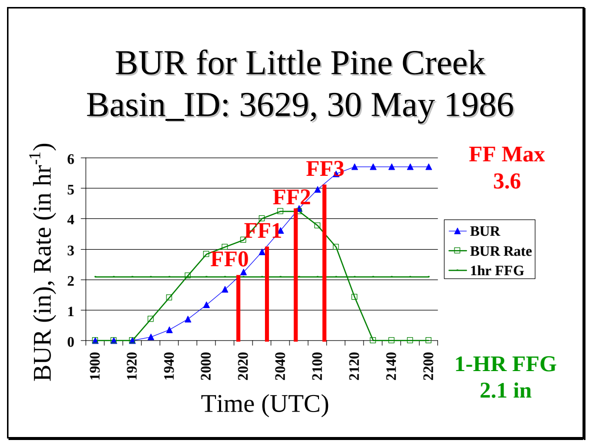

Fig. 24. FFMP basin trend graph for Basin_ID 30011/3629 showing the BUR, BUR Rate and FFG for the 30 May 1986.

with just about 3.5 inches in basin 3129, where all 9 fatalities occurred. The BUR in Fig. 22 shows a much increased flood threat near the mouth of the creek (3629), compared to the ABR of Fig. 21.

The ABR and ABR Rate trend graphs in FFMP now provide plots of 1hr, 3hr, 6hr, 12hr and 24 hr time durations. The graph in Fig. 23 shows what the FFMP basin trend graph would look like for Basin_ID 3631 on 30 May 1986. The red vertical lines have been added to show at what time the Blue ABR trace reach FFG (FFG0), one inch over FFG (FFG1), two inches over FFG (FFG2), etc. Fig. 24. shows the same graph of BUR for Basin_ID 3629. If the Little Pine Creek basin was not divided into three parts in the FFMP database, then Fig. 24 would represent the ABR of the entire Little Pine Creek watershed, (Basin_ID 30011) as delivered by NBD.

Comparing these two graphs, an additional 20 minutes of lead time would have been gained if a warning was issued when the ABR first reached FFG at 2000 UTC in Fig. 23 and at 2020 in Fig. 24. The extreme intensity of the event was better depicted by the headwaters in Fig. 23 reaching 5 inches over FFG, compared to 3.6 inches over FFG in Fig. 24 for the entire watershed. BUR may most effectively be used to determine the downstream extent of a warning, but should not be used in place of ABR observed in the headwaters for the warning issuance. This case is another solid indicator of the value of dividing larger

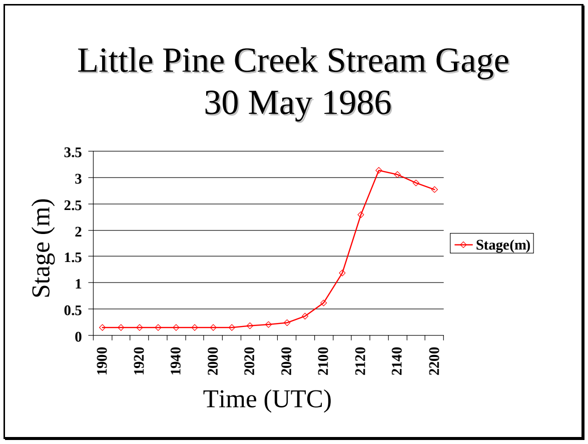

Fig. 25. Stream gage on Little Pine Creek near the mouth of basin 30011.

watersheds, like Little Pine Creek only 6 mi^2 (16 km^2) in area, into even smaller FFMP basins.

Small watersheds like Little Pine Creek seldom have a stream gage. The Army Corps of Engineers has a flood control project on Pine Creek and did establish a stream gage on the Little Pine Creek watershed. The gage was in operation during the flood and the trace of the stage is shown in Fig. 25, showing the very rapid rise as the flood wave traveled downstream.

8. GIRTYS RUN -- 09 AUGUST 2007

A serious flash flood hit the city of Millvale, which is located in the most downstream basin segment of Girtys Run. All 12 basin segments in the Girtys Run watershed are highly urbanized. Portions of the main stream channel through Millvale are in underground culverts. Because of the high degree of urbanization, the FFG has been locally modified to 0.70 inches for one hour FFG and 1.00 inches for three hour FFG (Davis, 2004a). Experience with past flood events in the Girtys Run basin has shown that one inch of rain in an hour brings the creek to near bank full, and two inches in one hour produces significant flooding of homes and streets.

Looking at the observed ABR in Fig. 26 the basin containing Millvale received the least rainfall (1.70 inches), but the headwaters areas of Girtys Run had significantly more rain. All of the rain fell in a time period of about an hour and fifteen

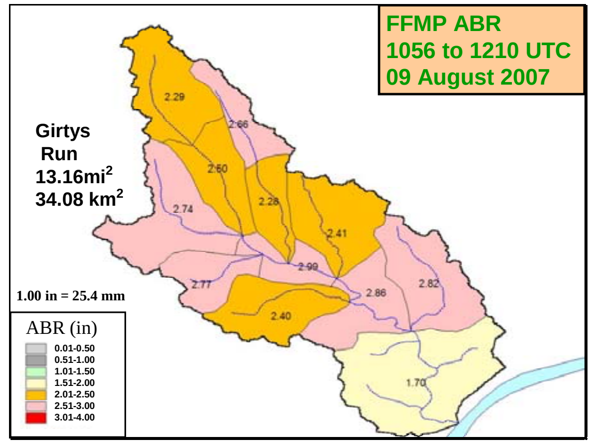

Fig. 26. Tropical Z/R ABR for Girtys Run on 09 August 2007 from 1056 to 1210 GMT.

minutes. Davis (2002) has shown that the "Diff" column in FFMP (ABR – FFG) can be considered a flash flood index similar to the Fujita Index for Tornado intensity, with higher values of FFMP "Diff" (ABR – FFG) directly related to the severity of the observed flash flooding.

Fig. 27 shows the corresponding BUR computation for the 09 August 2007 event in Girtys Run. Notice that the basin containing

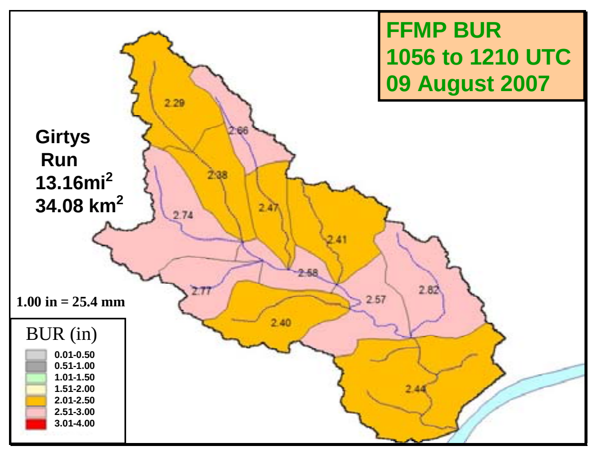

Fig. 27. Tropical Z/R BUR for Girtys Run on 09 August 2007 from 1056 to 1210 GMT.

the city of Millvale has a BUR of 2.44 inches compared to an ABR of 1.70 inches in Fig. 26. Serious flash flooding did occur along the main stem of the Girtys Run stream channel in the city of Millvale. The BUR value of 2.44 (1.74 inches over FFG) indicated the increased flood risk for the city of Millvale.

9. GIRTYS RUN – 17\18 JUNE 2009

A serious urban flash flood occurred across portions of the city of Pittsburgh during the evening hours of 17June 2009. While serious flash flooding was reported in the Oakland section of the city and east into Ninemile Run (stream 2 in Fig. 1) and the Turtle Creek basin (stream 20 in Fig.1), the Girtys Run watershed was on the northern fringe of the heavy rain. Some basement flooding was reported in the city of Millvale, but Girtys Run did not flow out of its banks during this event.

Unlike the August 2007 flood in Girtys Run, Fig. 28 shows the downstream portion of the watershed received more rainfall that the headwaters. When heavier rain occurs in the headwaters the BUR will be increased in the downstream portion of the watershed. When the heaviest rain falls near the mouth of a watershed, the downstream BUR will be reduced. Notice how the BUR in Fig. 29 indicated a much reduced flood threat for the Millvale main stem channel. But the “Diff” (ABR-FFG) flood threat for the small tributaries in basin 3629 remains and some basement flooding was observed.

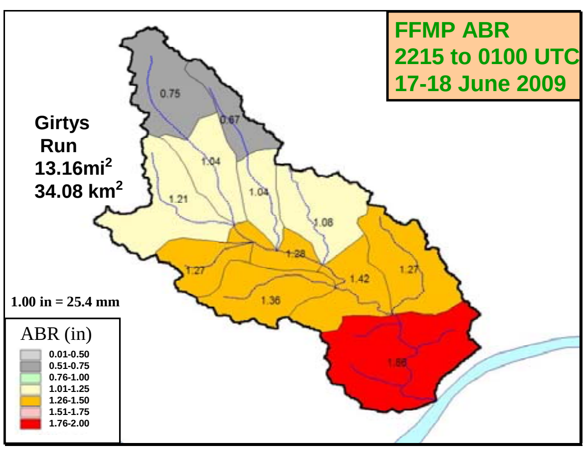

Fig. 28. Standard Z/R ABR for Girtys Run on 17-18 June 2009 from 2215 to 0100 GMT.

The ABR shown in Fig. 28 at Millvale was 1.86 inches was reduced to 1.25 inches with the BUR computation. The time duration of the rain was two hours and 45 minutes with the 3-hour modified urban FFG of one inch in three hours was used for this event.

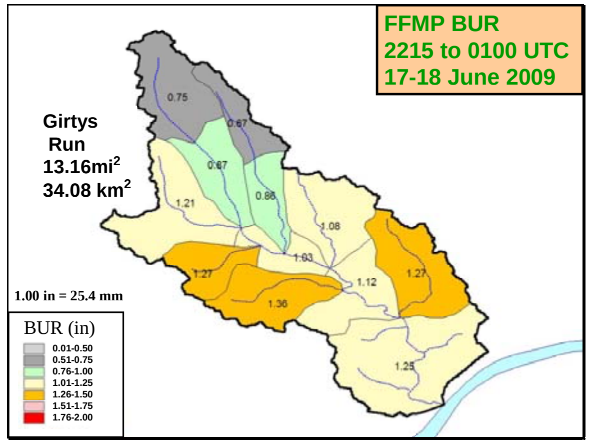

Fig. 29. Standard Z/R BUR for Girtys Run on 17-18 June 2009 from 2215 to 0100 GMT.

10. GIRTYS RUN – 17 September 2004

Widespread rainfall from the remnants of Hurricane Ivan produced serious stream flooding across most of Allegheny County. The Girtys run watershed was no exception and serious flash flooding resulted from the ABR shown in Fig. 30. Heavy rain with tropical storms tends to be spread across

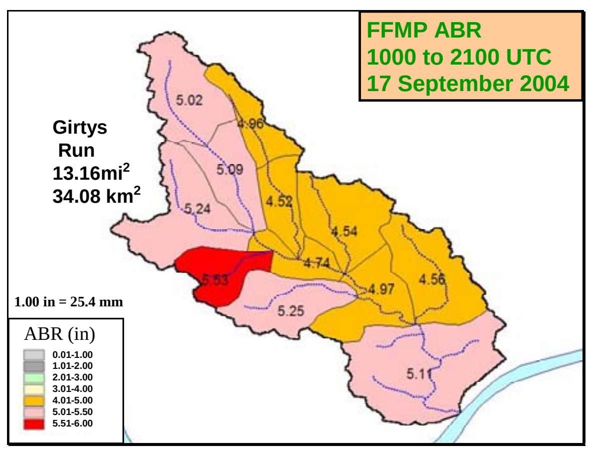

Fig. 30. Tropical Z/R ABR for Girtys Run on 17 September 2004 from 1000 to 2100 GMT.

larger areas with less spatial variation usually observed with deep warm summer type convective events. Notice that the BUR computation for Millvale does not change much, from 5.11 inches in Fig. 30 to 4.98 inches in the BUR computations shown in Fig. 31.

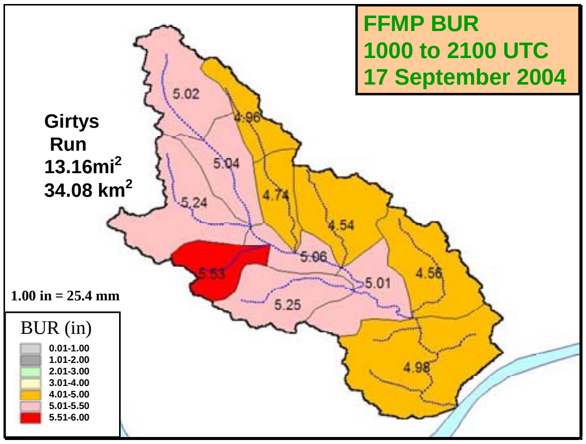

Fig. 31. Tropical Z/R BUR for Girtys Run on 17 September 2004 from 1000 to 2100 GMT.

Fig. 32 corresponds to the 24-hour FFMP Basin Trend Graph. The rainfall rate, the green trace in this figure, is actually the one hour rainfall and the blue trace shows the total rainfall accumulation of 6 inches. Is this a flash flood with a rainfall duration of over 12 hours? Enough rain fell in the first 8 hours to reach the 6-hour FFG by about 17 UTC. The heaviest rain fell from 17-20 UTC.

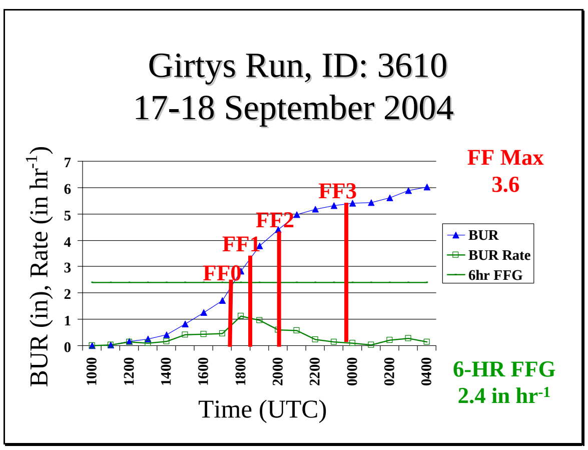

Fig. 32. FFMP Basin Trend Graph of BUR for Girtys Run, Basin_ID 3610

This heavy burst of rain in three hours, just as the stream had reached a near bank full level, cause a rapid stream rise and widespread flooding from 1700 to 2000 UTC. It could be argued that this was indeed a flash flood from 1700 to 2000 UTC with rapid stream rises that were truly life threatening. The first eight hours of rain just set the table for the main event to follow.

11. POSSIBLE FFMP SOLUTIONS FOR LARGE WATERSHEDS

FFMP does an excellent job of detecting flash floods in watersheds of 5 mi^2 or less. The FFMP support for the wide variety of larger watershed areas, such as those displayed in Fig. 1 is not nearly as robust as the detection capability afforded by the small stream database of FFMP. How can FFMP be improved to better support the detection of flash flood on larger watersheds of 25 to 500 mi^2? There are several possible solutions to the detection of flash flooding on larger watersheds. The authors will put forward four different ideas and try to show which might be most effective and useful.

11.1 *Add map Backgrounds*

Map backgrounds of the larger watersheds can be created from the small stream data base provided by NBD. The map overlay solution has been in operational use at the Pittsburgh NWSFO since 2004. Fig. 33 shows a portion of an aggregated stream layer map overlay for basins of 5 mi^2 (13 km^2) to 50 mi^2 (130 km^2) for the portion of Allegheny County north of the Allegheny River. Basins with the letter P in Fig. 22 are parts of the Pine Creek (Stream 19 of Fig. 1), broken into its smaller tributaries, including Little Pine Creek (Basin_ID 30011) which is immediately adjacent to basin 3. The Pittsburgh NWSFO is using an aggregated stream layer

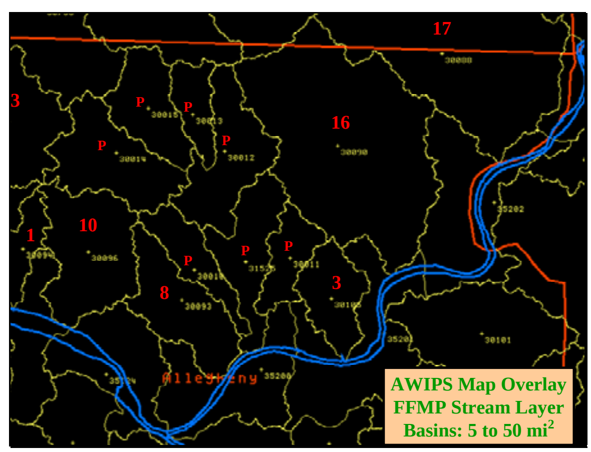

Fig. 33. AWIPS map overlay of aggregated streams for use with FFMP. Red numbers correspond to the basin numbers in Fig. 1.

(Fig. 33) with basins of 5 mi^2 (13 km^2) to 50 mi^2 (130 km^2), and a larger aggregated “Primary” stream layer for watersheds of 50 mi^2 (130 km^2) to 500 mi^2(1,295 km^2). Fig. 34 shows the 24-hour ABR for the IVAN flood event. Two watersheds from the ‘Primary” stream layer (Chartiers Creek, stream 22 and Pine Creek, stream 19, from Fig. 1) are displayed in Fig. 34. A major drawback to the watershed boundary approach is that the user must visually attempt to construct the ABR for the larger watershed basin by averaging the multiple FFMP basins contained within the watershed boundary.

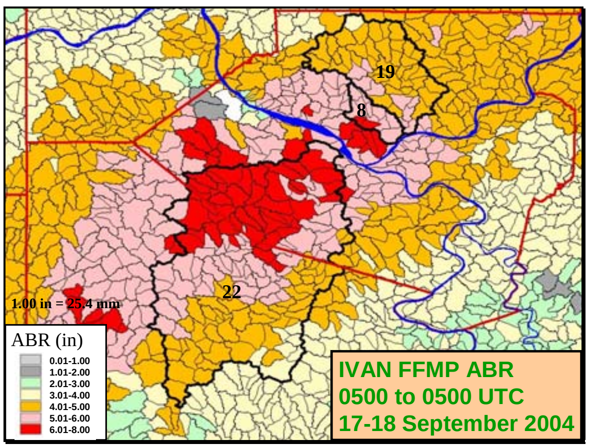

Fig 34. 24-Hour ABR for Allegheny County for 17-18 September 2004. Black numbers are stream numbers from Fig. 1.

The ABR for the entire Chartiers Creek watershed, 276.6 mi^2 in area (716.4 km^2), may be a very useful number to know, especially during an event like Ivan. Try to visually estimate the average ABR the 288 FFMP basins of Chartiers Creek displayed in Fig. 34. Zooming in on the Allegheny County portion of Chartiers Creek in Fig. 35, the main stem FFMP basins are highlighted in yellow and labeled with their Basin_ID. Notice the mouth of Chartiers Creek is basin 1408. The BUR for basin 1408 is plotted as the FFMP basin trend graph in Fig. 36. Remember the blue trace of accumulated rainfall is the Average Basin Rainfall over the entire 276.6 mi^2 (716.4 km^2), of the Chartiers Creek Basin. If you visually estimated an ABR of 5.7 inches from Fig. 34, you were correct.

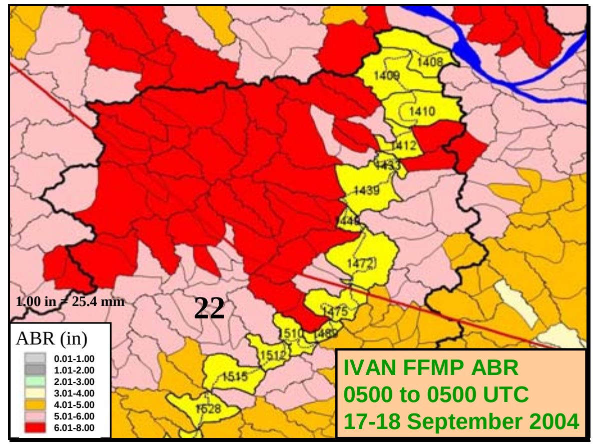

Fig. 35. A zoom of Fig. 34. showing the Allegheny County portion of Chartiers Creek, Stream 22 in Fig. 34. Yellow highlighted basins are the main stream channel basins of Chartiers Creek and are labeled with their Basin_ID.

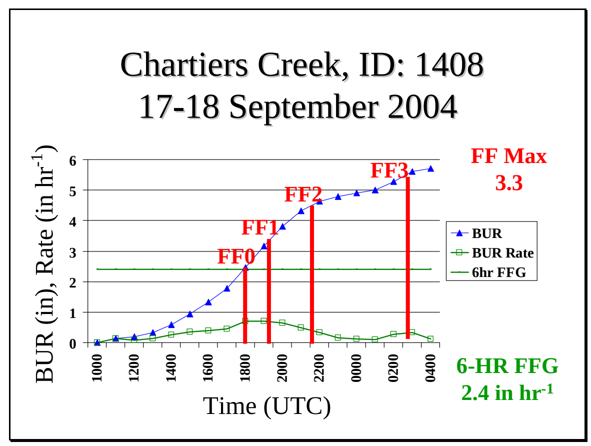

Fig. 36. Tropical Z/R Basin Trend Graph of BUR for Chartiers Creek Basin_ID 1408 for 17-18 September 2004.

Notice that the maximum hourly BUR occurs from 18 to 19 UTC. Watersheds greater than 100 mi^2 (259 km^2) are difficult to inundate with high rainfall rates, so lower hourly rates of BUR will typically be observed in larger watersheds.

11.2 *Add Aggregated Basin Layers*

A second method to support flash flood detection on large watersheds would be to have FFMP compute ABR for the larger aggregated basins directly, as FFMP does now for the smallest basin layer. A limited version of this method is in place as the HUC0, HUC1, HUC2, HUC3, and HUC4 aggregated basin layers in the 2009 version of FFMP. The FFMP users guide at the web site listed below provides additional information on HUC aggregated layers. (http://www.nws.noaa.gov/mdl/ffmp/FFMPA_Guide_Users_OB9.pdf)

Fig. 37 shows the FFMP layer selection menu that allows the display of the HUC_0 through HUC_4 layers. The number of HUC layers will vary from office to office and is determined by the FFMP localization process. While there seem to be a lot of

Fig. 37. FFMP layer selection menu.

choices in this menu, this section describes what each of these choices represent.

The most widely used FFMP display mode is the second choice, "County". The "County" display mode opens a table of all counties in the local warning area. The heaviest rainfall in each county is displayed and by left clicking on the county name, the FFMP basin table will display a list of all FFMP basins in that county only. FFMP was designed this way since flash flood warnings were issued for counties in years past, and displaying the thousands of FFMP basin for the entire warning area was too cumbersome to work with. Right clicking on a single basin in the FFMP basin table produces the FFMP Basin Trend Graph which is perhaps the most valuable of all the FFMP displays. The county display is most frequently used in all NWS forecast offices.

The "All & Only Small Basins" mode displays all FFMP basins for the entire warning area and puts thousands of basins into a single table. The large number of basins in the table makes this mode cumbersome to use and is of limited operational value. The original design of FFMP was to use the "county" selection table to display only the basins for a single county, reducing the number of basin in the table to a much more manageable list.

The HUC choices in the Layer menu are layers of stream aggregation determined by Pfafstetter numbering of the basins done by NBD. The thirteen digit Pfafstetter numbers are provided by the NBD for each FFMP basin and uniquely number all FFMP basins defined in the continental United States. See the web site below for more information: (http://proceedings.esri.com/library/userconf/proc97/proc97/to350/pap311/p311.htm)

The HUC layers refer to the Hydrologic Unit Code (HUC) used by the United State Geologic Survey to identify all hydrologic units such as river and stream basins across the continental United States. The USGS web site below provides additional information on the HUCs. (http://water.usgs.gov/GIS/huc.html)

The following figures graphically show the impact of the HUC aggregation method on the Big Sewickley Creek, as currently implemented in FFMP. Figure 38 shows how Big Sewickley Creek would appear in the HUC_4 display mode (Least Aggregation) with the 22 FFMP basins in Big Sewickley aggregated into 7 basins. By lopping off one more significant digit from the Pfafstetter

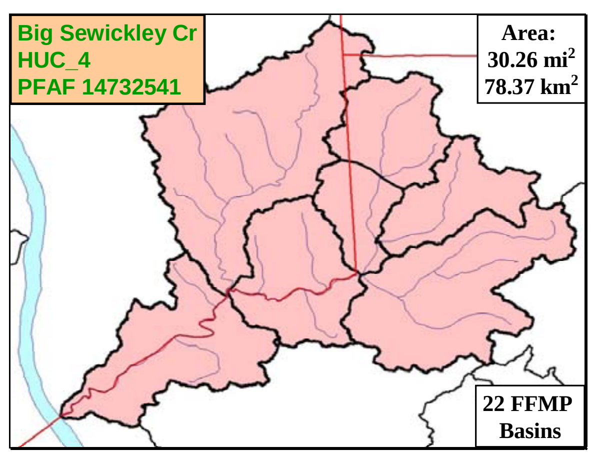

Fig. 38. HUC_4 FFMP layer with least basin aggregation (smallest basins).

number (PFAF in the figure) Fig. 39 shows the HUC_3 layer where Big Sewickley Creek aggregates into the single watershed shown in Fig. 1 as stream 13.

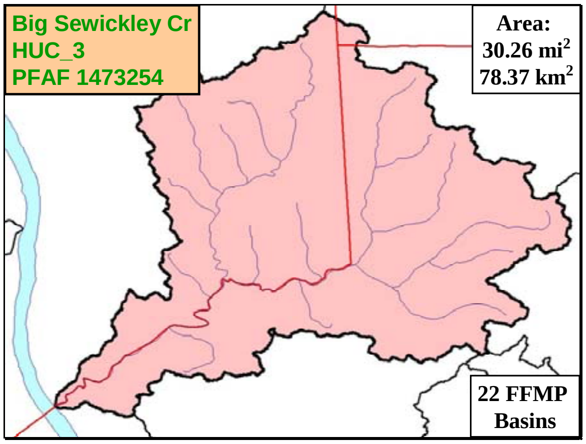

Fig. 39. HUC_3 FFMP layer with least basin aggregation (smallest basins)

As the aggregation process continues, the HUC_2 display mode shown in Fig. 40 lumps Big Sewickley Creek with other neighboring creeks along with a large segment of the Ohio River in Beaver and Allegheny Counties. Major rivers such as the Ohio act as natural barriers to flash flooding. For this reason the calculation of ABR for a large area on both sides of a major river is of little or no value for determining flash flood threat. Since the Pfafstetter number is

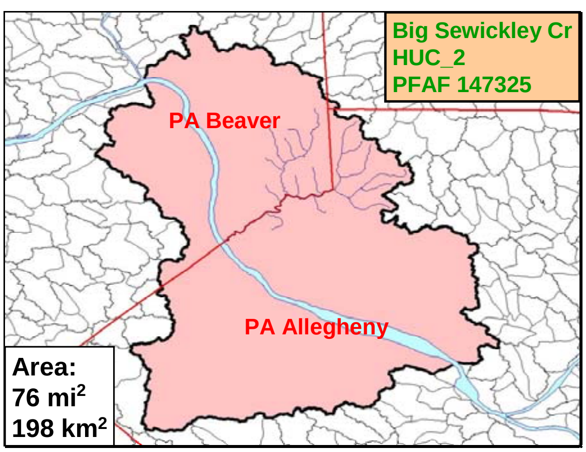

Fig. 40. HUC_2 FFMP layer with least basin aggregation (smallest basins) created as a function of stream branching, some streams may aggregate completely in HUC_4 while others may not aggregate to their entire watershed until HUC_2. So some aggregated streams in the HUC_4, HUC_3, or HUC_2 layers may be of used for possible flash flood detection. But there is no easy way to determine which aggregated stream is in which HUC layer.

A more definitive statement can be made about HUC_1 in Fig. 41 and HUC_0 in Fig. 42. Neither of these layers is helpful for flash flood detection. The average area of a USGS HUC across the continental United States is 1,622 mi^2 (4,200 km^2). The very large area of the HUCs will make its ABR computation for flash flood detection worthless. HUC_1 and HUC_0 should be removed from the FFMP layer table as options.

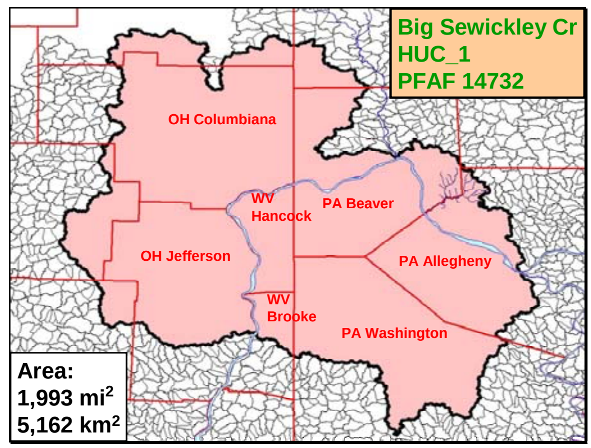

Fig. 41. HUC_1 FFMP layer with least basin aggregation (smallest basins)

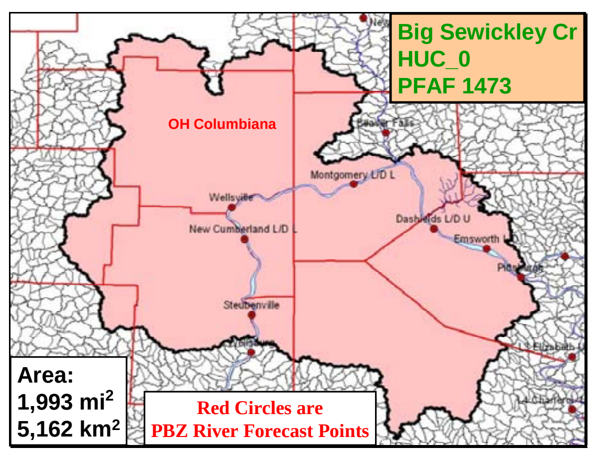

Fig. 42. HUC_4 FFMP layer with least basin aggregation (smallest basins)

Several serious drawbacks to using the current FFMP HUC aggregation for flash flood detection exist. First no map backgrounds of the various HUC layers were created for display in FFMP. Second, all of the aggregated basins in a single HUC layer are put in a FFMP Basin Table for the entire county warning area, not for a single county. The makes the stream list very long and makes finding a particular stream very difficult. Third, there is no FFMP Basin Trend Graph for any stream entry in any of the HUC layers. This is a very serious limitation that does not allow the display of the trend of ABR Rate and accumulated ABR. The time involved in finding a particular creek and the lack of FFMP Basin Trend Graphs makes the "HUC Layers" attempt at determining flood threat in large watersheds of little practical value.

11.3 *Add BUR to the FFMP Basin Table*

The third method of providing support for the detection of flood threat on large watersheds is the addition of area, flow accumulation, and BUR to the FFMP basin table. The advantages over the HUC aggregation system are many.

First, the FFMP user does not have to leave the "county" display mode that is most commonly used by FFMP users. The BUR information could be included in the FFMP basin table along side the ABR.

Second, the "BUR method" creates a computation of BUR for every non-headwaters FFMP basin in the watershed. Look at the large Chartiers Creek watershed of Fig. 34 with 288 FFMP basins. Of the 288 total basins, 158 are headwaters basins and 130 are non-headwaters basins. The non-headwaters basins include the yellow highlighted basins along the main stem shown in Fig. 35. The HUC_2 layer, which has Chartiers Creek as a single basin, computes BUR for just one basin (1408) at the mouth of the creek. The BUR method will compute BUR for all of the 130 non-headwaters basins in Chartiers Creek.

Third, the Basin Trend Graph could be generated for the BUR along with the ABR and could be accessed from within the FFMP Basin Table.

Staying within the "County" display mode of FFMP would save valuable time by eliminating the need to change displays from "County" to "HUC" display and back. All of the HUC layers could potentially be deleted.

11.4 *Run a Distributed Model*

The fourth and most robust method would be to run a distributed model for each of the larger watersheds. In FFMP the potential flood intensity is assumed to relate to the "Diff" Column of ABR – FFG. This might be considered a very coarse version of the "rational method" of estimating peak flow on small streams. Ponce(1989) sums up the assumptions of the rational method on small catchments as (1) rainfall is distributed uniformly in time, (2) rainfall is uniformly distributed in space, (3) storm duration is greater than time of concentration, (4) runoff is primarily due to overland flow, and (5) channel storage is negligible. Ponce states the upper limit for a small watershed is 12.5 km^2 or 4.83 mi^2. The cases shown earlier in the paper clearly indicate that the assumption of uniform distribution of rain in space and time for summer convection is unlikely for watershed areas of 5 mi^2 (13 km^2) and larger. A MBA of 2 mi^2 (5 km^2) or less is needed to approach the assumption of uniformly distributed rainfall in space and time. This is yet another reason to divide FFMP basins down to at least 2 mi^2 (5 km^2) and indicates that some form of distributed hydrologic modeling is needed for basins larger than 5 mi^2 (13 km^2).

Several approaches for detecting flash flooding with distributed modeling have been proposed. The DHM model is described in "Flash Flood Modeling Using the DHM-TF Approach" at the web site: (http://forecasts.weather.gov/oh/rfcdev/docs/DHM-TF.pdf). The DHM model is currently being tested at the Pittsburgh NWSFO.

The Kineros distributed model (Goodrich, D.C., et al. 2006) has been running at the Binghamton, NY NWS office since 2008 for selected flash flood basins.

Running a distributed model is the most robust method of determining flood threat. But the computer resources required along with the hours needed to setup and maintain a distributed model for an entire county warning area, make this an unlikely solution for the near term.

FFMP is not attempting to estimate a forecast stage for the streams and creeks, but is trying to provide some guidance about the potential for flooding. Estimating flood potential on larger creeks is more difficult and involved than a simple ABR-FFG comparison, but this FFMP estimation of potential runoff certainly is a significant indicator of flooding. Record stream flooding occurred at the Carnegie stream gage on Chartiers Creek during the Ivan flood. When FFMP indicates that an area as large as Chartiers Creek (basin 22, in Fig. 36) receives such widespread heavy rainfall, flooding of some significant magnitude can certainly be expected. The addition of area, flow accumulation, and BUR to FFMP would provide excellent tools for the detection of flash flooding on large watersheds.

12. CONCLUSIONS

FFMP needs some improved tools to aid in the detection of flash flooding on larger watersheds. The addition of area, flow accumulation, and BUR to the FFMP Basin Table would provide a simple and easy method for detecting flash flood threat on large watersheds, without leaving the familiar operating environment of the FFMP "County" display mode. Speed and ease of use are essential in the often hectic environment of real-time flash floods.

The addition of map backgrounds for the larger watersheds would be a very effective tool to use in conjunction with the FFMP graphic display. These map overlays have been very effectively used at the Pittsburgh NWSFO for a number of years and provide valuable guidance for the flood threat in the large watersheds. The maps could be produced nationally by the NBD group at the National Severe Storms Laboratory for all offices if resources could be made available. Another option would be to create the map backgrounds locally at each NWS forecast office using the FFMP small basin database as a starting point.

13. REFERENCES

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