J4.7 SOME PRACTICAL APPLICATIONS OF FLASH FLOOD MONITORING AND PREDICTION

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1. INTRODUCTION

The Flash Flood Monitoring and Prediction (FFMP) software deployed nationally by the National Weather Service (NWS) in 2002 (Smith et al. 2000), provides guidance for the issuance of flash flood warnings. Average Basin Rainfall (ABR), based on rainfall estimates from the Weather Surveillance Radar, 1988 Doppler (WSR-88D), is compared to Flash Flood Guidance (FFG) to determine the risk and severity of flash flooding (Davis 2003). All ABR, ABR Rate, and FFG data in FFMP is displayed in inches (in), inches per hour (in h^{-1}), and inches (in), respectively. For consistency with the FFMP output the ABR, ABR Rate, and FFG data will be maintained in English units. (1 inch = 25.4 mm).

Two FFMP case studies from eastern Ohio will be presented. The first case study describes the flash flood along Mill Creek on 30 May 2002 in the town of Mound, Ohio in Coshocton County. In the second event, severe flash flooding occurred in the town of Neffs, Ohio in Belmont County on 04 June 2002 along the Little McMahon Creek. FFMP provided excellent guidance in both cases on the severity and timing of the observed flash flooding.

2. FLASH FLOOD DETECTION WITH FFMP

FFMP provides three basic tools to detect developing flash floods. The first tool is a “base layer” of flash flood watersheds defined for the entire continental United States. This “base layer” of watersheds was created by the National Basin Delineation (NBD) project at the National Severe Storms Laboratory (Cox et al. 2001). The second tool is the ABR data computed every five minutes for each watershed in the “base layer”, using rainfall estimates from the WSR-88D. The third tool is the ABR Rate, which is an hourly rate based on the most current 5 minute ABR estimate. Both the ABR and ABR Rate tools were developed at the NWS Pittsburgh, Pennsylvania office in the Areal Mean Basin Estimated Rainfall (AMBER) project (Davis and Jendrowski 1996). The FFMP tools along with their application to flash flood detection will be described.

2.1 *ABR Rate*

The ABR rate is a direct measure of the rainfall intensity being received in a specific watershed. High ABR rates occur before a significant accumulation of ABR occurs, providing an early alert for watersheds at risk of flash flooding. The ABR rate is a function of rainfall intensity, spatial extent of the heavy rainfall rate, and watershed area. Larger watersheds tend to have lower ABR rates than smaller watersheds.

2.2 Rate ABR Duration

Flash floods occur when intense rainfall persists over the same watershed for a significant period of time (typically15 to 120 minutes). High ABR rates occur frequently in deep moist convection. However, the persistence of high ABR rates over a specific watershed is a relatively rare event. The persistence of high ABR rates that produce flash floods might be defined as a “rain burst”. In FFMP, the “rain burst” may be defined as three or more volume scans consecutive (five-minute WSR-88D rainfall observations) of ABR rate of more than one inch per hour. As will be shown in the case studies to follow, these “rainfall bursts” seldom last more than 90 minutes. ABR rates during the “rainfall bursts” can vary from one to five inches per hour.

2.3 ABR Accumulation

The combination of ABR rate and duration results in an accumulation of ABR for each “base layer” watershed. FFMP stores a five-minute rainfall accumulation for each watershed. The five-minute values may be summed into any user selected time duration of ABR. FFMP allow the display of a variety of rainfall durations from 30 minutes to 6 hours.

2.4 *Conversion of ABR to Runoff*

With the ABR determined for a given time period, FFG can be subtracted from ABR to determine the amount of runoff produced by the observed ABR for each “base layer” watershed (Davis 2001). FFG is defined as the amount of ABR needed in a specific period of time to initiate flooding on a stream. The difference between ABR and FFG has been described as the Flash Flood (FF) Index (Davis 2002). The FF-Index is computed and displayed in FFMP and can be used as a direct measure of flash flood severity.

FFG has a severe limitation with soil moisture accounting in small watersheds. The soil moisture accounting is based on average rainfall

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across a Mean Areal Precipitation Area (MAP) shown as black lines in Figure 1. Mill Creek in eastern Ohio is plotted on the Coshocton MAP area. Average rainfall across the Coshocton MAP (232 mi^2 in area) may not be representative of the rainfall that occurs in small watersheds in the Mill Creek basin.

The MAP areas are established by the NWS River Forecast Center (RFC) to accomplish modeling of the flow and stages along major rivers. The computation of areal average rainfall of a MAP is similar to the ABR calculation of a FFMP watershed. WSR-88D rainfall estimates and rain gage information are used to compute the MAP rainfall for six-hour time durations through the past 24 hours.

Consider a hypothetical event where the gridded one-hour FFG for the MAP is 2.5 inches. During the next 24 hours, the average rainfall observed across the Coshocton MAP area is a three-tenths of an inch. In that same 24-hour period, the ABR for Mill Creek was two inches. The gridded FFG updated by the RFC is based on the observed three-tenth of an inch of rainfall in the MAP area. The locally heavy rainfall observed in Mill Creek has greatly increased the soil moisture content in that watershed. The gridded one-hour FFG may drop to 2.3 - 2.4 inches, based on the three-tenths of an inch received across the Coshocton MAP. A more realistic value for one-hour FFG in Mill Creek may be closer to 1.0 inch. Comparing the recent history (past 72 hours) of ABR in a small watershed with the average rainfall in the MAP containing the basin, may help determine if the FFG is representative of current soil moisture.

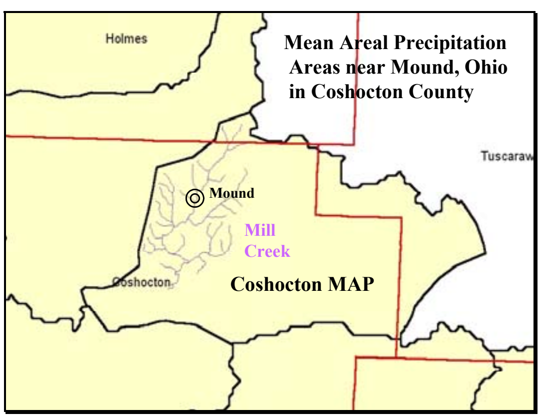

Fig. 1. River forecast areas (black lines) in eastern Ohio. County boundaries are shown as red lines. The Mill Creek stream system is shown as purple lines.

2.5 *Determine the stream reach at risk*

With the magnitude of runoff estimated, the stream channel to be impacted by the runoff must be determined. The stream channel, or dry arroyo, contained in the "base layer" watershed segment with the highest value of FF-Index will be at the greatest risk of flooding. Multiple adjacent watershed segments (upstream or downstream) may have high FF-Index values, or the ABR may be concentrated in just a few small watersheds.

Once runoff moves into the stream channel, a significant stream rise may move into the next downstream watershed, where little or no ABR may have fallen. The connectivity of the stream in the "base layer" watershed network becomes critical. The basin customization course (Davis 2003) provides Geographic Information System (GIS) tools to build hydrologic connectivity into the "base layer" of streams. This defined basin connectivity will be critical in determining the movement of the flood into downstream segments. One of the GIS tools developed for the basin customization class is an upstream tool that highlights all watershed segments upstream of a selected watershed. The downstream tool traces the stream flow by highlighting all downstream segments from the selected watershed.

2.6 *Watershed Aggregation*

Flash floods generally occur on small streams or systems of small streams that flow into larger rivers, lakes, or the ocean. The aggregation of the ABR for the "base layer" of small streams into larger stream systems can be important in detecting flash flooding along larger stream channels. The GIS tools developed in the basin customization class allow aggregation of the

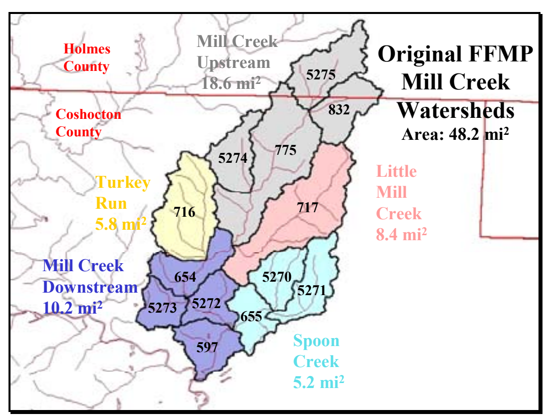

Fig. 2. The Mill Creek watershed showing major tributaries shaded in unique colors. The name and area of the tributaries is shown in matching colors. The county boundaries are red lines and the FFMP watersheds are black lines. Streams and major rivers are purple lines. The black numbers are FFMP Area_Ids.

"base layer" of watersheds into layers of larger streams.

The aggregation of watersheds is controlled by setting the "minimum basin area (MBA)" in the GIS tool used for basin delineation. For example, in the original "base layer" watersheds (black lines in Fig. 2) Mill Creek has13 segments based on a MBA of 2 mi^2. If the MBA is raised to 5 mi^2, only the five color-coded watersheds remain as individual basins. If the MBA is raised to 10 mi^2, then Mill Creek would appear as a single watershed with no tributaries. Using this GIS aggregation tool, new layers of FFMP streams can be created. ABR can then be calculated for the larger aggregated watersheds. These new layers of larger streams would not replace the "base layer", but would be added as additional stream layers to the FFMP computation.

2.7 *Basin Customization Improvements*

Flash flood detection and increased lead-time usually result from dividing watersheds into smaller segments (Davis 2001). The basin customization course provides instructions on how to divide existing FFMP watersheds into smaller segments. Both of the case studies to follow will show examples of customized FFMP watersheds.

3.0 ELEMENTS OF FFMP CASE STUDIES

A post-analysis of a flash flood event often provides important information on how FFMP might be better applied during future flash flood episodes. The flash flood detection method described above moves from the observation of heavy rainfall, to the creation of runoff, to the hydrologic response of the stream, to the resulting damage or casualties. The FFMP case study simply reverses the sequence of events as described in Section 2. First, the precise location of the damage and/or casualties must be found. The stream segment in which the damage occurred can then be determined. The ABR that occurred from this stream segment and upstream was the causal event for the flash flood. The Mill Creek and McMahon Creek flash flood events will be presented as FFMP case studies.

3.1 *The Mill Creek Flash Flood*

On 30 May 2002 slow moving thunderstorms inundated a small portion of Coshocton County, Ohio with peak values of almost four inches of rain in less than 2 hours. Two small tributaries of Mill Creek were especially hard hit. Severe damage was done to State Route 83 where it parallels Turkey Run (716 in Fig. 2). Several homes in the town of Mound, Ohio, at the confluence of Beards Run (5274) and Mill Creek (Fig. 2) suffered significant flood damage as both creeks overflowed their banks.

3.2 *Use FFMP Graphics for Case Studies*

The screen capture utility of the Advanced Weather and Information Processing System (AWIPS) can be used to create graphics for FFMP case studies. Figure 3 is a screen capture of the FFMP "Threat Basin Display" and "Threat Basin Table" for Coshocton County, Ohio at 0036 UTC on 31 May 2002. The graphic map display shows the 6-hour accumulation of ABR from 1836 UTC on 30 May 2002 to 0036 UTC on 31 May 2002. The Mill Creek watershed is highlighted with a white line. Notice that the northern two watershed segments of Mill Creek have been cropped at the county border. The threat basin display for Holmes County would display ABR data for these two northern watersheds of Mill Creek.

The time duration of ABR is user selectable in time intervals from 30 minutes to six hours. The highest observed ABR in the county is the dark red area (ABR from 2.00 to 2.50 inches).

The FFMP Threat Basin Table is directly related to the graphic screen display of ABR. A left mouse click on one of the column labels (Area_Id, Rate, Precip, FFG, Ratio, or Diff) will sort the data in that column. The Precip column, which is the ABR for each watershed in the county, is currently sorted as indicated by the purple column heading. Only one stream in the county (Area_Id: 5274) has received more than 2 inches of rain in the last 6 hours. The Area_Id column is a basin identifier for each stream in the county display. A left mouse click on any Area_Id re-centers the display on that watershed and places an "X" in the watershed. A right mouse click on the Area_Id produces a graph of ABR, ABR Rate, and FFG for the past 6 hours. Hovering the cursor over the Area_Id produces a

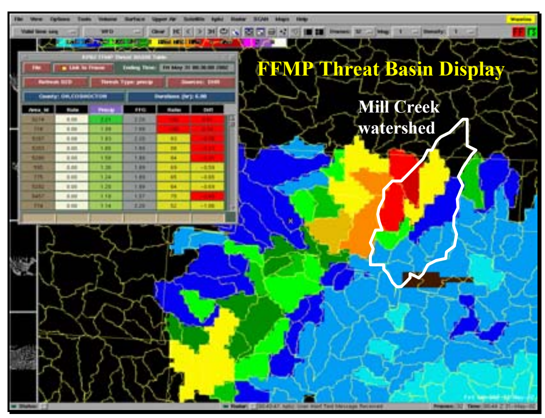

Fig. 3. FFMP ABR graphic and Basin Threat Table for Coshocton County, Ohio on 31 May 2002 at 0036 UTC.

pop-up window with the name of the stream or river. The Rate column shows the ABR Rate, the hourly rate of ABR in each watershed based on the most current five-minute ABR estimate. The FFG column shows the gridded FFG issued by the RFC based on the time duration of the ABR selected for display. The value of the gridded FFG is constant within any MAP area. The Ratio column is the ABR divided by the FFG multiplied by 100. So a value of 100 indicates that the ABR is equal to the FFG. The Diff column is the ABR-FFG. If ABR equals FFG the Diff column will be zero. Negative values indicate ABR is less than FFG, while positive values of Diff is the amount of ABR in inches over FFG. The Diff computation has been described as the FF-Index (Davis 2002), a direct measure of flash flood severity.

3.3 *Use GIS Graphics to Enhance Case Study*

A PC-based GIS display can be used as an enhanced FFMP graphic display for use in case studies. Figures 1, 2, 4, 5, 6, 15, 16, 17, 18, and 19 were all created using commercial GIS software available in all NWS offices. The GIS graphics have the advantage of the availability of additional data sets such as streams and rivers (Figs. 1,2,4,5,6), detailed roads, population centers, and many other geographic data sets. Using the GIS display, the ABR threshold categories for display can be easily modified, while the thresholds for the FFMP screen captures can not be easily changed. Figure 4 shows the distribution of ABR in Mill Creek during the 90 minutes of the heaviest rainfall.

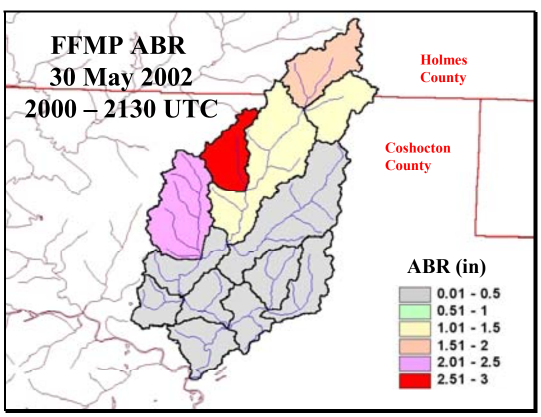

Fig. 4. The observed ABR in the Mill Creek watershed on the original FFMP (black lines).

The NWS Pittsburgh office is running both FFMP and Paul Jendrowski's current version of the AMBER program in real time (Davis and Jendrowski 1996). The AMBER database of streams in use at the Pittsburgh NWS is more detailed than the original FFMP dataset, and will in time become the customized FFMP dataset for the NWS Pittsburgh office. Figure 5 shows the customized Mill Creek watersheds that can be compared to the original FFMP dataset (Fig. 2). Little Mill Creek (717) and Turkey Run (716) and part of Mill Creek (775) have each been divided into three distinct segments. The "customized" Mill Creek watershed has 19 segments compared to the original FFMP watersheds of 13 segments.

Figure 6 shows the ABR observed in the customized FFMP watersheds. Notice the distribution of ABR that occurred across Turkey Run (8388, Fig. 5) was not visible in the original FFMP ABR display (Fig. 4).

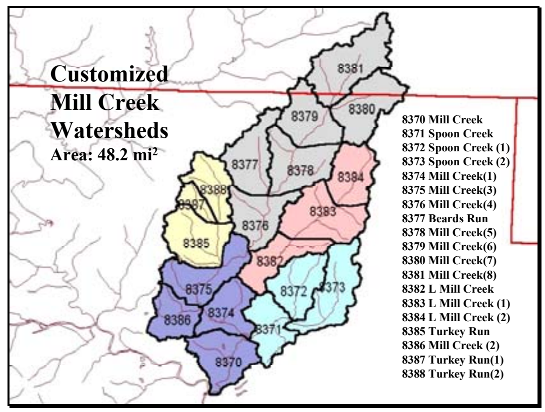

Fig. 5. Customized Mill Creek watersheds in Coshocton County, Ohio.

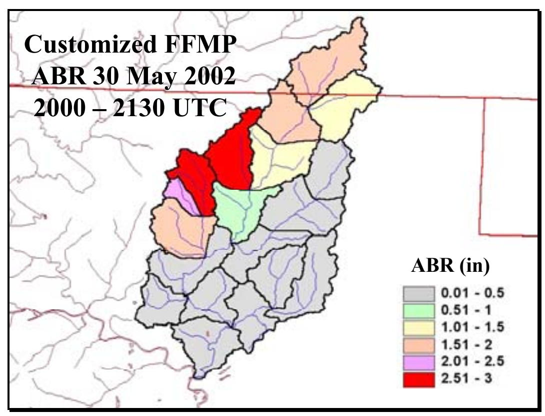

Fig. 6. Observed ABR for the Mill Creek watershed on the customized FFMP watersheds in Coshocton County, Ohio.

3.4 *Use Line Graphs for ABR/ABR Rate Plot*

Presentation software can be used to create line graph plots of ABR, ABR Rate and FFG. The purpose of the FFMP display (Fig. 3) is to direct the forecasters attention to the watersheds with the heaviest rain, high values of ABR, and then display a line-graph plot of ABR and ABR rate for each watershed. Figures 7-14 show the ABR and ABR Rate plot, generated by presentation graphic software, for the FFMP segments with the heaviest rainfall during the Mill Creek flash flood.

Figures 7-10 are the ABR/ABR Rate plots for the headwaters of Mill Creek upstream of the town of Mound, OH. The ABR increases going upstream, with the highest ABR observed in Mill Creek (6) and Mill Creek (8). The most intense ABR of the event, and most of the observed flash flood damage, occurred in Beards Run (Fig. 11) and Turkey Run (Figs. 12-14). The great majority of flash floods occur on small watersheds, frequently less than 25 mi^2 in area (Davis 2001). The combined area of the Beards Run and Turkey Run watersheds is 24.4 mi^2.

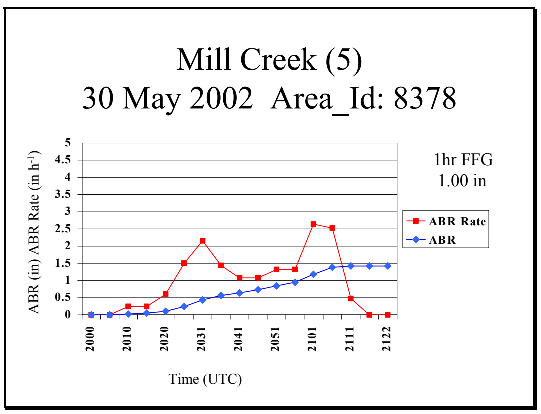

Fig. 7. ABR and ABR Rate for Mill Creek (5).

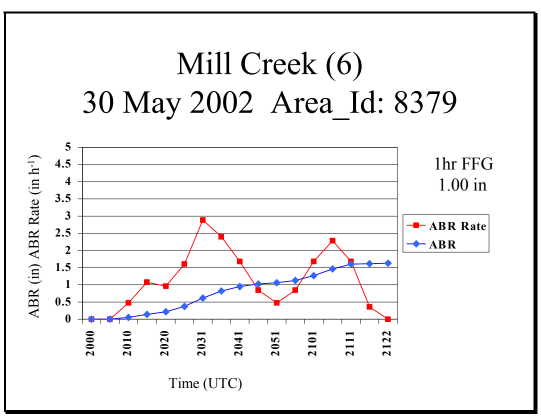

Fig. 8. ABR and ABR Rate for Mill Creek (6).

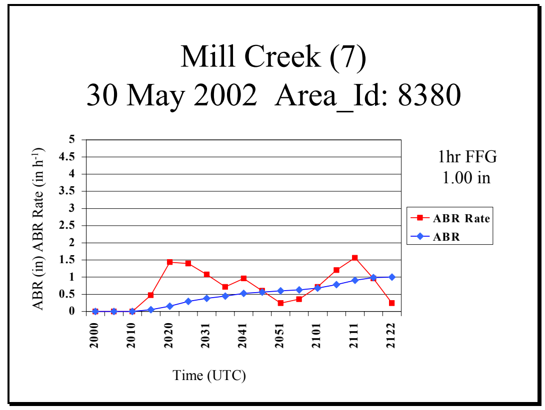

Fig. 9. ABR and ABR Rate for Mill Creek (7).

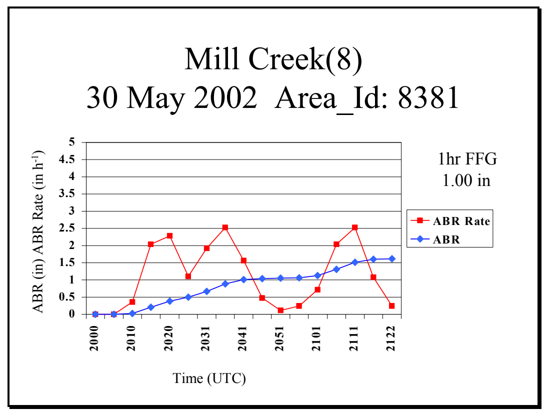

Fig. 10. ABR and ABR Rate for Mill Creek (8).

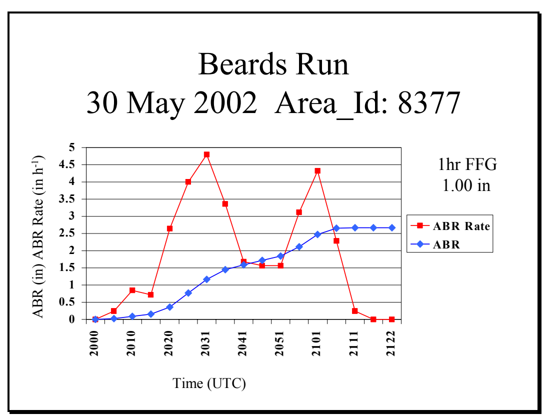

Fig. 11. ABR and ABR Rate for Beards Run.

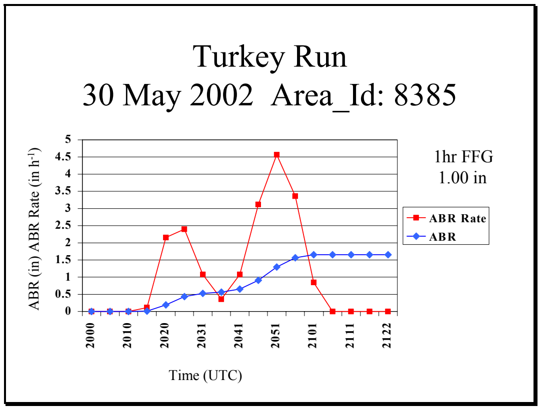

Fig. 12. ABR and ABR Rate for Turkey Run.

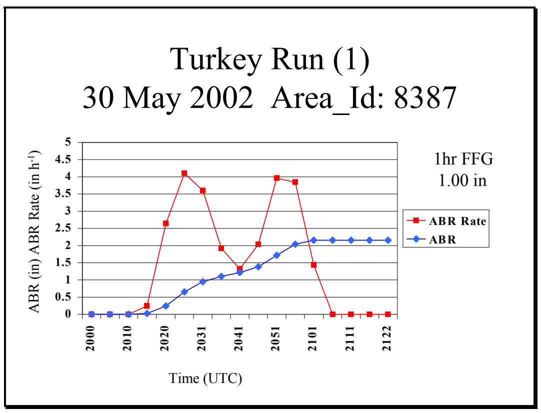

Fig. 13. ABR and ABR Rate for Turkey Run(1).

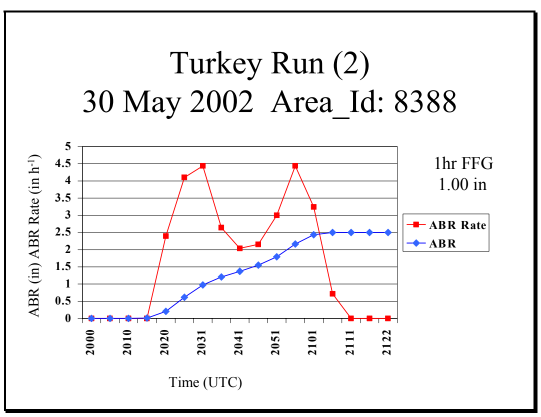

Fig. 14. ABR and ABR Rate for Turkey Run(2).

Notice that all the ABR rate traces (red lines) show that two waves of heavy rainfall hit all of these Mill Creek watersheds. The longest "rain burst" occurred in Beards Run (Fig. 11) where rates remained above one inch per hour for 50 minutes. Turkey Run (2) had a "rain burst" of 45 minutes, and the ABR rate remained above two inches per hour for the entire burst. The one-hour FFG value of one inch was reached within the first hour of rain in most of these watersheds. Flooding should be most severe in the watersheds with the highest amount of ABR over FFG, the highest FF-Index value. For the Mill Creek flash flood, Beards Run and Turkey Run (2) had the highest FF-Index, with an ABR of 1.5 to 1.6 inches over FFG.

3.5 *The McMahon Creek Flash Flood*

Severe flash flooding occurred along the length of Little McMahon Creek, and into the town of Neffs, Ohio in Belmont County on 04 June 2002. The location of McMahon Creek in Belmont County is show in Figure 15. The Hannibal North MAP that contains McMahon Creek is 434 mi^2 in area. Figure 16 shows the

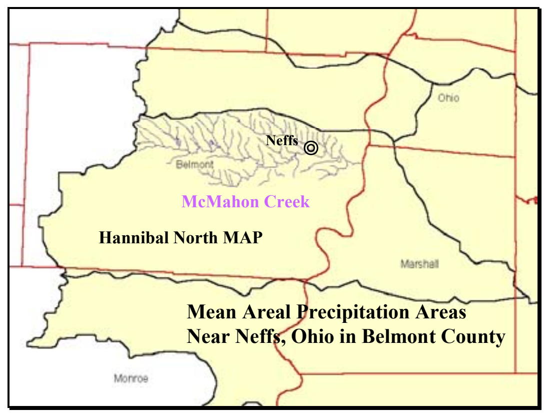

Fig. 15. The MAP boundaries in Belmont County, Ohio are black lines and county borders are red lines. The McMahon Creek stream network is shown in blue. The location of the town of Neffs, Ohio is shown as a black circle.

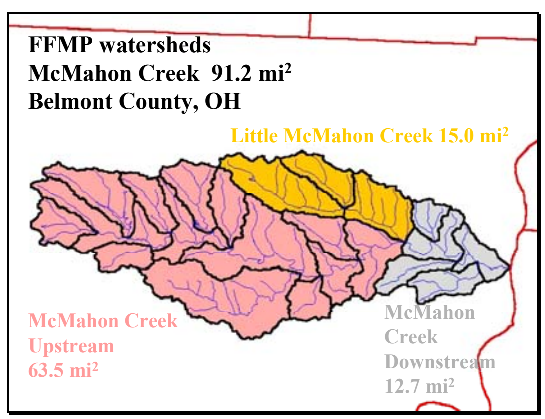

Fig. 16. The original FFMP watershed segments (black lines) for McMahon Creek. County boundaries are shown in red.

original 22 FFMP watershed segments for McMahon Creek. If a MBA of 15 mi^2 is used to aggregate the FFMP segments into the large watershed, McMahon Creek divides into the three color-coded watersheds shown.

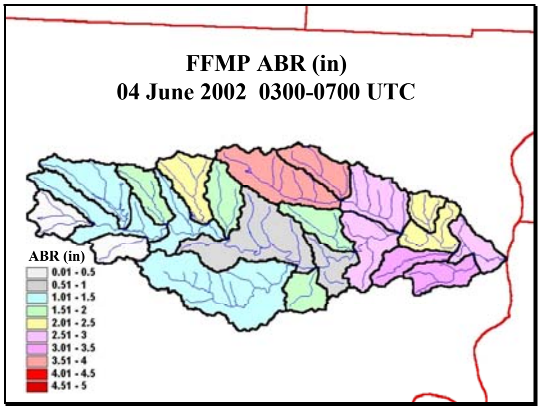

Fig. 17. ABR plot for the original FFMP watersheds on 04 June 2002.

Figure 17 displays the ABR plot for the original FFMP watersheds. Notice the highest ABR is concentrated in Little McMahon Creek, with significantly less rainfall observed in the main stem of McMahon Creek upstream of Little McMahon. No flooding was observed along the main stem of McMahon Creek upstream of Little McMahon Creek. The majority of the flash flood damage occurred along the Little McMahon Creek, with some flooding reported along the main stem of McMahon Creek downstream of Neffs, Ohio.

The customization of the original FFMP watersheds for McMahon Creek (Fig. 18) increases the number of defined segments from 22 to 47. Notice that the watershed segments defined for Little McMahon Creek increase from three to eight segments. The heaviest rainfall occurred in the headwaters region of Little McMahon Creek (Fig. 19). Decreasing ABR occurred in the watershed segment downstream toward Neffs. The town of Neffs, Ohio is located in segment 475 (Fig. 19) at the confluence of Little McMahon Creek and McMahon Creek. Much of the Little McMahon Creek watershed has been strip-mined so large segments of the watershed have been stripped of trees and vegetation. Although no fatalities occurred, two people were swept into the creek in their camper and were lucky to survive after being rescued out of the flood-waters by emergency workers.

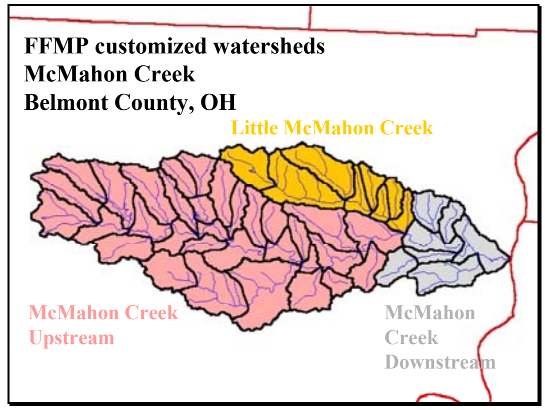

Fig. 18. FFMP customized watersheds for Little McMahon Creek.

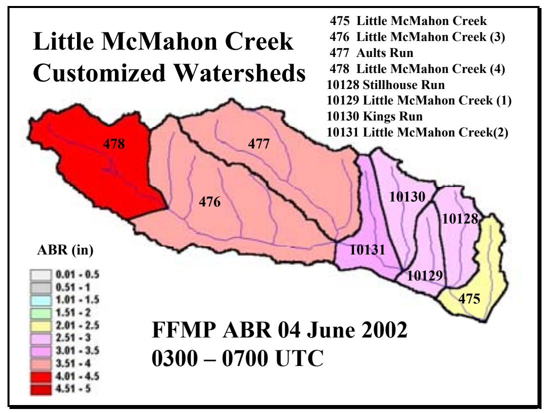

Fig. 19. FFMP estimated ABR for the customized watershed segments for Little McMahon Creek in Belmont County, Ohio.

Figures 20-27 show the ABR and ABR rate plots for all the customized segments of Little McMahon Creek. The pattern of observed ABR and ABR rate on these plots represent one of the worst flash flood scenarios. Enough rainfall occurs in the first hour of the event to satisfy the one-hour FFG. The streams rise to near bank full, and the ground is now saturated. At this point in time the ABR rates increase dramatically causing a rapid stream rise above bank full. The “intense rainfall burst” with ABR rates of two inches per hour or more for 30 minutes in Aults Run (477, Fig. 25), and for 55 minutes in Little McMahon Creek (3, Fig. 26) and Little McMahon Creek (4, Fig. 27) caused the severe flash flood damage observed along Little McMahon Creek.

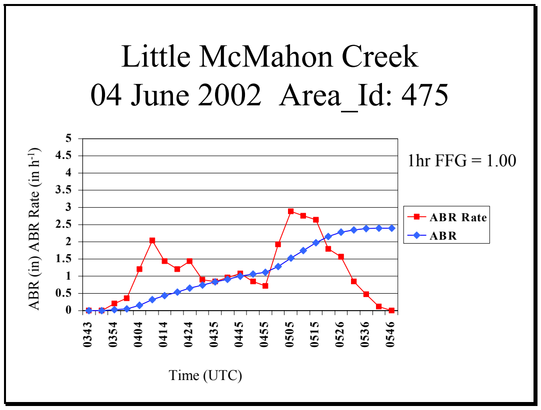

Fig. 20. ABR and ABR rate for Little McMahon Creek.

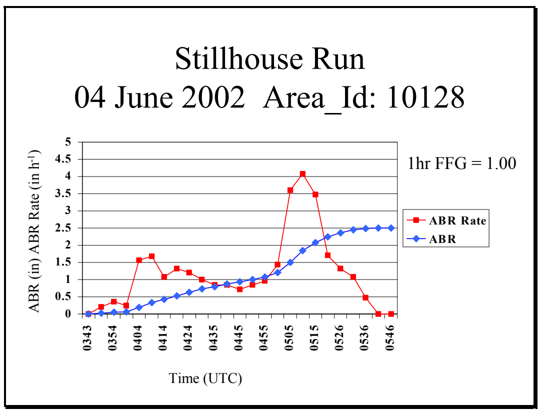

Fig. 21. ABR and ABR rate for Stillhouse Run.

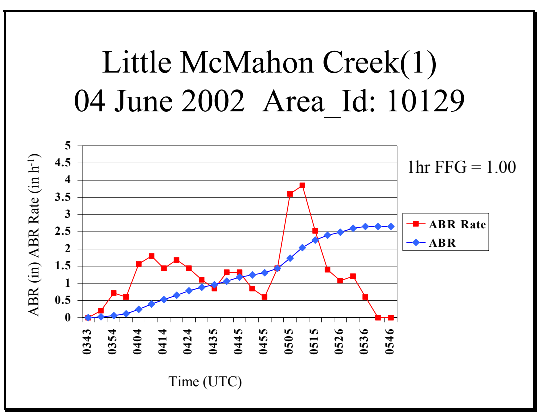

Fig. 22. ABR and ABR rate for Little McMahon Creek(1).

Notice the "rain burst" of ABR rates greater than one inch per hour for Aults Run, Little McMahon Creek (2), and Little McMahon Creek (3) lasted for 90 minutes. The "rain burst" for Little McMahon Creek (4) was 85 minutes. The combination of high ABR rates and the duration of those rates in time determine the actual accumulation of ABR.

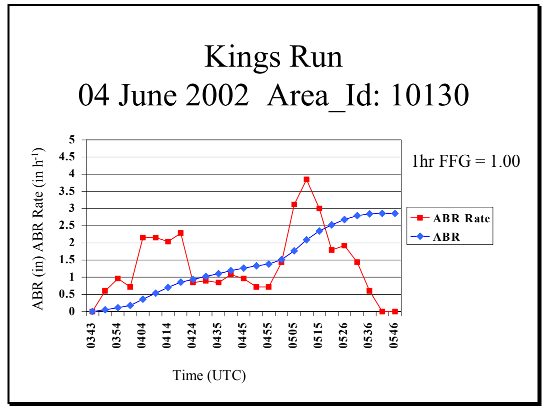

Fig. 23. ABR and ABR rate for Kings Run.

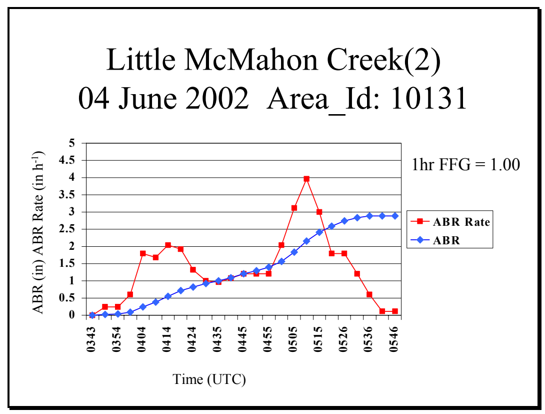

Fig. 24. ABR and ABR rate for Little McMahon Creek(2).

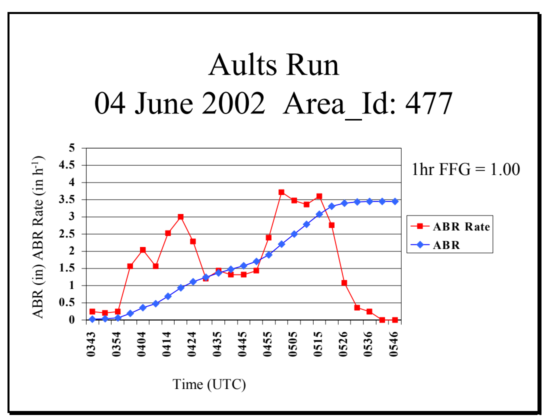

Fig. 25. ABR and ABR rate for Aults Run.

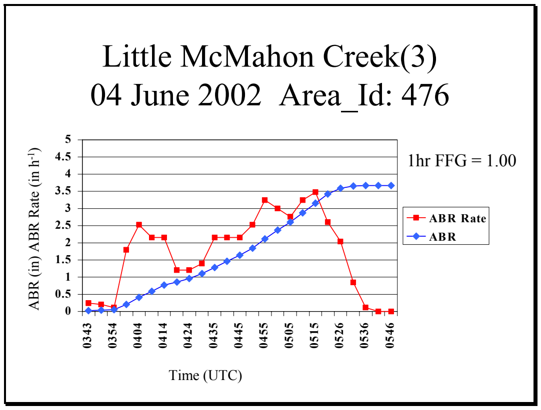

Fig. 26. ABR and ABR rate for Little McMahon Creek(3).

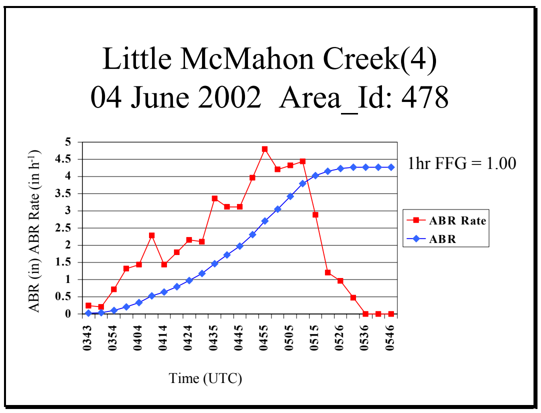

Fig. 27. ABR and ABR rate for Little McMahon Creek(4).

4. CONCLUSIONS

The tools provided by FFMP provide important guidance to the forecaster for the issuance of flash flood warnings. ABR rate alerts the watersheds receiving heavy, potentially flash flood producing, rainfall before the actual accumulation of heavy rain occurs. The ABR accumulation can be compared with FFG to determine both the starting time of the flooding and the potential severity of the flash flooding. Prior to the availability of the NBD stream network, ABR and ABR rate were not available to the forecaster.

The hydrologic response of the watersheds to the heavy rainfall is of extreme importance to the correct issuance of flash flood warnings. The routing of the water downstream and the contribution of upstream watershed segments to the flooding must be anticipated. The hydrologic connectivity required to determine these factors is supplied by the GIS tools from the basin customization course. A more robust tool to accomplish this end would be a distributed hydrologic model that could be run on the defined watersheds, but that solution remains some years away.

Creation of FFMP case studies is important in determining the effectiveness of the FFMP data sets and the underlying WSR-88D rainfall estimates provided as input to the system. The case studies will provide ideas for additional features needed in FFMP. Many enhancements to FFMP will be included in future software releases, such as additional basin layers, and comparison of rain gage data with radar rainfall estimates.

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