THE POTENTIAL USE OF WSR-88D DIGITAL RAINFALL DATA FOR FLASH FLOOD APPLICATIONS ON SMALL STREAMS

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Abstract

The three rainfall data formats associated with the Weather Surveillance Radar 1988 Doppler (WSR-88D) were compared for their utility in flash flood applications. For this comparison, data sets in these three formats were generated from radar rainfall estimates of the Radar Data Processor (RADAP-II; Saffle 1976; Greene et al. 1983) at the Weather Service Forecast Office (WSFO) in Pittsburgh, PA.

Two case studies of major flash flood events in WSFO Pittsburgh's area of warning responsibility were completed. They contained an examination of the usefulness of each of the pseudo WSR-88D data sets. Stream basin average and maximum rainfall were determined from each data set for the Pine Creek Flood of 1986 and the Turtle Creek Flood of 1987. The radar rainfall estimates of basin average rainfall were then compared to the National Weather Service (NWS) County Flash Flood Guidance to determine if each data set contained adequate information to identify the severity of the flooding threat.

The case studies clearly indicate that the most detailed radar rainfall estimates available on the WSR-88D are needed by the forecaster to produce more accurate and timely flash flood warnings.

1. Introduction

The timely issuance of flash flood watches and warnings requires detailed stream basin average rainfall information. For a given stream basin, flash flooding will begin to occur when the average rainfall over the entire stream basin area exceeds County Flash Flood Guidance (FFG) in a specified period of time. If the basin average rainfall increases to 2 in or more over FFG, serious flash flooding will very likely occur.

Prior to the advent of radar rainfall estimates on the RADAP-II computer, it was impossible to operationally compute basin average rainfall on small streams in a timely manner. This was of concern because flash floods most frequently occur in stream basins of 100 km^2 or less. All nine fatalities during the 1986 flood in the North Hills of Pittsburgh occurred in the Little Pine Creek Basin, which is only about 16 km^2 (6.1 mi^2) in size. A tragic flash flood occurred in southeast Ohio in 1990 on Pipe Creek and Wegee Creek, each about 40 km^2 in size. In this paper, the proposed rainfall data sets for the WSR-88D were examined to compute basin average rainfall over small stream basins.

2. Approach

Basin average rainfall in each stream basin and the time period in which the rainfall occurs are observed quantities required by the flash flood forecaster, along with the FFG and the topographic features of the basin, to issue accurate and timely warnings.

The Pine Creek stream basin (Fig. 1) is given as an example to define the stream basin variables used in the analysis that follows. The solid line surrounding the stream basin is the ridge line that forms the outside boundary of the stream basin. All run-off occurring from rainfall inside this boundary is assumed to eventually flow into the creek. The solid line in the center of the basin is the main stem of Pine Creek. The dashed lines are the ridge line boundaries of the sub-basin areas, with an arrow indicating the outflow point into the main stem of Pine Creek.

County FFG is the basin average rainfall needed in a given time interval to bring streams and creeks out of their banks in a particular county. The FFG is based on the soil moisture conditions and does not take into account the current level of streams and creeks in the county. An excellent technical memo on the methodology used to compute FFG has been published by the National Weather Service (Sweeney, 1991). The FFG is issued once a day around noon time by the NWS River Forecast Centers (RFC's). The soil moisture conditions are updated based on the previous day's rainfall measured by the RFC's network of rainfall gages. In the Eastern Region of the NWS, the FFG is issued for time periods of 1, 3, 12 and 24 hr. The 1-hour FFG is produced by taking 60 percent of the 3-hr FFG value. In addition, the Pittsburgh WSFO calculates an estimated 2-hr FFG computed by averaging the 1-hr and 3-hr FFG, for comparison with two-hr radar rainfall estimates.

To determine if a stream will flood, basin average rainfall is compared with the FFG. If the basin average rainfall for the entire creek basin exceeds FFG within the specified period of time, flooding should occur along the main stem of the creek. If the basin average rainfall does not exceed FFG, then flooding most likely will not occur along the main stem of the creek.

Maximum basin rainfall may be an early indicator of potential flash flooding in a stream basin. The maximum basin rainfall will exceed FFG before the basin average rainfall. Thus the maximum basin rainfall can be used as a tool for increasing the lead time of flash flood warnings. From a hydrologic standpoint, the maximum basin rainfall cannot be compared to FFG to determine the risk of flooding. Only the basin average rainfall can be used to make a valid comparison with FFG.

For our Pine Creek stream basin example, if the maximum basin rainfall exceeds FFG in the Pine Creek stream basin, but the basin average rainfall does not, flash flooding may occur on one of the small tributaries to Pine Creek, such as Little Pine Creek—East, but not along the main stem. However, flash flooding will only occur on Little Pine Creek—East if the basin average rainfall for this small sub-basin exceeds FFG. This assumes that the FFG is correct and the radar rainfall estimates are representative of the actual basin average rainfall over the sub-basin.

If a flash flood forecaster is given a reasonably accurate estimate of basin average rainfall and a good estimate of FFG

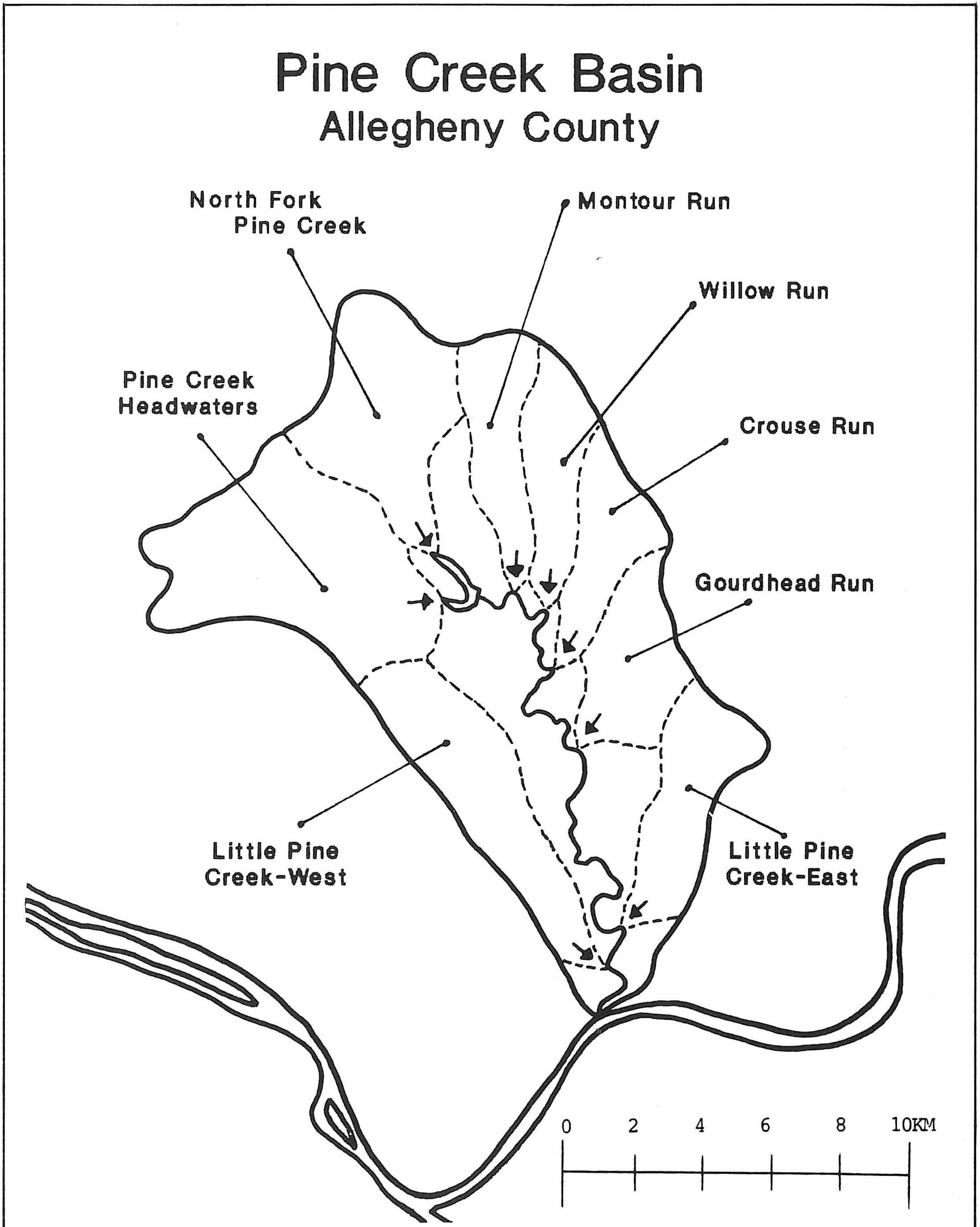

Fig. 1. Pine Creek Basin—Allegheny County, Pennsylvania, with sub-basin areas defined.

for a stream basin, a valid assessment of the flash flood potential in that stream basin can be made. The Pine Creek and Turtle Creek Floods are examined by computing stream basin average and maximum rainfall by using the three forms of digital radar rainfall estimates proposed for the WSR-88D system.

3. Data

The WSR-88D will internally generate digital rainfall in three different data formats (Hudlow et al. 1983): the radial grid, the Hydrologic Rainfall Analysis Project (HRAP) 4-km grid, and the HRAP 2-km grid.

3.1. The radial data grid

The most detailed of these data formats will be the radial data grid collected for each 1 km in range along each 1° of radar azimuth. However, it is very important to note that although radial rainfall data are being calculated, in one kilometer by one degree range bins, by the WSR-88D every 5 to 6 minutes, there are no plans to output these data to the forecaster.

For the purpose of this study, the radial information collected with the RADAP-II at WSFO Pittsburgh were used in place of the WSR-88D radial data format. The RADAP-II radial data are very similar to the WSR-88D radial data, but has a lower resolution. RADAP-II collects data along each nautical mile of the even-numbered radar radials, due to the two degree beamwidth of the Weather Surveillance Radar 1957 (WSR-57). The combination of a one degree beam and measurements along each kilometer of a radar radial will make the WSR-88D rainfall estimates four times the resolution of the RADAP-II radial data.

Figure 2 shows the RADAP-II radial data grid overlaid on a map of the Pine Creek basin. Radar range circles are drawn every 1 n mi, with radar azimuths drawn on the odd numbered azimuths every 2°. The range bins along the 10° radar radial, for example, would be bounded by the 9° and the 11° radial. RADAP-II generates a rainfall estimate for each of these range bins every 10 minutes. The 10-minute values are

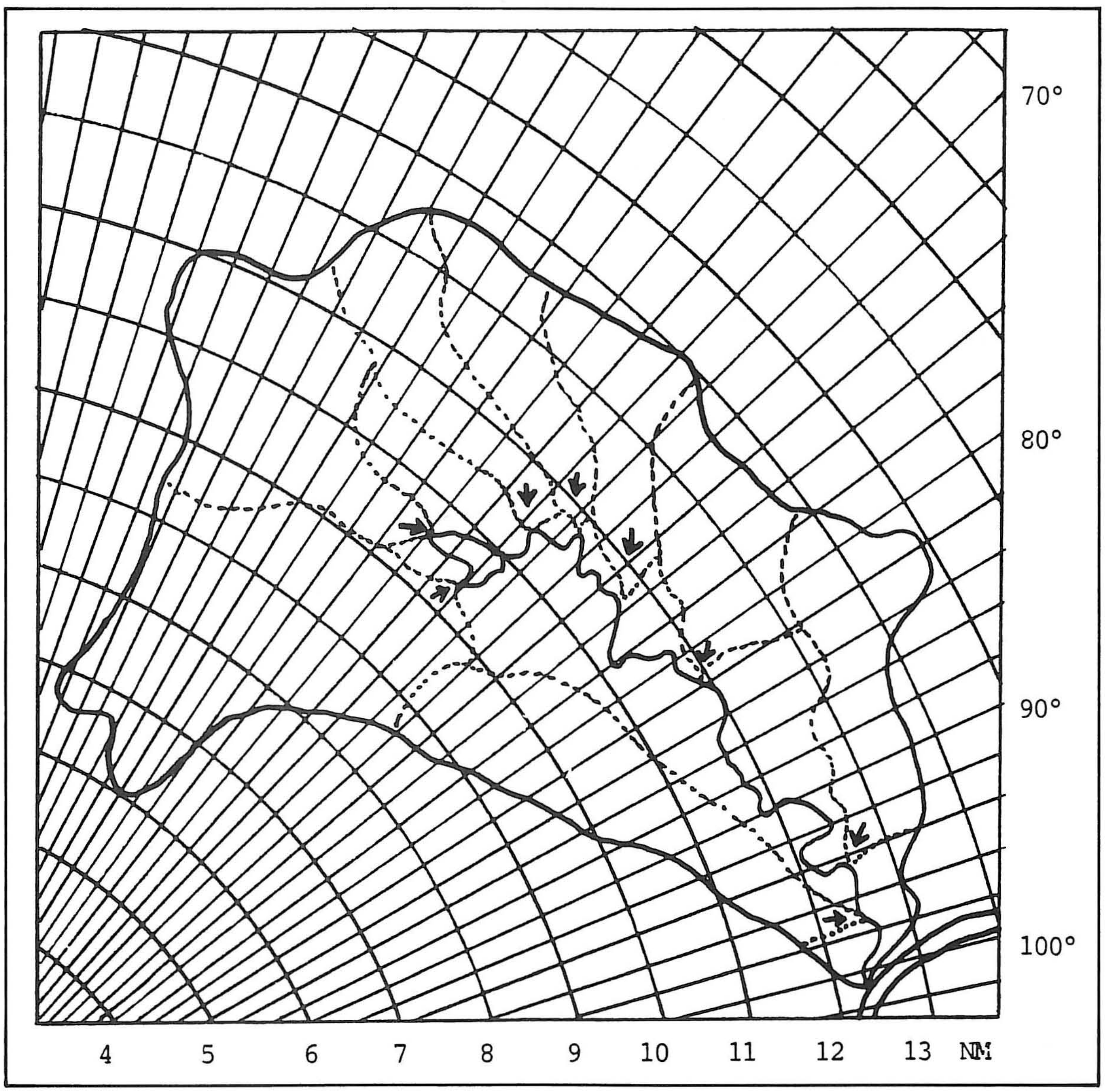

Fig. 2. Pine Creek Basin with RADAP-II radial grid format.

Fig. 3. Allegheny County in Southwestern Pennsylvania with a single Manually Digitized Radar (MDR) box divided into one hundred HRAP 4-km grid boxes. The dashed line in the northern portion of the county is the Pine Creek Basin boundary. The plus sign (+) is the location of the Pittsburgh radar.

summed into 1-hr totals. These 1-hr rainfall products are then summed into 2-hr and 3-hr totals.

A polar coordinate grid is less efficient for computations on a computer than a rectangular grid system. It is also very difficult to mesh adjacent radar sites when using the polar data grid. For these reasons, the NWS Hydrologic Research Laboratory developed a special rectangular hydrometeorological grid mapping procedure for the Hydrological Rainfall Analysis Project (HRAP) in the early 1980's. This HRAP grid has been incorporated into WSR-88D and will be the primary display grid for WSR-88D rainfall information. This rectangular HRAP grid system will allow adjacent WSR-88D sites to merge radar products onto a master grid system.

3.2. The HRAP 4-km grid

The HRAP 4-km grid is a subset of the Manually Digitized Radar (MDR) grid presently in use throughout the National Weather Service. Figure 3 depicts the MDR grid plotted on a map of Allegheny County in Southwestern Pennsylvania. The single MDR box covering most of the county is subdivided into 100 HRAP 4-km grid boxes. The dashed line in the northern part of the county is the outline of the Pine Creek stream basin. An expanded view of the twenty-five HRAP 4-km grid boxes highlighted over Pine Creek is shown in Figure 4. The HRAP 4 km data are the only rainfall data produced from the WSR-88D that will be output to the forecaster in digital form.

3.3 The HRAP 2-km grid

The HRAP 2-km grid is produced by dividing each HRAP 4-km grid gox into four equal parts. Figure 5 shows the HRAP 2-km Grid for the Pine Creek Basin. A radar rainfall estimate is produced for each HRAP 2-km grid by averaging all RADAP-II radial range bins whose center points fall within the 2-km grid box. The rainfall estimates for the HRAP 4-km grid are then determined by summing the four HRAP 2-km grid boxes within the 4-km grid box and dividing that sum by four. Although the WSR-88D calculates actual rainfall values in the HRAP 2-km format, this digital data is not output to the forecaster. In addition, the HRAP 2-km data are stored in four bit format, allowing the display of only 16 discrete values of rainfall. The rainfall is placed in one inch increments for the color display of 16 colors of rainfall. Thus a reading of 2.1 in and 2.9 in is stored and displayed as the same value (2.0 to 2.9 in of rain).

4. Procedures

The following procedures were used to compute stream basin average and maximum basin rainfall. For demonstration purposes, the HRAP 2-km grid is overlaid onto a stream

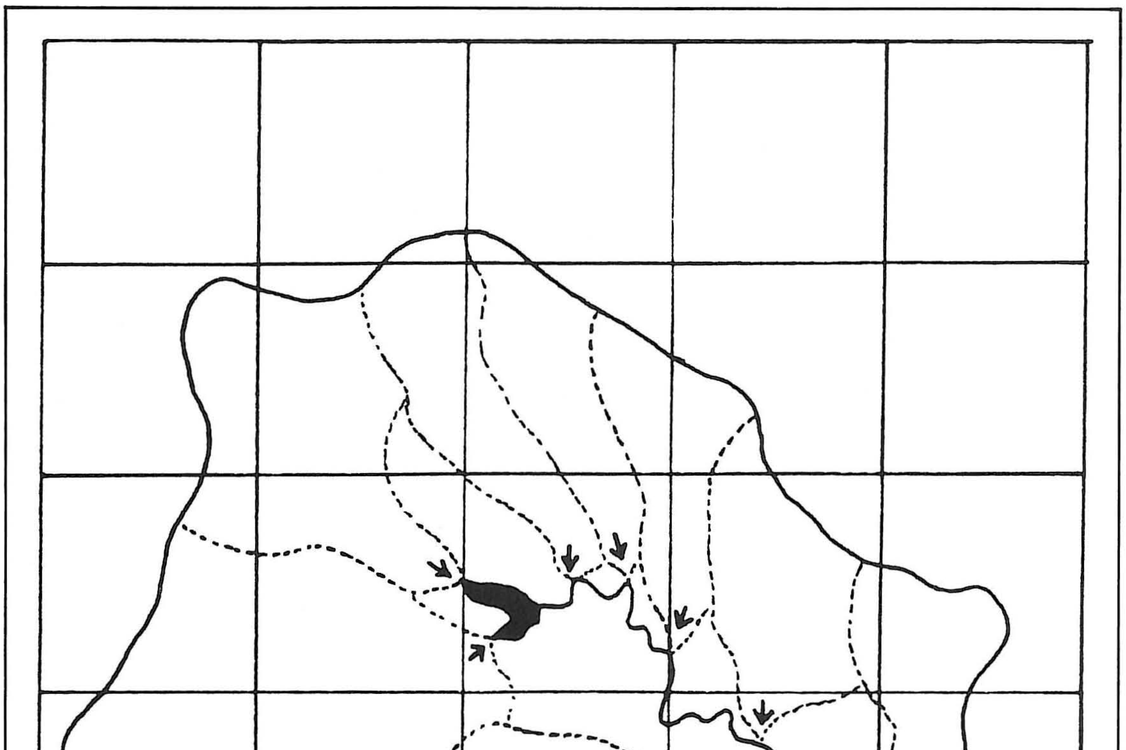

Fig. 4. Pine Creek Basin with the HRAP 4-km grid.

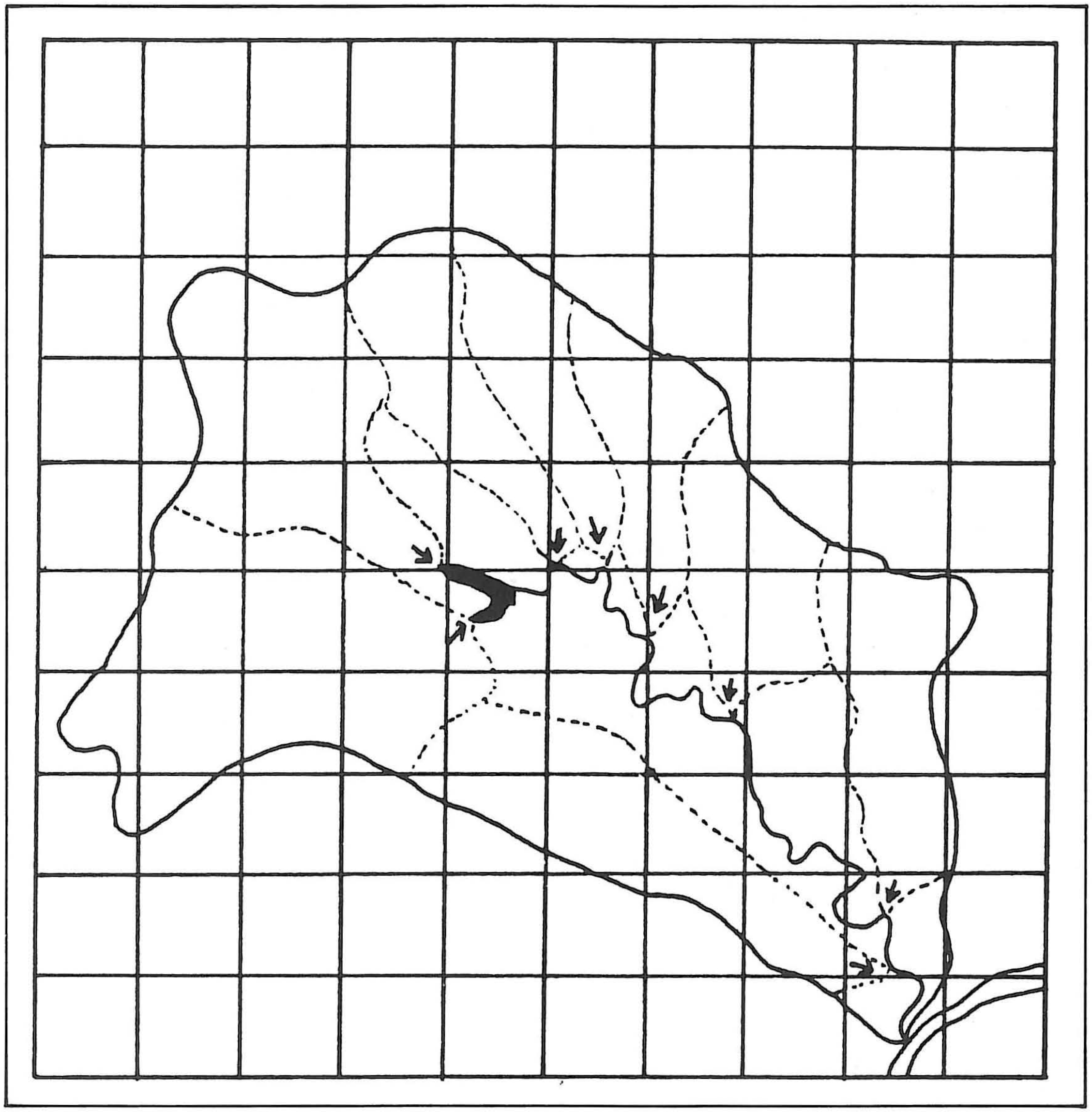

Fig. 5. Pine Creek Basin with the HRAP 2-km grid.

basin about 26 km^2 (10 mi^2) in size, at a distance of about one hundred km from the Pittsburgh radar in Figure 6.

4.1 Radial grid data

Circles are plotted at one km intervals at the center of each range bin along the WSR-88D radials from 6° to 9°. The WSR-88D computes a radar rainfall estimate for each of these range bins every five or six minutes, depending on scan strategy. The rainfall estimate for each of the 24 solid circles, that fall within the basin area, are averaged to compute the basin average rainfall for this stream basin. The open circles outside the basin boundary are not used in the stream basin rainfall calculation. The highest rainfall amount among the twenty-four rainfall estimates is stored as the maximum basin rainfall.

4.2 HRAP 2-km and HRAP 4-km grid data

The same stream basin is shown in Figure 7, with small circles plotted at the center of each HRAP 2-km grid box, and large circles at the center of each HRAP 4-km grid box. The stream basin average rainfall is computed for the 2-km grid using the ten solid small circles falling inside the stream basin boundary. The maximum rainfall is determined by scanning these same ten grid boxes. Note that only one HRAP 4 grid box center, the large solid circle, falls within the steam basin. As a result, the HRAP 4-km basin average rainfall and the HRAP 4-km maximum rainfall for this stream basin would be equal since there is only one datum point.

4.3 Stream sub-basins

Each rainfall data base (RADAP-II base radial scan, HRAP 4 km, and HRAP 2 km) was adapted to the Pine Creek and Turtle Creek stream basins using the procedure outlined above. The stream sub-basin areas, such as Little Pine Creek—East, were assigned range bins or HRAP grid boxes in the same manner. If a center point fell within the stream sub-basin area, that range bin or grid box was used for the rainfall calculation for the sub-basin area.

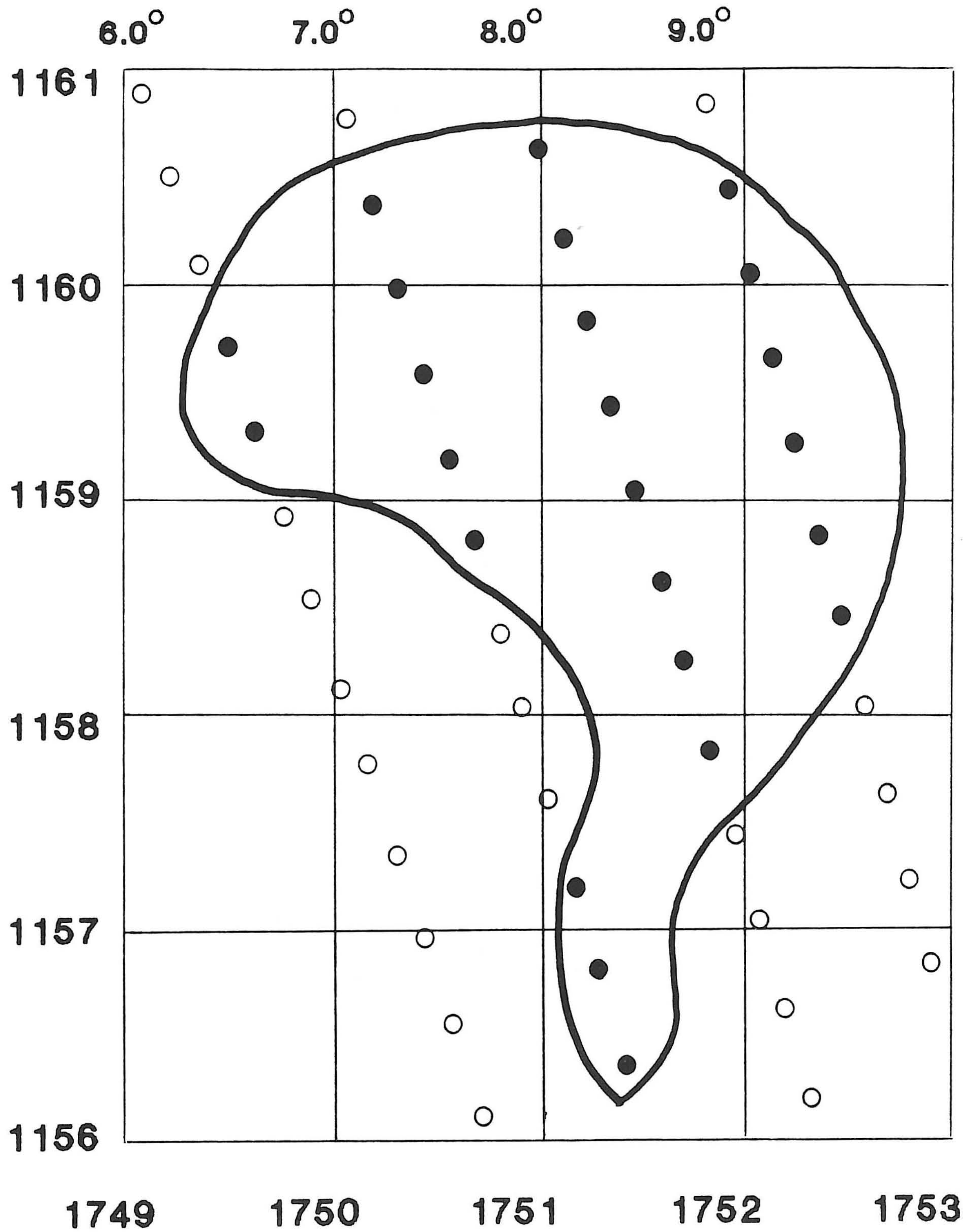

Fig. 6. Assignment of WSR-88D radial range bins to a stream basin. The dark solid line is the boundary of a stream basin at a range of about 100 km from the Pittsburgh radar. Circles are plotted in the center of the radial range bins along the 6° through 9° radar radials at intervals of 1 km. The four digit numbers are the values of the HRAP 2-km grid plotted for reference. Bins with solid circles are used in the basin calculation.

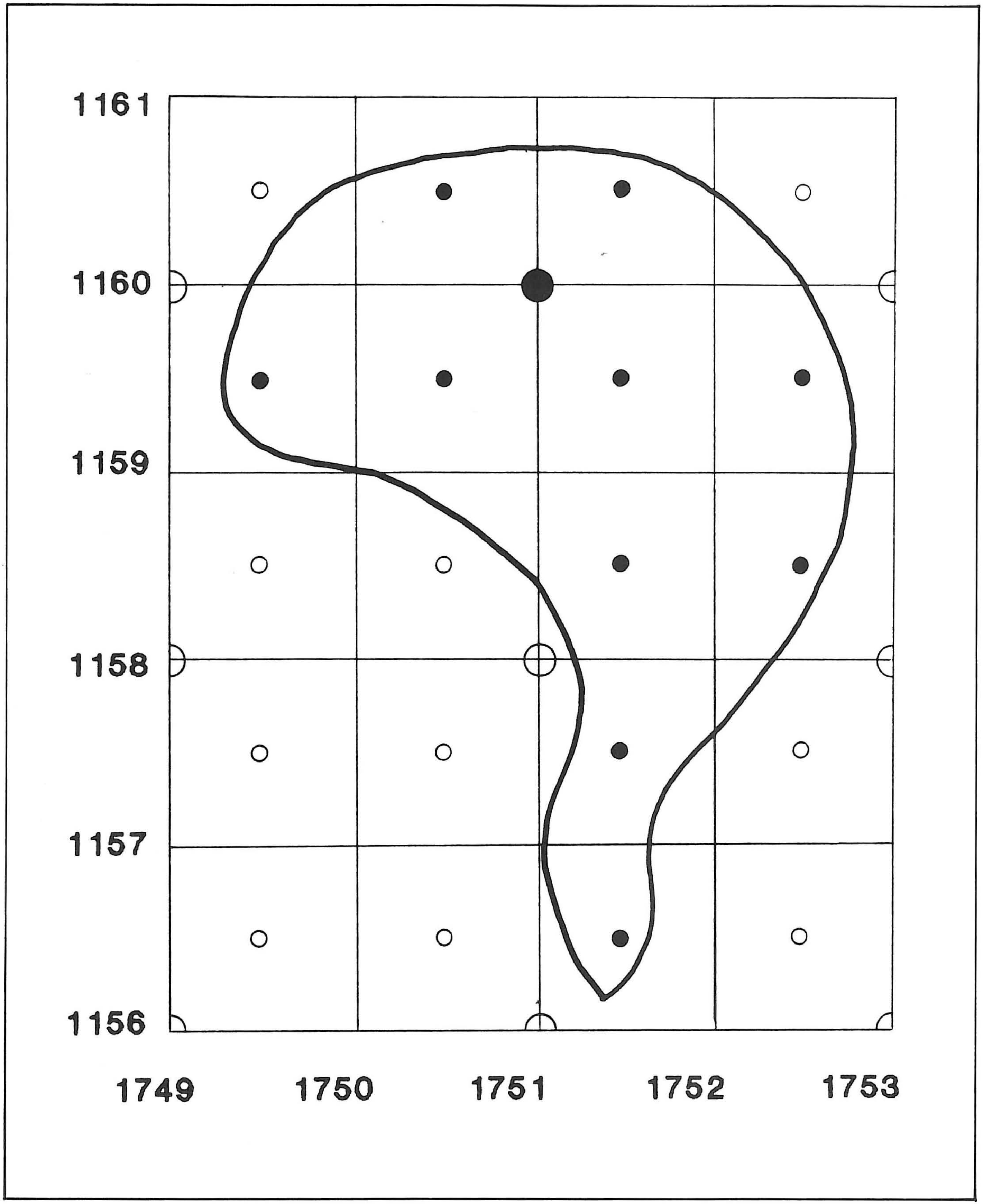

Fig. 7. Assignment of WSR-88D HRAP 2-km and 4-km grid boxes to a stream basin. The dark solid line is the stream basin shown in Figure 6. Small circles are plotted at the center of the HRAP 2-km grid boxes. Large circles are located at the center of the HRAP 4-km grid boxes. Bins with solid circles are used in the basin calculation.

4.4 Rainfall product conventions

Using the radial data, HRAP 2-km grid and the HRAP 4-km grid, a 1 hr basin average rainfall and maximum basin rainfall was computed for each hr of the flooding event. All one-hr time periods began at the top of the hour, while the rain may have started at any time during the hr. If only one centroid fell within a stream sub-basin area, then the maximum basin rainfall equaled the basin average rainfall for that basin. If no centroids fell within a stream basin, then no rainfall estimate was assigned to that basin.

5. Results

5.1 The Pine Creek flash flood of May 30, 1986

During this event the flooding in the Pine Creek basin (Fig. 1) occurred primarily in the Little Pine Creek—East and Gourdhead Run sub-basin areas. The bucket survey conducted after the flood revealed that a maximum of 8 in of rain fell in the head-waters of these sub-basin areas from 1930 to about 2130 UTC. The peak flooding occurred from 2100 to 2200 UTC. The 3-hr flash flood guidance for Allegheny county was 3.8 in before the start of the rain at 1930 UTC. The 1-hr FFG was computed to be 2.3 in with the estimated 2-hour FFG at 3.0 in.

The entire Pine Creek basin is about 175 km^2 (66.8 mi^2) in size. Figure 8 shows the maximum and basin average rainfall estimates from 1900 to 2000 UTC. The Base Scan (BSCAN) radar estimate is the radial data estimate taken off the base scan (0.5 degree elevation) of the radar by RADAP-II. The basin average rainfall for all three data types showed about 0.4 in during the first hr. One would expect this result since the BSCAN range bins are averaged over the HRAP 2-km and 4-km grids. Averaging the radial data over the same area as the HRAP grid boxes should result in similar values, especially when the basin size (175 km^2) is significantly larger than the largest grid size (about 16 km^2 for the 4-km grid).

The maximum rainfall, however, showed a wide disparity between the different grid sizes. The radial data indicated almost 2 in of rain fell during the first hr of the event, about equal to the 1-hr flash flood guidance. The HRAP 4 km grid showed a maximum of only 0.9 in, not even half of the 1-hr flash flood guidance. Based on the BSCAN rainfall estimate for 1930 to 2000 UTC, and the fact that a heavy thunderstorm remained over the area at 2000 UTC, a flash flood warning could have been issued almost 1 hr before the onset of the flooding. The HRAP 4-km grid data gave no such indication. The averaging process used to produce the HRAP 4-km data removed the rainfall peaks needed by the flash flood forecaster. In contrast, the HRAP 2-km data provided a very good approximation of the radial data with an estimation of 1.7 in during the first one-half hr of the heavy rain.

Figure 9 shows the 2-hr rainfall estimate from 1900 to 2100 UTC. By this time, the flooding was underway and the majority of the heavy rain had fallen. The basin average rainfall was just under 3 in for all three data sets. The maximum rainfall for the radial data indicated 5.5 in for 2 hr, while the HRAP 2-km grid indicated about 5.0 in. About 1.5 in was removed from the rainfall peak by the averaging process associated with the HRAP 4-km data.

The basin average rainfall for the sub-basin areas of Pine Creek is shown in Figure 10 for the 1900 to 2000 UTC period. The greatest basin average was in the Little Pine Creek—East basin with 1.2 in over the entire basin during the first hr of rain. The HRAP 4-km grid indicated only about 0.6 in, well under the 1-hr FFG of 2 in. The sub-basin analysis clearly showed that two sub-basin areas were in imminent danger of flooding. Little Pine Creek-East and Gourdhead Run both had over 1 in of rain, while all other sub-basin areas had less than 0.2 in as indicated by the radial data set.

An interesting computational "spill over" phenomena occurred in Gourdhead Run, Crouse Run and Little Pine Creek West basins. Since the HRAP 2-km and HRAP 4-km grid data are produced by averaging the radial data, the HRAP rainfall estimates should be less than or equal to the radial data. However, in this case, high rainfall amounts in the radial data just outside of the stream basin were included in the wrong stream basin during the production of the HRAP 2-km and HRAP 4-km data. We have found that as the size of the data grid increases, the probability of this type of computational error increases. Therefore, if the HRAP 2-km or the HRAP 4-km values for a given stream basin are higher than the BSCAN radial data, then this computational error probably is the cause. (Note that if no grid box center points fall within a sub-basin area, a negative value of rainfall is plotted. This is the case with HRAP 4-km data for Crouse Run.)

Figure 11 shows the 2-hr rainfall from 1900 to 2100 UTC for the Pine Creek sub-basins. Little Pine Creek-East and Gourdhead Run were 1 in above the 3-hr flash flood guidance. The 3-hr flash flood guidance is plotted because it was the only flash flood guidance available at the time. (The 1-hr flash flood guidance was developed as a result of this event and has proven to be invaluable for flash flood applications.) The "spill over" computational error discussed previously is again evident in Willow Run, Montour Run and Little Pine-West.

The maximum 2-hr rainfall for the Pine Creek sub-basins is shown in Figure 12. The Little Pine-East and Gourdhead Run basins stand out with 2 in of rain above the 3-hr flash flood guidance. An isolated rainfall maximum occurred in the Little Pine Creek-West basin, but the basin average for the same time period (Fig. 11) was well below flash flood guidance and no flooding was observed.

A stream gage was located on the Little Pine Creek East about 0.5 mi upstream from where the Little Pine empties into the main stem of Pine Creek. Figure 13 is a hydrograph of the gage readings from 2030 to 2330 UTC. The stream is normally around 6 inches in depth at the gage site. From 2045 to 2130 UTC the water rose 9 feet.

5.2 The Turtle Creek flood of June 15, 1987

The Turtle Creek basin (Fig. 14) is about twice as large as the Pine Creek basin. The southern portion of the Turtle Creek basin is Brush Creek. The flash flooding occurred during the night in the Bushy Run and Headwaters of Brush Creek sub-basin areas. Brush Creek flows through the city of Jeanette and is usually about a foot deep. The stream swelled to over 10 feet in depth in 30 minutes. Westmoreland county 3-hr FFG was 2.0 in, 1-hr FFG was 1.2 in and the estimated 2-hr FFG 1.6 in.

The 3-hr rainfall from 2100 to 0000 UTC June 16, for the entire Turtle Creek Basin, is shown in Figure 15. The basin average for all three data sets was almost identical with around 1 in of rain over the 3-hr period. However, the maximum rainfall amounts were much higher than the basin average rainfall, indicating that only a small portion of the Turtle Creek basin experienced the heavy rainfall. The radial BSCAN data showed the highest maximum with over 5 in of rain. The HRAP 4-km data indicated less than 4 in.

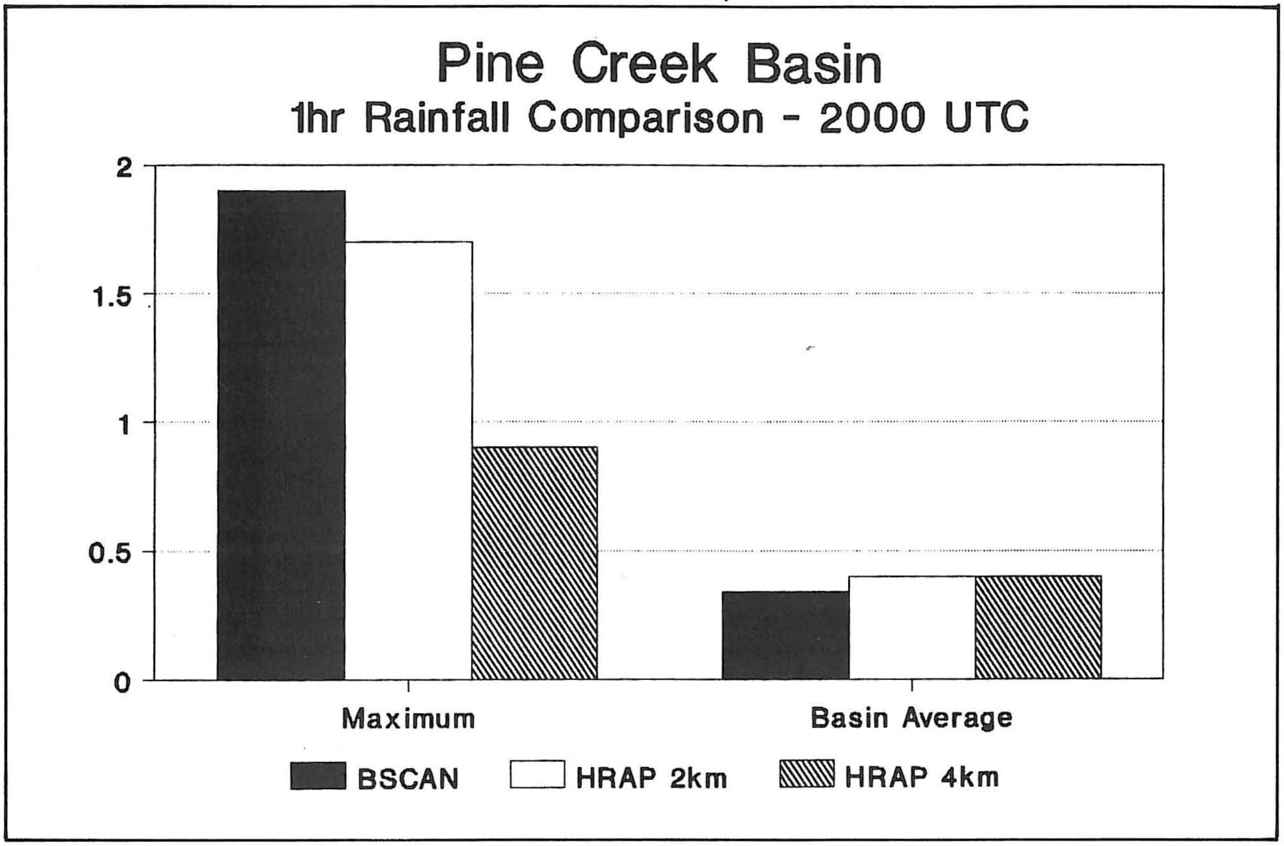

Fig. 8. One-hr rainfall, 1900 to 2000 UTC, 30 May 1986, for the Pine Creek Basin.

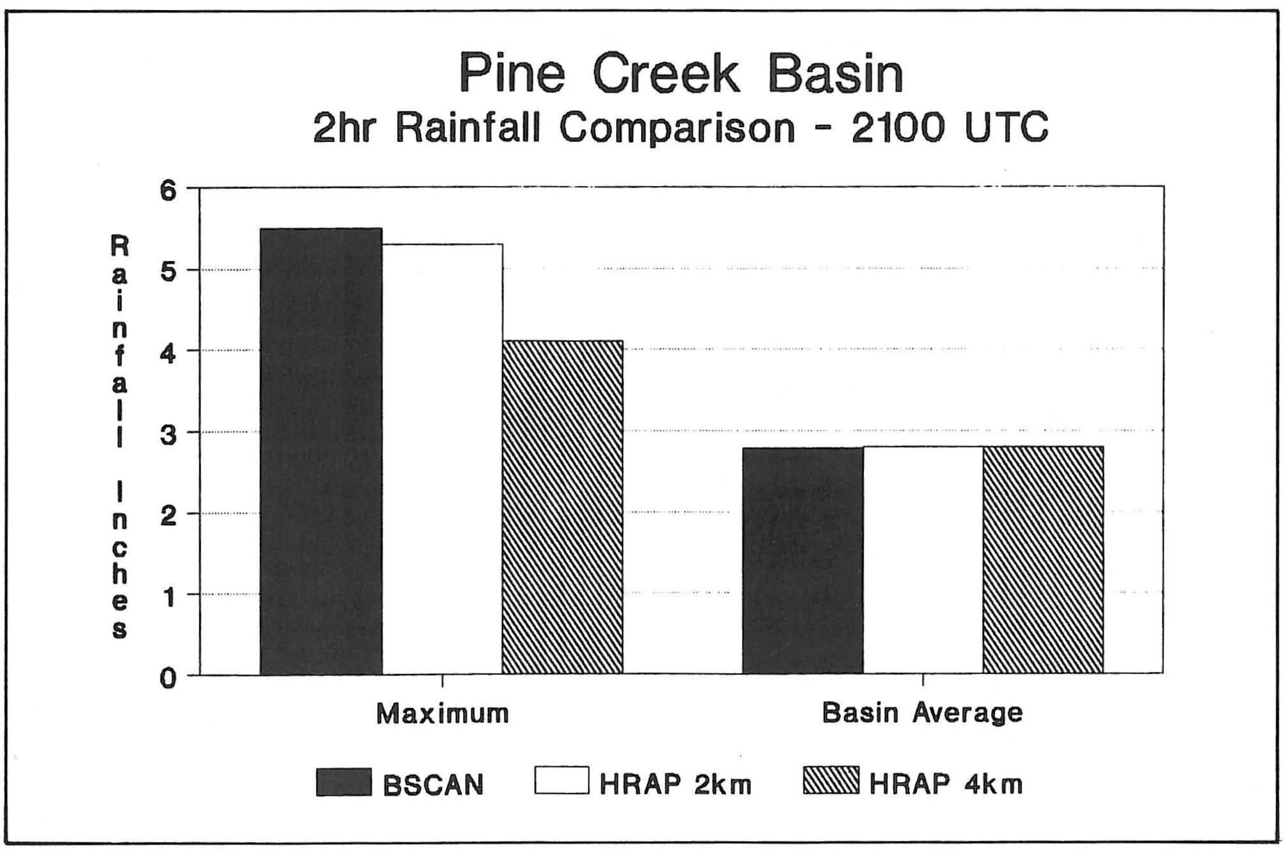

Fig. 9. Two-hr rainfall, 1900 to 2100 UTC, 30 May 1986, for the Pine Creek Basin.

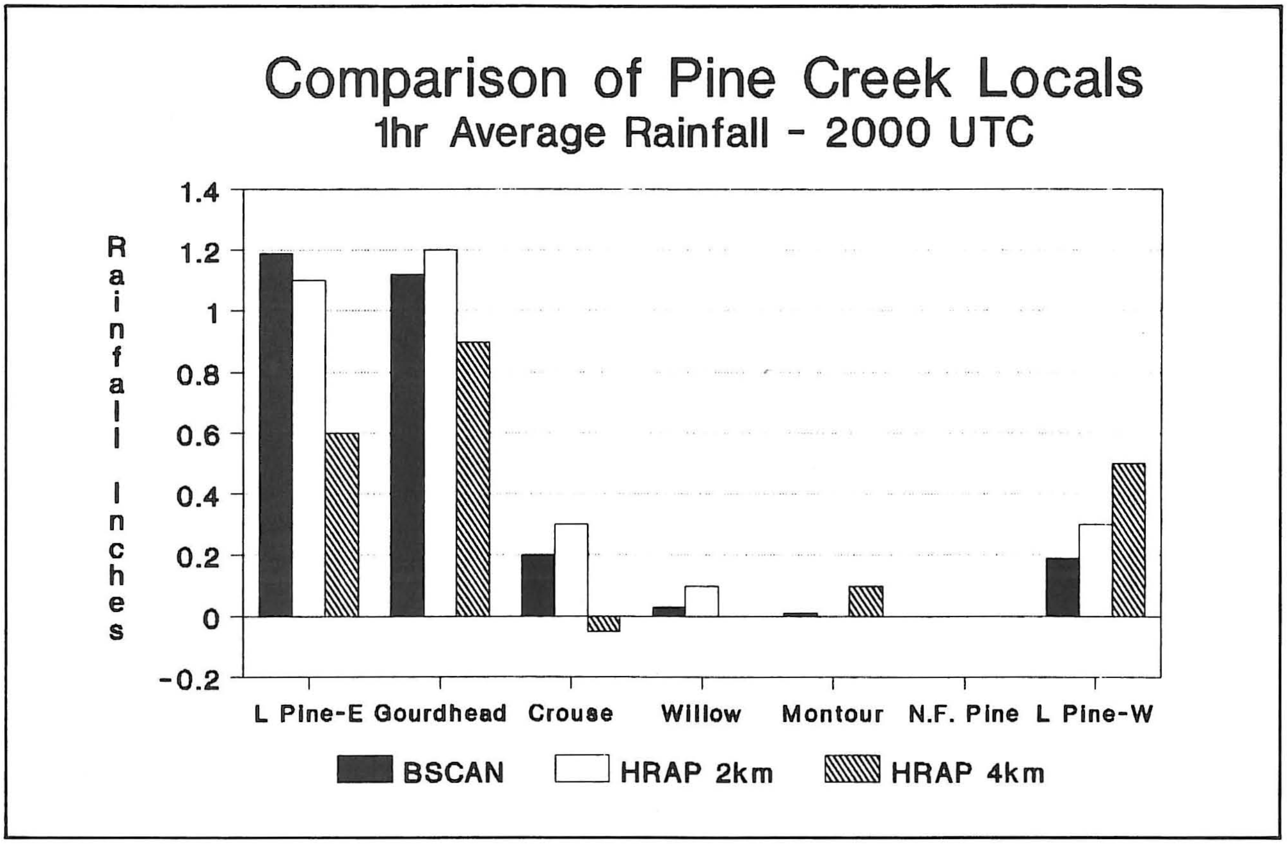

Fig. 10. Basin avergae one-hr rainfall for the Pine Creek sub-basins, 1900 to 2000 UTC, 30 May 1986.

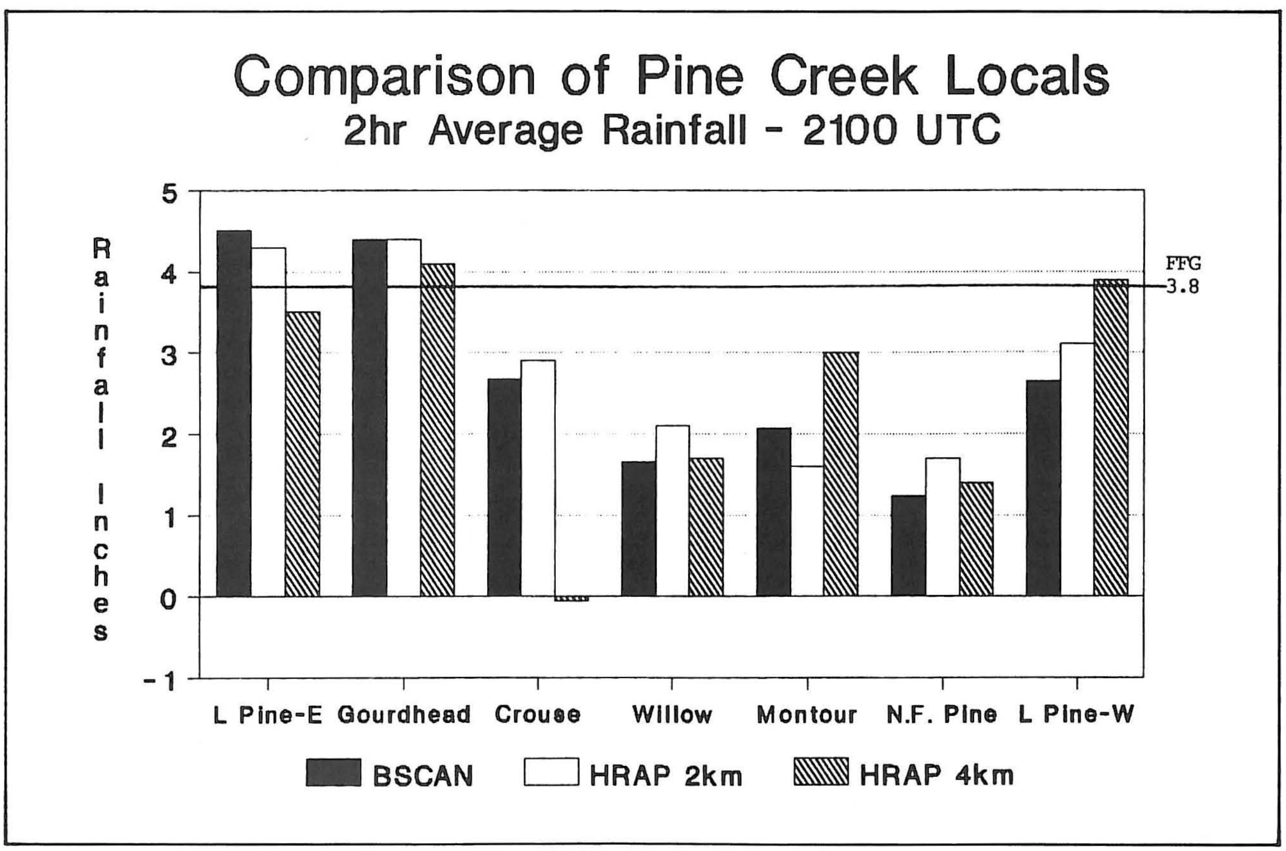

Fig. 11. Basin averge two-hr rainfall for the Pine Creek sub-basins, 1900 to 2100 UTC, 30 May 1986.

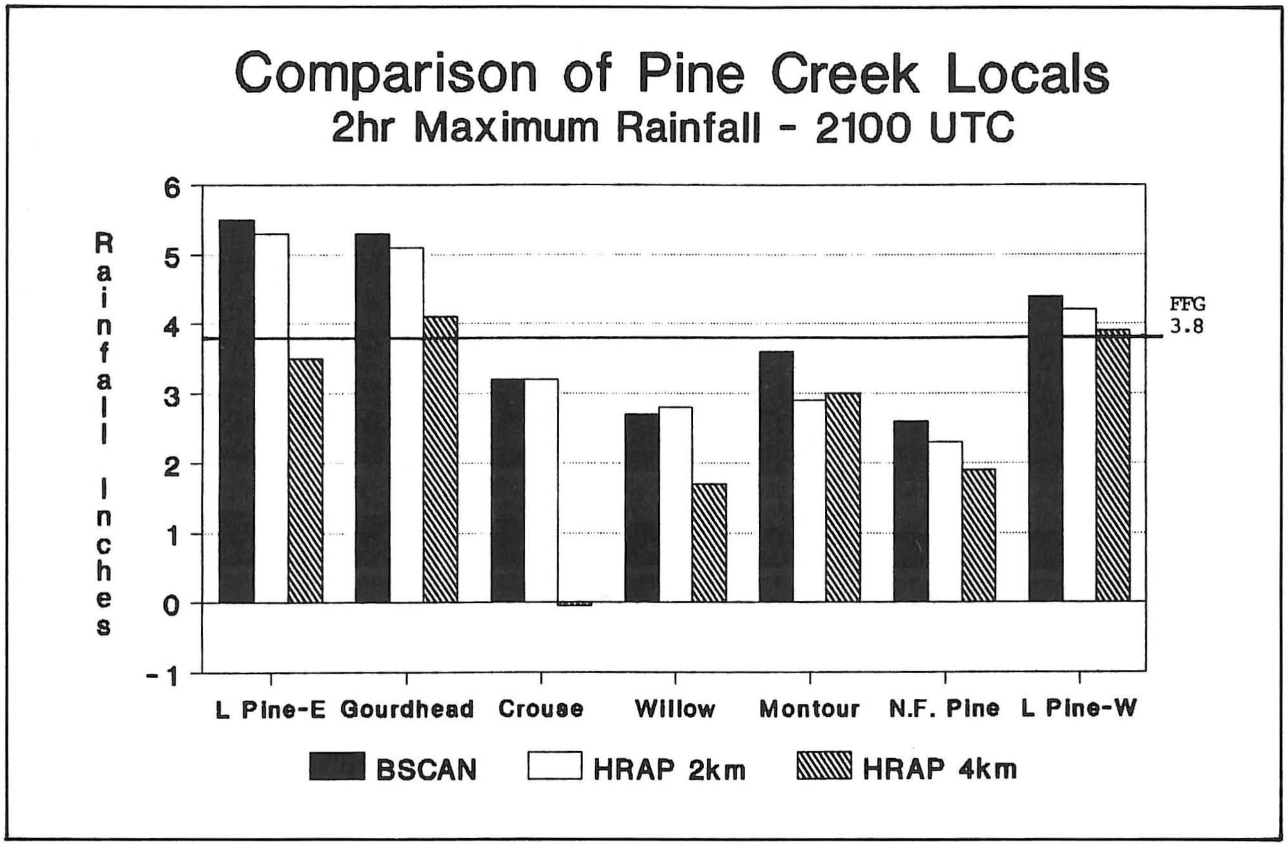

Fig. 12. Maximum two-hr rainfall for the Pine Creek sub-basins, 1900 to 2100 UTC, 30 May 1986.

Figure 16 shows the 2-hr basin average rainfall from 2100 to 2300 UTC for the Turtle Creek sub-basin areas. The Headwaters of Brush Creek and Bushy Run received 1.8 in in the first 2 hr of the heavy rain, close to the estimated 2-hr FFG of 1.6 in. Very serious "spill over" errors occurred in both of these sub-basin areas. The HRAP 4-km rainfall estimate for the Headwaters of Brush Creek was over 1 in above the radial estimate. Errors of this magnitude could result in issuing unnecessary warnings or warnings for the wrong stream basin area.

The 3-hr basin average rainfall in Figure 17, showed the same basic trend. The headwaters of Brush Run and Bushy Run were clearly the most likely sub-basins for flash flooding. Over 2 in of rain was indicated in both sub-basin areas. The computational "spill over" errors continued to be a problem.

The 2-hr maximum rainfall estimates for the 2100 to 2300 UTC period are shown in Figure 18. The headwaters of Brush Creek and Bushy Run had almost 4 in of rain in the 2-hr period. The HRAP 2-km grid values were very close to the radial data because the RADAP-II radial range bins were very close in size to the HRAP 2-km grid boxes at 25 n mi from the radar. The HRAP 4-km grid showed almost 1 in less rain in the Bushy Run basin than was indicated for both the radial data and the HRAP 2 km estimates.

In the 3-hr period from 2100 to 0000 UTC on June 16, over 15 in of rain was indicated in the headwaters of Brush Creek and almost 5 in in the Bushy Run basin. The HRAP 4-km data continued to grossly underestimate the rainfall maximum. Despite a peak rainfall amount of 3.5 in in Haymaker Run and Abers Run, no flooding was reported in either basin because the basin average rainfall (Fig. 19) was only around 1 in.

6. Conclusions

Digital radar estimates can be used to provide detailed stream basin average rainfall and maximum basin rainfall for small streams in near real time. The results from these two case studies show that this vital information, unavailable from any other data sources, can be produced from digital radar rainfall estimates.

The radial data produced by the WSR-88D will provide excellent digital rainfall estimates for flash flood applications. However, a small rainfall data grid must be used to maximize the accuracy of basin average rainfall and to minimize computational "spill over."

Because of averaging, the HRAP 4-km rainfall data can sharply reduce the critical rainfall peaks needed for flash flood applications. In addition, the large grid size when applied to small streams produces computational "spill over" errors that might cause the flash flood forecaster to highlight the wrong stream basin in a critical flooding situation. These HRAP 4-km data do not provide the detail needed for flash flood detection on small streams.

The HRAP 2-km data grid appears to be a good compromise between the radial data and the HRAP 4-km data. If the radial data cannot be made available in digital form from the WSR-88D, the digital HRAP 2-km data would appear to be a viable alternative for flash flood applications. However, the HRAP 2-km data would have to be available in eight bit

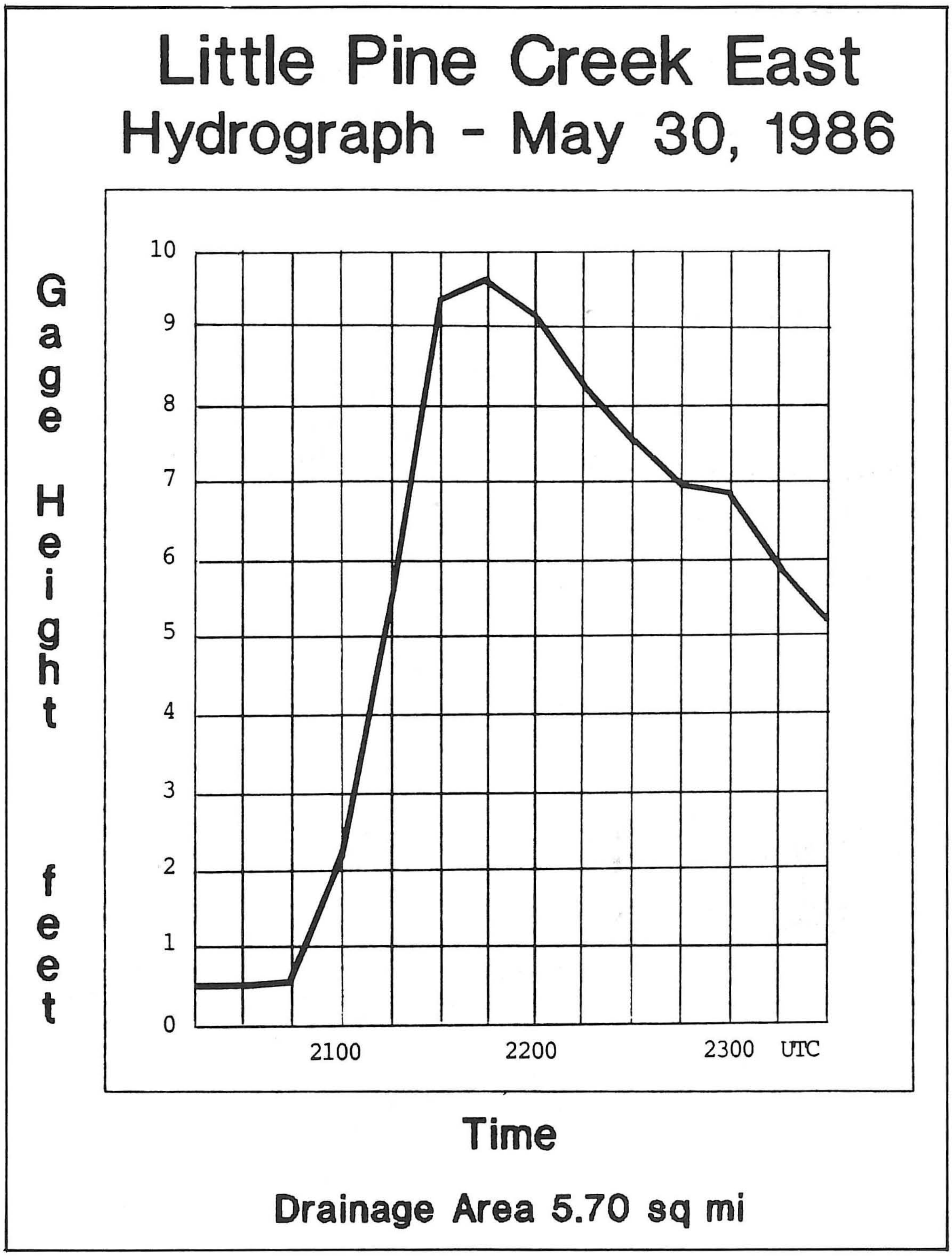

Fig. 13. Hydrograph for Little Pine Creek East, 2015 to 2330 UTC, 30 May 1986.

digital format to provide a direct comparison with FFG. The four bit data available on the WSR-88D for graphic display does not have the required resolution for computation of basin average rainfall on small streams.

The radial data from the WSR-88D will be four times the resolution of the RADAP-II radial data. This increased resolution will produce more accurate basin average and maximum basin rainfall estimates than the RADAP-II BSCAN data used in this study. The radial rainfall estimates are the best tool produced by the WSR-88D for the detection of flash floods. Therefore, every effort should be made to make these data available to the flash flood forecaster in real time.

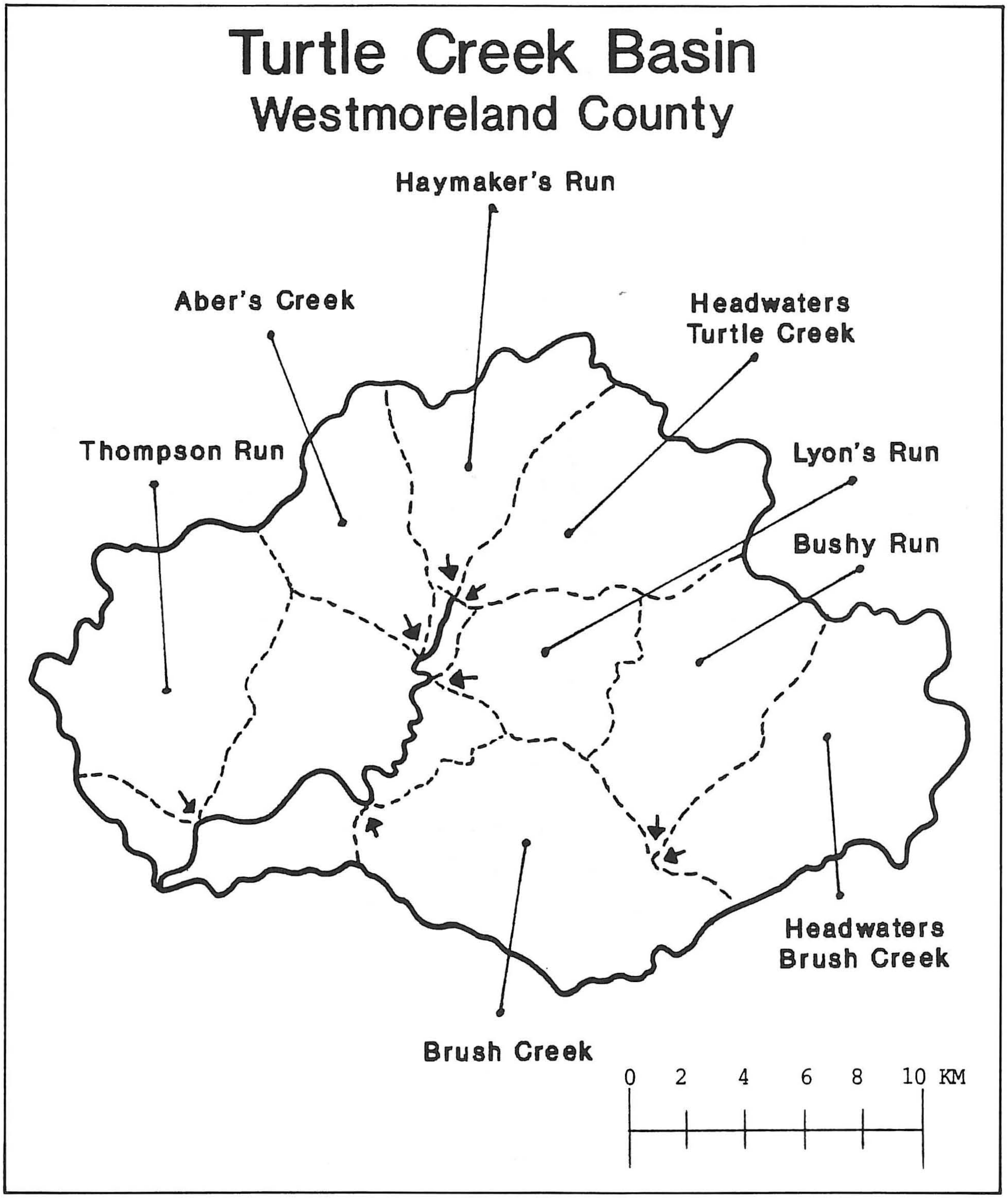

Fig. 14. Turtle Creek Basin—Westmoreland County, Pennsylvania, with sub-basin areas defined.

Acknowledgment

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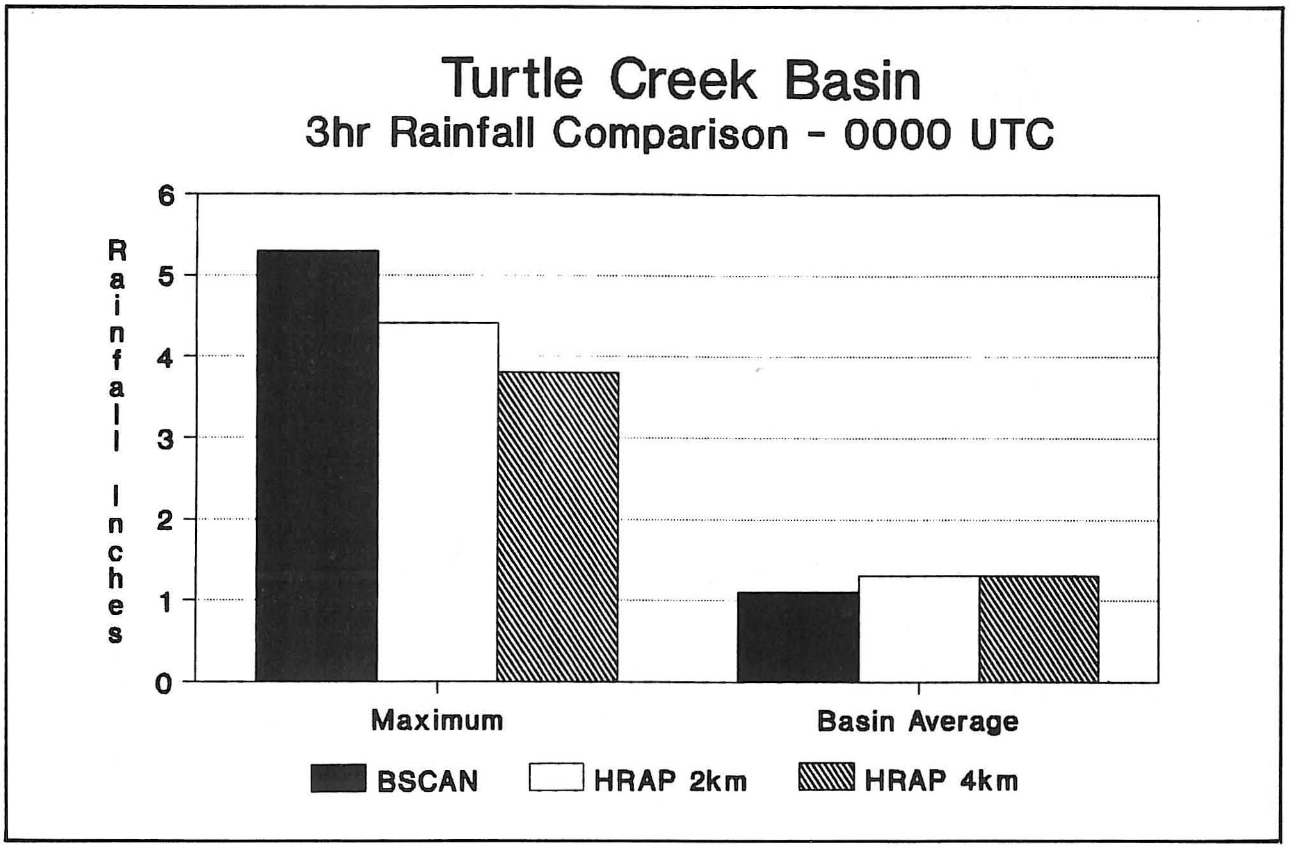

Fig. 15. Three-hr rainfall for the Turtle Creek Basin, 2100 UTC, 15 June 1987 to 0000 UTC, 16 June 1987.

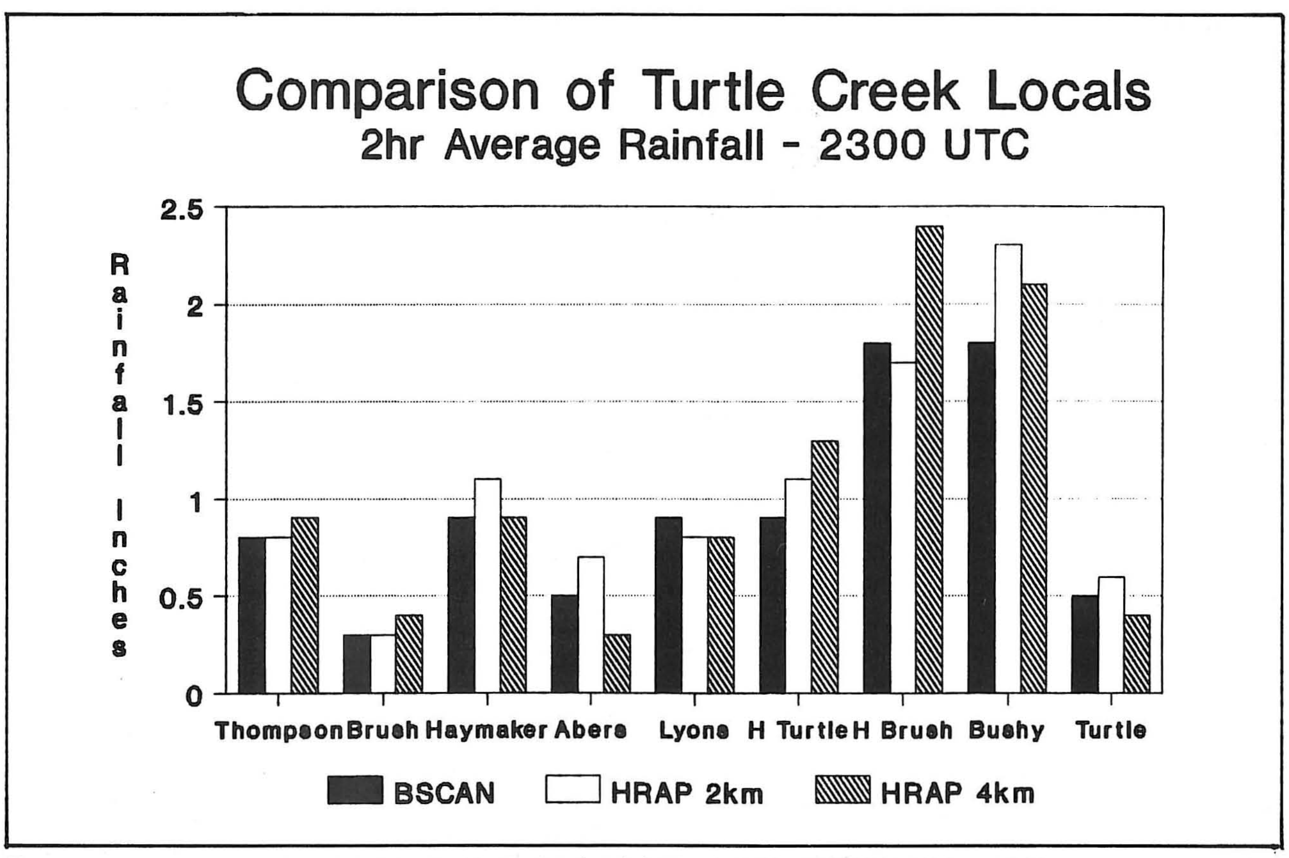

Fig. 16. Basin average two-hr rainfall for the Turtle Creek sub-basins, 2100 to 2300 UTC, 15 June 1987.

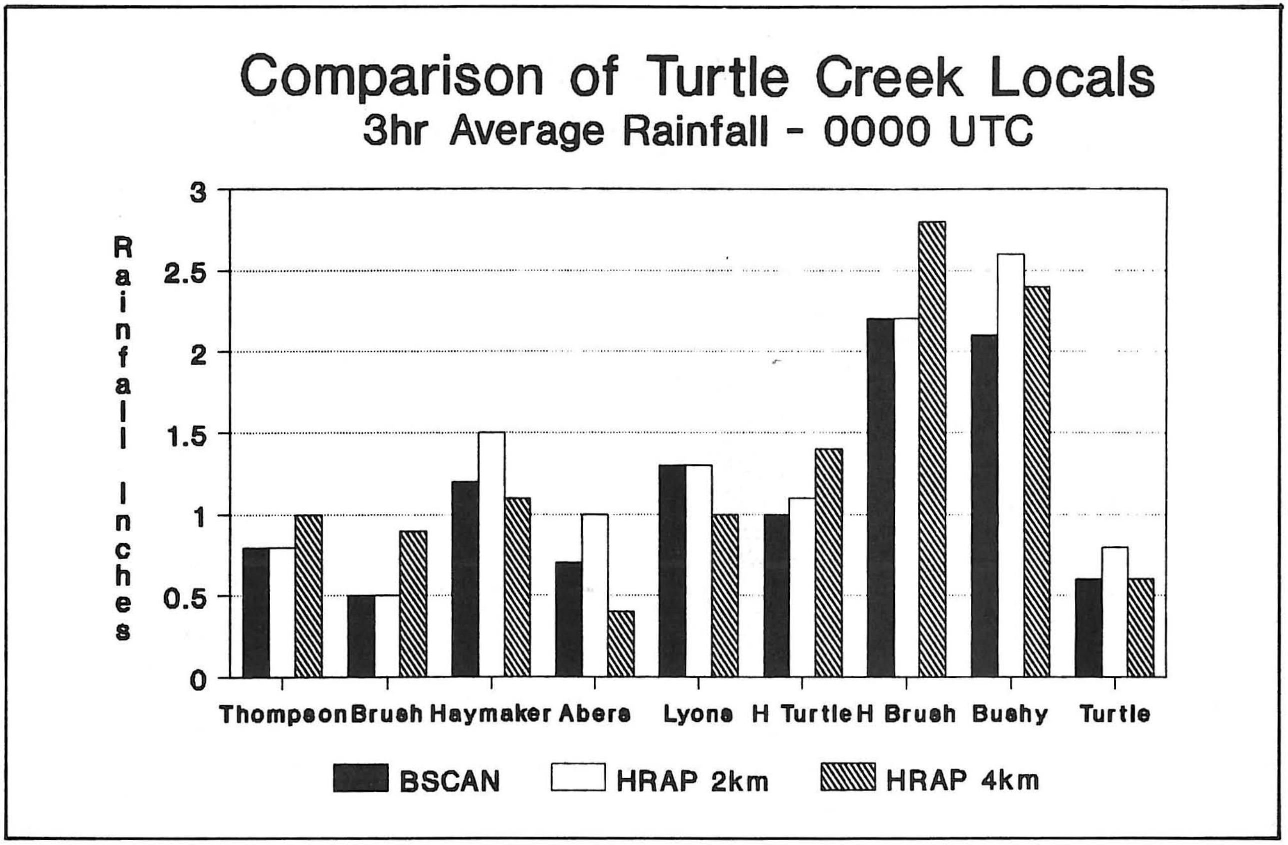

Fig. 17. Basin average three-hr rainfall for the Turtle Creek sub-basins, 2100 UTC, 15 June 1987 to 0000 UTC, 16 June 1987.

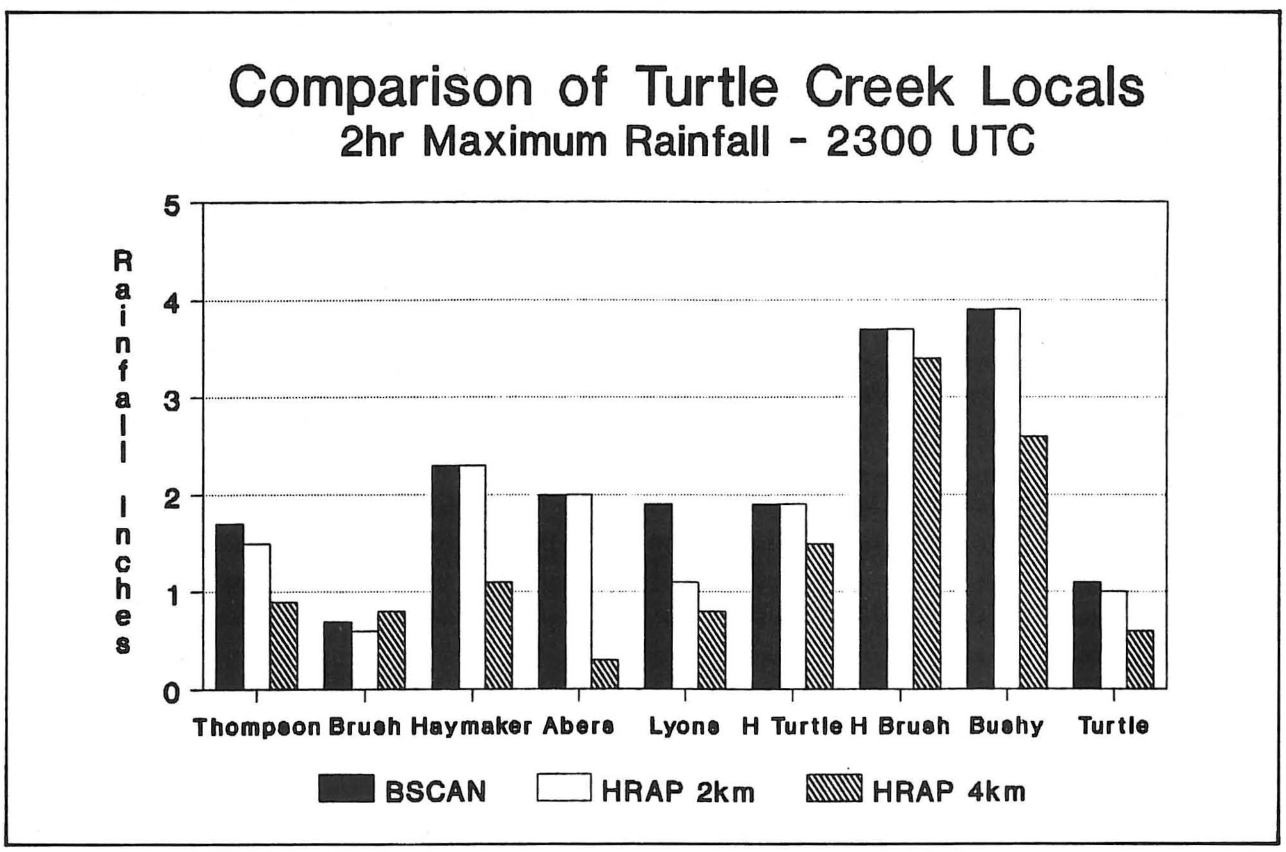

Fig. 18. Maximum two-hr rainfall for the Turtle Creek sub-basins, 2100 to 2300 UTC, 15 June 1987.

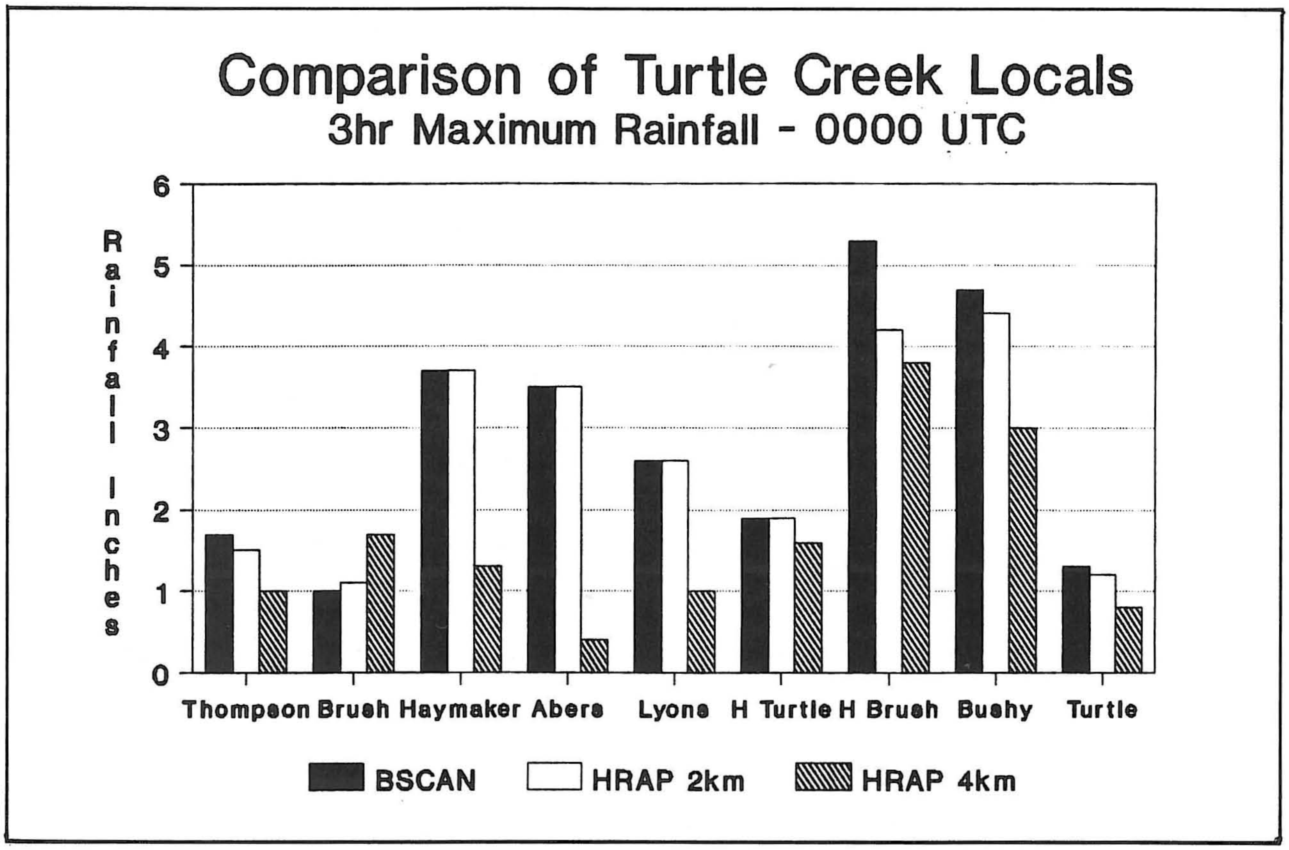

Fig. 19. Maximum three-hr rainfall for the Turtle Creek sub-basins, 2100 UTC 15 June 1987 to 0000 UTC, 16 June 1987.

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